Full-Spectrum Fluorescent Lighting Effects on People: A Critical Review

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Abstract
Full-spectrum fluorescent lighting has been credited with causing dramatic improvements in a wide variety of behaviours, mental health outcomes, and physical health effects. These effects include reduction in dental caries, improved classroom behaviour in schoolchildren, enhanced academic achievement, more efficient visual performance, more attractive appearance of both people and spaces, and improved mood in cases of seasonal depression. Popular media reports have tended to emphasize studies that have demonstrated differences in outcomes as a function of light source spectral power distribution. However, the scientific literature also includes reports with null and contradictory effects. This comprehensive review covers the period 1945-1993 and includes a critical appraisal of the methodology in each study. The studies are grouped according to their dependent variables under the broad headings "Behaviour and Performance", "Mental Well-Being and Affect", and "Physiology and Health". In general, the quality of the research is poor, making it difficult to determine whether or not treatment effects may legitimately be attributed to light source spectral power distribution. A few rigorous investigations of full-spectrum fluorescent lighting have demonstrated small effects; however, few researchers have taken up the challenge to replicate their work. These small effects do not support the claims that full-spectrum fluorescent lighting will produce better performance, mood, or health in the general population. More fruitful avenues for future research include investigations of other lighting parameters including intensity, variability, and flicker and an emphasis on the possibility that individual differences exist in sensitivity to the spectral composition of light sources. The role of mental processes -- for example, beliefs, memories, and expectations -- in mediating the effects of lighting on behaviour stands out as most promising for future research.

1. Introduction

1.1 Background: Lighting Quality

Most people in Western society spend the majority of the day indoors, with the result that most of their light exposure comes from electrical lighting sources. This practice is unlikely to change in the near future. The use of natural daylight to illuminate the interiors of large buildings is a complex architectural problem; without sophisticated design, it is nearly impossible to have daylight more than 6 or 7 metres inside a window (Sundstrom, 1986). Successful use of daylight also requires that the light not be blocked by neighbouring buildings. Moreover, at extreme latitudes, the day length is too short for much of the year to allow sole reliance on natural daylight as a light source.

Whatever the source, the critical issue is the provision of light to meet human needs. The quality of interior lighting is a contentious topic among the lighting industry and lighting researchers, but there is some consensus on the elements that a quality lighting design should provide:

1. There is no disagreement that we light interiors so that people can see.

2. We also use lighting to encourage or to allow certain behaviours and to discourage others. For example, merchandisers use light to highlight particular products in order to attract the attention of passers-by.

3. We use light to maintain health and safety. There are specific treatment regimes that use certain lighting products; codes and standards regulate lighting for emergency situations.

4. In the theatre and in everyday settings, we use light to trigger particular moods or feelings, or to make an aesthetic statement.

The issue is complex because there are no simple rules or products for lighting design that can provide universally good lighting. Needs change depending on the activities or tasks that will go on in each space, and depending upon the characteristics of the people who will perform them. For this reason, the community of people who try to provide lighting continues to disagree on a definition of lighting quality.

Over the past twenty years there have been persistent claims by certain lamp manufacturers and other interested parties that full-spectrum fluorescent lamps provide superior quality light than other types of fluorescent lamps used for general interior illumination in offices, institutions, commercial settings, and light industrial buildings (e.g., Blumenthal, 1992; Henderson, 1986; Ott, 1973, 1982; Tibbs, 1981). As early as 1970, two prominent American researchers suggested that the spectral composition of light sources might be an appropriate target for federal legislation to ensure the maintenance of public health (Wurtman & Neer, 1970). The claims for full-spectrum fluorescent lighting have included reports that these lamps improve visibility, reduce hyperactivity in children, improve academic performance, reduce fatigue in office workers, and improve health generally. A substantial proportion of the public accepts these claims, believing that light that mimics natural daylight is better for work performance and for mood (Veitch, Hine, & Gifford, 1993).

In 1986, however, the United States Food and Drug Administration (FDA) issued a "Health Fraud Notice" against one manufacturer of full-spectrum fluorescent lamps because, in the view of the FDA, there was an absence of sound scientific evidence in support of the health claims made in the lamp's labelling. The notice stated that "much more research is required before firms could justify medical claims for nonprescription use of full-spectrum lamps" (FDA, 1986, p. 1).

1.2 Full-Spectrum Fluorescent Lamps

This review adopts the definition of full-spectrum fluorescent lighting described by Boyce (this volume). A full-spectrum fluorescent lamp is one that emits light in all parts of the visual spectrum and some in the ultraviolet-A region of short-wavelength, high-energy light (UVA, 320-400 nm; UVB is from 290-320 nm and UVC from 200-290 nm), has a correlated colour temperature (CCT) of 5000 Kelvin or greater and a CIE General Colour Rendering Index (CRI) of at least 90. The lamps are designed to mimic natural daylight, although none do exactly.

The colour temperature is an indicator of the colour characteristics of a light source (Helms & Belcher, 1991). Colour temperatures describe the colour of a light source in terms of the colour of a blackbody radiator, which is a theoretical object that radiates energy perfectly. As its temperature increases, the blackbody radiates energy through the visible range, beginning with red, then orange, yellow, blue-white, and finally white. The higher the colour temperature of a lamp, the more blue its appearance.

Fluorescent lamps are not radiators, so an absolute colour temperature cannot be assigned. Instead, we assign a correlated colour temperature, which is the colour temperature at which the blackbody radiator has the same colour appearance as the fluorescent lamp even though they differ in their spectral power distributions. A full-spectrum fluorescent lamp has a higher CCT than other common fluorescent lamps (cool-white, 4100 K; warm-white, 3000K), and therefore appears considerably more blue. Natural daylight varies in colour temperature from 5000 to 10,000 K depending on sky conditions.

The colour rendering index is a metric of the appearance of coloured objects under a given light source (Helms & Belcher, 1991). When we speak of CRI, we concern ourselves with the colour appearance of illuminated objects rather than the colour appearance of the light itself. CRI is a comparison of the colour appearance of objects under the test light source with the colour appearance of the same objects when illuminated by a reference (standard) light source *of the same colour temperature*. The more similar the colour appearance under the test lamp and the reference lamp, the higher will be the colour rendering index of the test lamp. The International Commission on Illumination (Commission Internationale de l'Éclairage, CIE) establishes the standard lamps used as reference lamps for CRI comparisons and other purposes.

It is only meaningful to compare CRI values for lamps tested against the same standard. When the test lamp is as good as the standard lamp in rendering colour, then its CRI equals 100. However, it is incorrect to compare the CRI values of lamps having different colour temperatures because the values are calculated using different reference lamps. The fact that an incandescent lamp has a CRI of 100 and a cool-white fluorescent lamp has a CRI of 62 does not mean that the incandescent lamp renders colours better than a cool-white lamp, but that the incandescent lamp's colour rendition properties are more similar to its standard than the cool white lamp is to its standard. The high CRI of a full-spectrum lamp informs us that these lamps render colour well, in comparison to the 5000 K standard.

The ultraviolet component of the full-spectrum lamp is said to be critical to its beneficial properties (e.g., J. N. Ott, quoted in Cameron, 1986). This component is not visible, and therefore is not perceived; however, light can exert non-visual effects on physiology (see below) that are said to affect behaviour, mood, and health. For this reason, the properties of the luminaires that house the full-spectrum lamps must be taken into consideration. The lighting system will not, by definition, be capable of delivering full-spectrum light if it incorporates a lens that absorbs UV radiation. The commonly-used plastic and glass lenses and diffusers absorb almost all the UV radiation below 400 nm (Whillock, Clark, McKinlay, Todd, & Mundy, 1988), although special UV-transmitting plastics and glass are commercially available.

1.3 Terms of Reference

The present paper is a critical review of the scientific literature concerning full-spectrum fluorescent light, current to January, 1994. In searching the literature for this review, every effort was made to obtain copies of unpublished research reports, doctoral dissertations, and master's theses, as well as published journal articles, book chapters and case studies. In some cases, it was apparent that the same study had been reported in more than one publication, and these cases are noted in the text. The search strategy included all available types of publication; however, the conclusions are based upon an evaluation of each report based on generally-accepted criteria for causal inferences in science (cf. Cook & Campbell, 1979; Platt, 1964). Anecdotal reports and speculation are reported where appropriate, and identified as such.

Stanovich (1989), in *How to Think Straight about Psychology*, provided a popular treatment of the principles of scientific proof that were used in the preparation of this review. There are two questions that one should ask when evaluating a research report. The first question to ask is "Has this study eliminated all the plausible alternative explanations?" If the answer is no, then one cannot conclude that a cause-and-effect relationship exists. Science proceeds by a process of elimination, eliminating rival explanations that do not fit the facts. If a plausible alternative explanation still exists, there is more work to be done before one can make confident claims about causes.

The second question is, "Does this study apply to the situation or people that interest me?" That is, one must take care not to generalize far beyond the original sample, setting, or methodology used in that study. For example, learning techniques that are effective for a four-year-old learning how to play with other children are probably not going to be equally effective in teaching a thirty-year-old to work effectively in a team. The judgement of what is reasonable generalization is often subjective, but fortunately we have methods to avoid excessive generalization: We can collect additional data in new samples and settings to gain a more complete understanding of the phenomenon.

Gifford (this volume) presented a checklist of research design and analysis issues for lighting research that neatly summarizes the criteria used in evaluating the literature reviewed here.

Several difficulties were encountered during the literature review because of the broad variety of different fluorescent lamps used in various investigations and countries. Many research reports included few details about the lamps involved. The label "full-spectrum lamp" has been used in this report only to describe lamps that met the criteria given above. In many studies it was impossible to determine whether a full-spectrum lamp was among the experimental conditions. In those cases, the description as provided in the original publication is given and the ambiguity noted.

Research reports were not consistent in the manner of describing the luminaires housing the lamps. This is an important detail because the use of a standard acrylic prismatic lens would absorb any ultraviolet radiation emitted from the lamp, whereas open fixtures or louvres would permit the transmission of ultraviolet radiation. In general, unless otherwise noted, all experimental conditions within a single study used the same type of luminaire and cover treatment. The specifics of the lighting system are described below, where appropriate.

The presence of daylight in some or all of the rooms used for investigations of lamp type is another potential confounding variable. The variability in illuminance and spectral qualities of daylight over the course of the day and with weather conditions is considerably greater than any differences between fluorescent lamp types. Therefore, it is impossible to characterize precisely to which stimulus conditions subjects responded. Laboratory experiments in general have included controls for this problem by using windowless rooms. Field studies were inconsistent in reporting the presence or absence of windows in the target setting; the presence of windows has been assumed unless otherwise specified.

Special procedures are necessary for correct photometric measurements of different light sources. Common photometric measurements, both of illuminance and luminance, are made using meters calibrated against an incandescent standard. Where the standard differs from the spectral power distribution (as fluorescent lamps do from incandescent), substantial errors in measurement can occur, and the size of the errors varies for each wavelength (Ouellette, 1993). When lamp data for spectral emissions are available, it is possible to calculate the theoretical values for radiant energy, although this procedure assumes that the lamps were operated in the field under conditions identical to the laboratory conditions under which the lamp data were obtained. For measurements of various light sources, Ouellette recommended that researchers use one of three procedures:

- calibrate each photometer separately for each illuminant to be measured;
- use spectroradiometric photometry instead of broad band photometry; or,
- use a broad band photometer having superior spectral responsivity correction

(Ouellette, 1993, p. 29)

The expense and technical difficulty of these careful photometric procedures have resulted in their being relatively uncommonly reported. This makes it difficult to establish that, in fact, the light energy from two fluorescent sources in a single study was the same. Owing to the difficulty in identifying the lamps used in some studies, and the impossibility of obtaining the spectral emissions data for each lamp (some of which are no longer in production), radiant energy calculations were not attempted for this review. The experimental conditions used in each experiment are reported using the metric equivalents of the units in the original report, whether these were radiant energy ($\mu W/cm^2$), luminance (cd/m^2), or illuminance (lux).

The review is organized into three broad headings: Behaviour and Performance; Mental and Emotional Well-Being; and, Physiology and Health. These are summarized in a Conclusion section that includes suggestions for future research. The final section of the paper makes recommendations for lighting applications using full-spectrum fluorescent lighting.

The goal of this endeavour is to provide guidance for lighting designers, building managers, occupational health and safety officers, and others with an interest in providing a quality lit environment. Accordingly, the focus of the discussion is on the use of full-spectrum fluorescent light in lighting interior spaces for everyday use. A complete consideration of its use in treating specific medical conditions is beyond the scope of this review, although the broad issues are discussed where relevant.

2. Behaviour and Performance

In this section we consider the outcomes most traditional to psychology: effects on the acts of organisms. The discussion begins with full-spectrum lighting effects on visual performance because it is a truism that we light interiors to make them visible. Judgements about the appearance of spaces and people within them follow. The final portions of this section deal with the actions of people in places: activity levels, motor task performance, and cognitive task performance.

2.1 Visual Performance

2.1.1 Theoretical rationale. One of the most-often repeated claims is that full-spectrum fluorescent lighting decreases visual fatigue and makes things easier to see. Under demanding and tightly controlled conditions, there is some experimental evidence to suggest that differences in spectral power distribution will affect visual performance. Blackwell (1985) compared four light sources, one of which was a fluorescent lamp described as "chosen to represent as nearly as possible an equal energy spectral power distribution" (p. 344). The figure provided to show this distribution suggests that this lamp would meet our criteria for a full-spectrum lamp. The subjects performed the Landolt ring task for various contrasts, luminance conditions, and viewing distances. (The Landolt ring task is a standard visual performance test. Subjects identify the cardinal direction of a gap in a circular ring.) Blackwell found that the relative "spectral effectiveness" of high pressure sodium, clear mercury, and incandescent lamps all were significantly lower than the spectral effectiveness factor calculated for the full-spectrum lamp.

Berman (1992) has interpreted this finding as consistent with his theory of scotopic sensitivity. The conventional wisdom holds that at the light levels typical of interiors, only the cone photoreceptors in the retina are important to vision; these cells respond most strongly at 555 nm, which is in the yellow-green region of the visible spectrum. The visual sensitivity of this system is known as photopic sensitivity, and is defined by a mathematical function called V_λ. Night vision is dependent on the rod photoreceptors, which are most responsive at 508 nm. This sensitivity function is scotopic, and its mathematical function is known as V'_λ. Conventional wisdom holds that the scotopic system is inactive at the relatively high light levels in buildings today.

Berman's theory differs from the conventional wisdom in that he has found that the size of the pupil depends on the amount of light available to the scotopic system, even at light levels typical of interiors. That is, the more light in the spectral regions to which the rods are sensitive, the smaller the pupil size. Berman (1992) theorizes that two mechanisms are responsible for vision at light levels used in interiors: pupil size controlled by the scotopic system, and foveal sensitivity for detecting colour and shape, controlled by the photopic system. The pupil size effect is important because the smaller the pupil, the greater the depth of field and the better the visual acuity. According to the theory, the improved acuity more than offsets the decrease in retinal illuminance that accompanies the smaller pupil size.

Berman's (1992) theory predicts that lamps having a greater relative proportion of blue wavelengths in the distribution will produce better visual performance. Simonson and Brozek (1948) compared three types of incandescent lamps. The spectral differences between the lamps were tiny, as were the effects on visual functions, but in general the lamp that produced the best performance (a small, but statistically significant, effect) was a lamp then known as a Verd-a-Ray lamp. This lamp indeed had slightly greater emissions in the range 500-540 nm (scotopic), and lower emissions at the photopic peak wavelength of 550-560 nm, than the other two lamps studied.

Berman (1992) examined the outcome of the study by Blackwell (1985) and concluded that one possible explanation for the order of outcome was that the order of spectral effectiveness factors obtained for the four lamps was consistent with the scotopic content of their spectral emissions. The best lamp was the one that appears to have been a full-spectrum source. Full-spectrum fluorescent lamps, according to Berman, should produce better visual performance than other fluorescent lamps because of their greater scotopic content.

Berman (1992) has predicted that a light source with strong emissions around 508 nm in addition to the photopic spectrum will produce optimal visual performance. One benefit of a narrow-band scotopic lamp, he calculated, would be the possibility of energy savings. The overall brightness levels in interiors could be reduced because a scotopically rich light source should be perceived as brighter than conventional sources and should produce better visual performance even at a lower light level. Berman endorsed the use of narrow-band, scotopically-enriched lamps for general office lighting and energy-efficiency; however, as yet such lamps are not generally available. The closest alternative for general use would be a full-spectrum lamp.

To test this prediction, Berman, Fein, Jewett, and Ashford (1993) compared the effects of varying spectral composition and luminance (photometric brightness) on the performance of the Landolt ring task. In this case, variations in spectral composition were achieved by varying the combinations of fluorescent lamps that provided the light around the task (the surround). The task itself was presented on a computer screen so that the brightness of the immediate background and the target ring itself could each be varied independently.

In their first experiment, the photopic brightness of the surround was kept constant at 63 cd/m^2 (measured spectroradiometrically) for the different combinations of lamps, but the composition of the light varied. In one condition the lamps consisted of three red and one pink lamp; in the other condition, one green-blue lamp was used. The contrast levels for the task were relatively low at 15, 23, and 32 per cent. The green-blue lamp produced smaller pupils than the red/pink combination, and there was an interaction of lamp and task contrast on visual performance. For both lamps, performance increased with increasing task contrast, but the increase was linear for the red/pink combination. For the blue-green lamp, the increase in performance was smaller at higher contrast. Performance was greater for the blue-green lamp than for the red/pink combination.

Berman et al. (1993) conducted two additional experiments to examine the effects of changing the surround luminance with the blue-green lamp alone (Experiment 2) and of varying the task background luminance as well as the light source spectral composition (Experiment 3). As predicted, pupil size increased when the surround luminance decreased, and visual performance was also lower. The results of Experiment 3 replicated Experiment 1. In general, the results support the predictions of Berman's scotopic sensitivity theory. However, the task was a demanding one, the detection of a low-contrast target viewed for a brief period. The conditions were not at all similar to the acts typically performed in offices, schools, or homes. It is possible that the subtle effects observed in the laboratory would not generalize to the sorts of visual demands encountered in everyday settings.

2.1.2 Empirical investigations. The final verdict is not in; however, there is evidence to suggest that the effects are not as powerful in the field as Berman and his colleagues have found under strict laboratory conditions. Historically, experiments involving lamp type effects on visual performance have not consistently found the effects predicted by the scoptic sensitivity model.

Maas, Jayson, and Kleiber (1974; also discussed in brief by Kleiber, Musick, Jayson, Maas, & Bartholomew, 1974) varied the fluorescent lamps in a university study hall in one frequently cited experiment. Students did their own work during 4-hour sessions. Every subject attended four sessions, two under cool-white lighting (A) and two under full-spectrum lighting (B); the order of presentation was either ABBA or BAAB. The illuminance levels were equal for both lamp types. The luminaires were equipped with "standard translucent covers" which would have absorbed all light below 400 nm. The presence or absence of windows or natural daylight was not noted. Both subjective and objective measures of fatigue were made; the subjective measures are discussed in a section below.

Hand-eye coordination, measured using a rotary pursuit task, showed no effect of lighting condition. Regarding visual acuity, they reported that after the full-spectrum study sessions, visual acuity had increased, whereas after the cool-white sessions there was no change. Statistical significance was not reported for this effect, however (Maas et al., 1974).

Critical flicker fusion is believed to relate to visual fatigue in that the higher the flicker rate at which the flicker is still perceived, the more sensitive the visual system. A decrease in scores over time is believed to reflect visual fatigue. Maas et al. (1974) reported a (statistically significant) smaller decrease in the full-spectrum condition than in the cool-white condition.

Thus, only one of the three objective measures of visual or neurological fatigue in this widely-cited study showed a statistically significant effect. Its size is unknown because of the absence of the means, standard deviations, and test statistics in the report.

In a field experiment in a classroom, O'Leary, Rosenbaum, and Hughes (1978a) found an effect opposite to the one reported by Maas et al. (1974). Hyperactive children had lower critical flicker fusion rates, indicating greater visual fatigue, following the weeks of full-spectrum lighting than following weeks with cool-white-type fluorescent lamps. The authors reported having attempted to prevent any natural daylight from entering the room, and having approximately equivalent illuminance levels on the desks in both lighting conditions. However, this report also lacks detailed statistical reporting, so the size of the effect cannot be judged.

In 1980, Krtilova and Matousek presented a summary paper at a meeting of the International Commission on Illumination (CIE). They referred to studies that compared a variety of electric lamp types and natural daylight, and measured a variety of physiological and psychological measures of mental workload and visual performance and visual acuity. The paper does not include any details of the data that were obtained, making it impossible to evaluate their statement that "statistical evaluation of control tests shows best result for daylight, Daylight fluorescent and discharge RVLX lamps" (p.

231). The Daylight fluorescent lamp in their sample was said to have a correlated colour temperature of 6500 K, making it likely to have met our definition of a full-spectrum lamp.

Several studies have failed to find significant effects of spectral distribution on visual performance measures. Rowlands, Loe, Waters, and Hopkinson (1971) reported that six types of fluorescent lamp, including a full-spectrum source, did not differ in their effects on the performance of either simple or complex high-contrast (black on white) Landolt ring tasks. For each lamp type, subjects completed Landolt ring tasks at several matched illuminance levels. For the simple tasks, performance increased with illuminance up to asymptote around 1000 lx. Increasing illuminance had little effect when the visual task was more complex, involving the detection of gaps in a convoluted ring.

The 1983 doctoral dissertation study by Chance, which is discussed in greater detail below, involved subjects attending 4-hour sessions in a windowless room lit with either full-spectrum or warm-white fluorescent lamps in luminaires with metal louvres. The Physiological measures were the primary focus of the study, but at the end of each hour of exposure there was a measure of visual acuity using a standard Snellen chart with black letters on a white background. Neither lamp type nor practice effects were found.

Hathaway, Hargreaves, Thompson and Novitsky (1992; also see Hathaway, this volume) compared the visual acuity before the installation of special lamps in five schools with the visual acuity two years later. The students were age 10 at the start of the study. The change in acuity over the two-year period was not statistically significant within any school. However, the statistical test they reported did not test for between-school differences and therefore was not a test of the differential effects of lamp type on visual acuity.

During day-long sessions in a windowless laboratory mock-up of an office, Kuller and Wetterberg (1993) tracked physiological and behavioural outcomes of exposure to either full-spectrum or warm-white (triphosphor) fluorescent light at either 450 lx or 1700 lx. Regarding the visual performance data, they found that visual performance scores were "somewhat better" under full-spectrum lamps than under warm-white lamps. They did not specify exactly how visual performance was measured, except to say that subjects read 6-point texts at a distance of 100 cm; nor did they provide the means or standard deviations of the scores for the four groups. Therefore, it is impossible to determine whether the effect was large or small, nor whether the test was purely visual in nature. When asked to rate the readability of the texts, subjects gave higher scores to the texts when viewed under warm-white lamps. There was no effect of illuminance on either visual performance or readability.

Boyce and Rea (1993; also presented in brief by Rea, 1993b) examined a variety of visual and cognitive performance measures, colour judgements and mood and subjective assessments in three lighting conditions. The results for the visual acuity measure will be discussed here, and other results as they apply in following sections. Each lighting condition was installed in a separate small, windowless office in a commercial office building, and each of the 28 subjects performed the battery of tasks in each of the three rooms. One of the rooms was lit with bright (470 lx) cool-white fluorescent light with parabolic louvres, which is a standard lighting practice for this setting. A second room was lit with bright (470 lx) full-spectrum fluorescent lighting with a multilayer polarizing diffuser (not UV-transmitting). The third room was lit with dim (170 lx) full-spectrum polarized light (the polarizer was not UV-transmitting). Boyce and Rea (1993) observed that this experimental design was selected to permit comparisons of standard practice with bright or dim full-spectrum polarized light; but from an interpretive point of view it poses some problems. It is not possible to separate entirely the effects of spectral composition from those of polarization.

Nonetheless, it is telling that performance on the visual acuity task was poorer for the dim room than for either of the two bright rooms. Only under extreme conditions did performance in the bright full-spectrum polarized lighting room exceed that in the bright cool-white lighting room. When the task was of low contrast, and when contrast was further reduced by the addition of veiling reflections (reflections in the task of light sources overhead), there was a small effect favouring the full-spectrum polarized light. Boyce and Rea (1993) concluded that this outcome is predictable based on what is known about polarization, and is unlikely to be attributable to a spectral difference.

2.1.3 Summary. Under the usual conditions experienced in interiors, it does not appear that full-spectrum lighting produces improvements in visual performance. There may be a small benefit in favour of full-spectrum lighting if the task demands are unusually difficult, but it is not clear that this laboratory finding has any implications for general lighting practice.

2.2 Judgements of Colour and Appearance

2.2.1 Colour rendering. By definition, full-spectrum sources provide good colour rendition: A full-spectrum source, as defined above, has a colour rendering index (CRI) of 90 or greater, in comparison to the standard source in that colour-temperature class (5000 K). Other common fluorescent lamp types, such as cool-white lamps, have colour rendering index values around 60 or 70 (Rea, 1993a), making them poor at colour rendition in comparison to the standard lamp having the same correlated colour temperature (4100 K). Most manufacturers also produce high-CRI lamps in the cool-white fluorescent lamp family, and at other CCT levels.

Boyce and Simons (1977) directly compared hue discrimination under various types of lamps in a series of eight experiments. In some of the experiments they also varied the age of the subjects, the subjects' prior experience with the Farnsworth-Munsell 100 hue task, and the illuminance level. In the experiments that used a full-spectrum source in comparison to sources with lower CRI values, the full-spectrum source produced the fewest errors in colour discrimination and these effects were statistically significant. However, when the full-spectrum source was compared to a lamp with high CRI but a colour temperature of 4100 K, there was no difference in the error rate. In general, colour rendering index was a good predictor of mean error scores. Older subjects did less well than younger ones, and increasing the illuminance level had an effect only on older subjects, whose performance was better under higher illuminance.

In the field study by Boyce and Rea (1993) described above, the subjects performed a colour sorting task with matte and glossy finish colour tiles. In each finish there were six tiles of similar hue, and the task was to sort them into three pairs of matching colours. Both the time taken to perform the task and the number of correct matches were dependent measures of colour sorting. The glossy colours were always sorted more slowly and less correctly than the matte colours, regardless of the room lighting. There was also a main effect of lighting: Colour matching was better in the two rooms (dim and bright) with full-spectrum polarized lighting than in the room with bright cool-white fluorescent lighting.

2.2.2 Judgements of people. One might expect that light sources with high CRI values should give a more flattering, more "natural" appearance to people. On the other hand, we have extensive experience with incandescent lamps for general interior lighting. We accept its warm colour appearance (low colour temperature) as natural; it is the standard for determining CRI in its colour temperature class (3000 K). Therefore, by definition, its CRI is 100, even though it makes blue shades appear dull, and emphasizes reds and yellows.

In the United Kingdom, the Medical Research Council standard for fluorescent lighting in patient areas in hospitals specifies a lamp with a correlated colour temperature around 4000 K and a high CRI (MRC [1965], cited in Lovett, Halstead, Hill, Palmer, Sonnex, & Pointer, 1991). This recommendation was made following experimental trials using a variety of lamps ranging from 3000 K to 6500 K. A recent clinical trial of newly-developed lamps reiterated the earlier findings in that the fewest reported problems of colour appearance and difficulty of diagnosis occurred with lamps having colour temperatures around 4000 K and high CRI (Lovett et al., 1991). However, as a clinical trial, and in view of the existing standard, the investigation necessarily used a limited range of lamp types.

In a laboratory experiment, Boray, Gifford, and Rosenblood (1989) compared judgements of the appearance of live models (among other variables, which will be discussed in the relevant sections below) under warm-white, cool-white, or full-spectrum fluorescent illumination. Groups of psychology undergraduate students were randomly assigned to the experimental conditions, which were equated for illuminance. None of the ratings for attractiveness or friendliness of the male and female model differed significantly in relation to the light source.

2.2.3 Judgements of spaces. An experiment by Aston and Bellchambers (1969) is frequently cited as evidence that full-spectrum lighting improves visual clarity (cf. Karpen, 1991). In fact, there was no full-spectrum lamp in their study. The experiment involved adjusting the illuminance in a model room lit by a "Kolor-rite" lamp (CCT = 4000 K, CRI = 92) until the model room appeared equal in "overall clarity" to a standard model room lit with either white, warm-white, or daylight lamps (3900 K), all of which gave poorer colour rendition. For all three pairs, the Kolor-rite lamp was judged to give equal clarity at lower illuminance. This is to say that the lamp with the best colour rendition (and probably the highest colour temperature) was judged to give equal overall clarity of appearance with less light. Similar results were obtained in full-scale rooms in a follow-up experiment by Bellchambers and Godby (1972). Berman (1992) has interpreted these effects as logical outcomes of scotopic sensitivity producing smaller pupil sizes and greater visual acuity and depth of field.

Laboratory evidence suggests that light sources with higher CRI are preferred over those with lower CRI, but give little indication that the colour temperature of the lamp is important. Wake, Kikuchi, Takeichi, Kasama, and Kamisasa (1977) used model rooms lit with a variety of light sources to examine the relationship between colour temperature, colour rendering index, and illuminance on subjective ratings of appearance. None of the lamps would have met the present definition of a full-spectrum lamp; the daylight fluorescent lamp in this study had a CRI of 77 and CCT of 6500K; the white fluorescent lamp was a 4500K lamp with CRI of 69. There also was a cool-white fluorescent lamp at 4000 K and CRI = 40, as well as clear mercury, high pressure sodium, and incandescent sources.

Wake et al. (1977) analyzed the data inappropriately. Forty-eight subjects is far too few for the number of questions (40 "image" questions and 25 "evaluation" questions) analyzed in the multivariate techniques they used: Factor analysis and principal components analysis both require at least 8 subjects per question in the rating scale (Tabachnick & Fidell, 1983). This weakness makes a discussion of the factor structure irrelevant. Judging from the graphical data representation, it appears that there were only small differences between the lamps, particularly between the fluorescent lamp types. There was a small tendency for higher colour rendering lamps to receive better subjective ratings than lower colour rendering lamps.

Boyce (1977) carefully examined and analyzed subjective assessments of paired comparisons of model rooms lit with various fluorescent lamp types. In the second experiment in this paper, a full-spectrum source was used. This lamp had a correlated colour temperature of 6500 K and colour rendering index of 95. This lamp and another with CCT = 4000, CRI = 92 both gave higher subjective ratings than the other lamps, and were judged to give an equally satisfying appearance at a lower illuminance when either was compared with white or daylight lamps (a replication of Aston & Bellchambers, 1969). For the present discussion, the important point is that there was no intrinsic benefit to the full-spectrum lamp over the others. [Further analysis by Boyce suggested that the best predictor of the balance between illuminance and colour properties of lamps is the Colour Discrimination Index (CDI). The CDI is a measure of the spread (area) between the chromaticity coordinates of the eight standard colours used in the determination of CRI by the International Commission on Illumination, when plotted in the standard way. The larger the area, provided the shape is a reasonable ellipse, the greater the colour discrimination.]

Students rated a university classroom after seminar sessions over eight weeks during which the lighting was varied between full-spectrum and cool-white (Bartholomew, 1975/Kleiber et al., 1974). The report is not clear as to the illuminance levels of the two conditions, but implies that they were equal. The students’ ratings showed no consistent preference for one lighting type or another. Bartholomew (1975) reported that the investigators received the impression that the cool-white lamps were preferred over the full-spectrum lamps, but they attributed this to the familiarity of the cool-white lamps.

McNelis, Howley, Dore, and Delaney (1985) reported that in a series of comparisons of pairs of fluorescent lamps illuminating photographs of common objects in side-by-side booths, the lamp with the higher CRI value was almost always the preferred lamp of the two. The lamp colour temperatures covered a relatively small range from 3000 to 4175 K. Statistical analyses of the data were not provided, and for some of the pairs the difference in relative preference was very small.

Boray, Gifford, and Rosenblood (1989) included a measure of the attractiveness of the room and estimates of its size in their experiment on fluorescent lamp type effects. There were no differences between the ratings for warm-white, cool-white, or full-spectrum lamps on any of these measures. The authors did caution, however, that the experiment was conducted in a relatively achromatic room decorated in beige and grey shades, and that the results might have been different in a more colourful setting.

Baron, Rea, and Daniels (1992, Experiment 1) found differences in the perceptions of a laboratory viewed under warm-white, natural-white, cool-white, or full-spectrum light. It appeared that the cool-white condition was less pleasing overall and that the warm-white condition was somewhat more favourably rated, but the ratings did not vary systematically with either colour temperature or colour rendering index. The low illuminance conditions were generally rated as more pleasing, but the high illuminance conditions were rated as brighter and higher in clarity.

The ratings of room appearance under bright and dim warm-white and full-spectrum fluorescent light did not differ in the mock office experiment conducted by Kuller and Wetterberg (1993). Without a significant omnibus test for the scores on the eight rating scales (none was reported), the univariate tests are suspect because the ratings are not independent. Kuller and Wetterberg reported that the full-spectrum lighting produced lower ratings of "social status" than the warm-white lighting, but this single, small effect is probably a chance occurrence.

Boyce and Rea (1993) found no difference in ratings of the two bright rooms in the experiment described above. The dim polarized full-spectrum room was rated consistently lower than the bright rooms except for ratings of flicker and discomfort glare, neither of which had been expected to vary between the lighting installations (and which did not).

Elderly people may prefer full-spectrum lighting to warm-white lamps (Kolanowski, 1990b). The doctoral dissertation (Kolanowski, 1990a) from which the journal article was adapted reported that the most frequently given reason for the preference was that the full-spectrum source appeared brighter. Illuminance was equated at 300 lux in the two lighting conditions in this study.

Two field experiments of lamp type have produced conflicting results. Cockram, Collins, and Langdon (1970) found that a daylight lamp (4300 K) was preferred for office work both day and night, and the full-spectrum source (6500K) was never preferred either by lighting experts or by occupants. However, there were differences in illuminance between the lighting conditions that may have influenced the outcome. The full-spectrum lamps produced generally lower illuminance than the other types.

Electronic assembly workers reported a preference for full-spectrum light over cool-white in a field experiment in which the factory lighting was switched from one to another (Berry, 1983). The preference was a forced choice question administered at the end of the experiment, after work periods under cool-white, then full-spectrum, then cool-white lamps. A variety of reasons were cited, including the belief that the experimental lamps were brighter (in fact, as discussed below, this experiment was confounded by lower illuminance in the full-spectrum condition than the cool-white condition), that they were "easier on the eyes", and improved visual clarity. It is possible that discomfort glare was lower in the full-spectrum condition because of the lower illuminance level, and this may account for the preference outcome. Alternatively, this may be an instance in which improved visual acuity resulted from a scotopically-enriched source (cf. Berman, 1992), making a demanding job easier, although not sufficiently so to affect performance (see below).

2.2.4 Summary. Fine discriminations between colours are easier under light sources with higher colour rendering indices, which may include full-spectrum lamps. If the task requires such careful judgements, then the use of full-spectrum lamps for interior lighting would be preferable to many other common fluorescent lamp types. Other fluorescent lamps with good colour rendering properties might be expected to provide similar outcomes (cf. Aston & Bellchambers, 1969)[1]. The evidence for effects on assessments of the appearance of people or spaces when fine discriminations are not required shows no substantive difference between lamp types.

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[1]Although Aston & Bellchambers (1969) is frequently cited in support of full-spectrum lamps, it did not include any lamp that would be considered a full-spectrum lamp by most researchers today.

Differences in relative preference, when they occur, appear to relate to differences in the actual or relative illuminance, rather than to lamp spectral qualities per se. The brighter, or apparently brighter, condition is generally the preferred condition. One theory (Berman, 1992) holds that differences in apparent brightness depend upon differences in spectral composition, such that lamps with relatively more blue light should appear brighter; however, the field studies cited above are not entirely consistent with this prediction (e.g., Cockram et al., 1970).

2.3 Arousal and Activity Levels

The suggestion that light from full-spectrum lamps can increase activity levels in animals appears to have originated in observations of captive snakes. Laszlo (1969) reported that certain species, known to be difficult to maintain in zoo cages, had exhibited increased activity when the cage lighting was changed to full-spectrum sources. This report has been widely cited (e.g., Ott, 1973; Blatchford, 1978) in support of the value of full-spectrum light.

Certain aspects of the original article, however, raise the possibility that the observations were the result of a change in illuminance. Laszlo remarked, without providing any photometric measurements, that the " inactivity of some 'difficult' species...may be explained, at least in part, by the use of the wrong type of light and the **inadequate light level** under which they are kept" (1969, p. 13, emphasis in original). Changes in behaviour noted immediately after new lamps were installed may have been the result of the high initial output of new lamps, in comparison to the relatively lower output of the aged lamps they replaced. Without photometric data, and without observations that continued over the life of the lamps, it is impossible to determine the causal factor underlying the behaviour change.

Furthermore, this informal case study has no experimental controls, and therefore cannot eliminate other plausible explanations. A snake that eats after a prolonged period of fasting may simply be hungry; the fact that new lighting had been installed may have been coincidence. Moreover, effects on reptiles may not generalize to humans. What evidence is there for effects of full-spectrum lighting on human activity or arousal levels?

2.3.1 Ratings of activity and arousal. Kolanowski (1990a, 1990b) hypothesized that full-spectrum fluorescent lighting would reduce motor activity and self-reported activity levels in elderly subjects as compared to warm-white fluorescent lighting. Note that this is opposite in direction to the effects cited above for snakes (Laszlo, 1969). Kolanowski's predictions were based on the popular assumption that blue light is less physiologically arousing than red, and on two studies of full-spectrum lighting, neither of which provided compelling evidence for this hypothesis: Maas, Jayson, and Kleiber (1974), as discussed above, did not show robust effects of full-spectrum light on fatigue; nor did Chance (1983, discussed below in the Physiology and Health section) provide unambiguous evidence of reduced arousal under full-spectrum light (the study was confounded by differences in illuminance between the two lighting conditions). [By contrast, Wise and Wise (1988) reviewed the literature on the human factors of colour and concluded that "it is unlikely that a direct physiological response to colour exists" (p. 10).]

The participants in Kolanowski's experiment were aware that the type of fluorescent lighting was the experimental manipulation and each participant was assessed under both lamp types (order effects were controlled by counterbalancing). The illuminance levels were constant at 300 lux in both lamp conditions (measured with an inexpensive light meter, not a spectroradiometer). During a twenty-minute exposure period, two observers rated the body movement of the subject using a standardized rating form. Interrater reliability was high, so an average of the two ratings was the score used in the statistical analysis. Participants rated their level of activation at various points during the twenty minutes. For both the observers' ratings of activity and the self-reports of activation level, there were no differences related to the type of fluorescent lighting (Kolanowski, 1990a&b).

One limitation of this study is its brief exposure time. It is possible that the exclusive use of one type of fluorescent lamp -- for example, in a residential home for the elderly --might have some effect on these variables. There do not appear to be any such field studies on the elderly, nor in other confined settings, performed to date.

However, experimental evidence from young adults also failed to find arousal or activity differences related to the type of lighting, which is consistent with Kolanowski's outcome. In 35-min sessions during which they performed a variety of paper-and-pencil tasks and judgements of appearance, subjects who were unaware that lighting was a variable were exposed to either full-spectrum, warm-white, or cool-white fluorescent light (Boray, Gifford, & Rosenblood, 1989). The mean score on self-report ratings of arousal did not differ between the groups exposed to the various lamp types.

Veitch, Gifford, and Hine (1991) compared full-spectrum and cool-white fluorescent lighting in a between-subjects design in which neither the subjects nor the experimenter in the session were aware of the experimental manipulations. The session was one hour in length. There were no differences between the lamp type conditions in self-reported arousal as rated on a standard mood questionnaire.

Veitch et al. (1991) also varied the information that was provided to subjects about the lamp type in their session. The information sets were positive (saying that full-spectrum light improves performance and mood), negative (saying that the claims for full-spectrum lighting effects have been overstated), or neutral (a description of the spectral power distribution of various light sources). When pre-existing beliefs about lighting were controlled, subjects in the positive and negative information conditions both reported increased Arousal scores on the mood scale and performed better on a reading test in comparison to the subjects in the neutral information condition.

Although there was no effect of the variation in lamp type, providing information about the lamp type affected behaviour. The authors suggested that separate mechanisms may explain the effects for the positive and negative information sets conditions. In the positive information set condition, higher arousal is consistent with the information; this could be an example of a demand characteristics effect, in which experimental subjects tend to provide the outcome the experimenter appears to want. The greater arousal for the negative information set condition is contrary to the information the subjects read; but the phenomenon of reactance occurs when people respond with increased effort to the suggestion that factors may prevent their success. Further investigation is required to determine whether either or both of these effects underlies some of the effects attributed by anecdote to full-spectrum lighting (Veitch et al., 1991).

2.3.2 Motor tasks. Motor tasks are those for which the dependent measure is a physical response: reaction time, grip strength, and the like. Some researchers consider them markers for autonomic arousal or some other (usually unspecified) type of neurological activation. According to arousal theory, there is an "inverted-U" relationship between arousal and performance: If arousal is too low or too high, performance is lower than when arousal is at some intermediate level (e.g., Landy, 1985). For each task there exists, in theory, an optimal arousal level for best performance.

However, although arousal is popularly used as an explanatory, intervening variable, it is not a unidimensional construct (Lacey, 1967/1984). Psychophysiologists (e.g., Blascovich & Kelsey, 1990; Venables, 1984) emphasize that in discussing neural activity, one must speak of *systems*, not of a symbolic construct specified in terms of a few arbitrarily chosen physiological indices. Nonetheless, many investigators do not tie their physiological measures to any psychophysiological theory. More commonly, as in the studies cited here, "arousal" effects are inferred after the fact. Depending upon the choice of response measure, either increases or decreases in "arousal" may appear to occur (cf. Landy, 1985, p. 537; Wise & Wise, 1988, p. 9). If performance dropped when the researcher expected it to increase, then the inference may be made that arousal was shifted to a level too high or too low for optimal performance. This argument is almost impossible to refute because there is no agreement for any task about what the optimal arousal level might be, nor how one might measure it.

The typical prediction is that full-spectrum fluorescent lighting is less arousing than other types (speculations as to why vary from "it mimics natural daylight, to which we evolved" to "it has more blue light, and blue is less arousing" (e.g., Kolanowski, 1990a&b), and that the specific task effects should be consistent with that explanation. If the full-spectrum lighting reduced arousal to a level below the optimum for the particular task, then it would cause performance to drop. Alternatively, if the subject's arousal level was otherwise high, then full-spectrum lighting would reduce arousal in the direction of the optimum level, and performance should increase.

However, Ott (1982) has claimed that fluorescent lighting other than full-spectrum lamps causes muscle weakness. According to Ott, full-spectrum lamps with special radiation shielding are the only fluorescent lighting product that maintain muscle strength; thus, full-spectrum lamps (with shielding, but see note below) should always produce better performance on motor tasks than other fluorescent lamps.

One widely-cited but poorly-reported study involved the addition of ultraviolet lamps to the regular fluorescent lamps in two Soviet classrooms. The study was conducted in 1963-1964, but not reported in the West until 1985 (Zamkova & Krivitskaya, 1985). No details are available concerning the classroom lighting, so the exact spectral composition in control and experimental classrooms is unknown. The mean monthly reaction time data are presented only in graphical form. There are no records of the variability in the data nor of any statistical tests. From the graphs it appears that the students became better over time on the reaction time task (reaction time dropped steadily over twelve months), a change which is likely to be attributable to practice effects. Any difference between the lighting groups was small, particularly in comparison to the change over time.

Chance (1983) hypothesized that full-spectrum lighting would induce less environmental stress than warm-white fluorescent lighting in adult subjects exposed for four-hour sessions that concluded with an exercise test. For reaction time, there was a very small interaction effect in which reaction time remained unchanged over four hours under warm-white lighting, but dropped very slightly under full-spectrum lighting. There was no main effect of lamp type, so neither fluorescent lamp could be said unambiguously to improve this measure. Other physiological measures from this study are discussed below. In general, Chance's results did not consistently support her hypothesis.

Reaction time was another of the dependent variables in the office simulation experiment by Boyce and Rea (1993). They varied the stimulus conditions to which the subjects responded. The stimuli varied systematically in brightness and in the presence or absence of a luminaire image in the VDT screen on which the stimulus was presented. Every subject performed the task in all three rooms (bright and dim full-spectrum polarized lighting and bright cool-white lighting). There was no effect of lighting on reaction time, but reaction times did increase with dimmer stimuli and with reflected luminaire images in the VDT screen. These effects are consistent with predictions based on the visibility of the stimuli (cf. Rea & Ouellette, 1991). There was also a complex three-way interaction, but it did not lead to the conclusion that full-spectrum polarized lighting improves reaction time under any stimulus conditions.

In a series of field experiments in classrooms, Ferguson and Munson (1987) included measures of hand steadiness, grip strength, and reaction time. The authors found that children exposed to full-spectrum lighting decreased in grip strength over a six-week period; this outcome occurred in two replications of the experiment. Hand steadiness was improved under full-spectrum lighting as compared to cool-white lighting for these children in the first experiment, but this outcome could not be replicated. There were no effects of lighting on the reaction time task during the experiments with 10-week exposures to each lighting type, but over 22 weeks, reaction time decreased for students in classrooms with full-spectrum lighting. These results, the authors suggested, may reflect a tendency for full-spectrum lighting to reduce activation; reducing activation would tend to improve performance on the relatively poorly-learned hand steadiness task as well as to decrease grip strength (Ferguson & Munson, 1987).

There were no differences between the cool-white, deluxe-cool-white (better colour rendering properties), and incandescent lamps in three separate groups whose lighting remained the same over the two data-collection periods. The spectral differences between the fluorescent sources and the incandescent source are far greater than the subtle difference between full-spectrum and cool-white lamps. Furthermore, fluorescent sources with conventional magnetic ballasts flicker at a rate of 120 Hz in North America (100 Hz in countries with 50 Hz alternating current). Incandescent sources, although their output does oscillate at the same rate, do so with a far smaller amplitude. Fluorescent lamp flicker at that rate is not perceptible, but there is evidence to suggest that it is detected and may influence neurological function (Wilkins, Nimmo-Smith, Slater, & Bedocs, 1989). These profound differences between conditions should also have caused differences in performance on the motor tasks, if lighting is the explanation. Ferguson and Munson (1987), in discussing all the findings of the classroom experiments, observed that the few effects were all very small in size, and not all could be replicated even with larger sample sizes. They stated that there are no practical implications for classroom lighting from their experiments.

Jewett, Berman, Greenberg, Fein, and Nahass (1986) tested Ott's claim that fluorescent lights affect muscle strength. When objective measures of muscle tension were used, and subjects were exposed to incandescent or fluorescent sources, there was no effect of lighting on shoulder muscle strength.

In the second experiment reported by Jewett et al. (1986), Ott himself was the judge of subjective muscle strength. All the lighting was Ott's daylight-simulating combination of fluorescent and ultraviolet lamps in a specially designed luminaire (the special lamp and luminaire would have met our criteria for full-spectrum lighting). An aluminum mesh screen surrounded the lamps to provide grounding of the electromagnetic field that Ott believed to be the source of the muscle effect. The system was wired so that the grounding could be switched off or on without Ott's awareness. Testing was performed under double-blind and unblinded conditions (in the latter, both Ott and the subject knew whether or not the fixture was grounded).

The results demonstrated that the expectancy of the judge was met in almost 100% of the unblinded trials: when the fixture was ungrounded, Ott reported muscle weakness; when grounded, Ott reported normal strength (Jewett et al., 1986). In the double-blind trials, the reports of muscle strength or weakness were consistent with the grounding condition at chance level. That is, there was no evidence for systematic muscle weakness as a function of the grounding of the wire screen, but powerful evidence that the judgement of muscle weakness is an expectancy effect on the part of either the observer or the subject.[2]

Full-spectrum and cool-white fluorescent lighting were systematically varied in an electronic assembly plant and established measures of work efficiency were examined during each period (Berry, 1983). The experiment used an ABA design in which cool-white lighting provided the baseline (A), full-spectrum the experimental condition (B), and then a second baseline period of cool-white lighting (A) was assessed. The assembly room was windowless and all the lamps were unshielded by lenses or louvres. Mood and preference results from this experiment are discussed elsewhere in this review.

If full-spectrum lighting improved neuromuscular function, one would expect work performance to improve under full-spectrum lighting. One difficulty with this experiment is that the lamp-for-lamp replacement of cool-white with full-spectrum lamps reduced workplane illuminance, which might have reduced work performance if it reduced the visibility of the fine components being assembled. However, this effect might have been offset by reduced pupil size improvements in depth of field and visual acuity, if one adopts Berman's (1992) theory of scotopic sensitivity. Berry's (1983) results showed no effect of lighting on work efficiency. It is not possible to determine whether competing mechanisms cancelled one another, or if the viewing conditions were not extreme enough to be influenced by scotopic sensitivity, or if the change in lamps also changed other aspects of the lighting geometry, such as discomfort glare.

Overall, there is no robust evidence to support the claim that full-spectrum lighting affects motor performance differently than other light sources. Only Ferguson and Munson (1987) found small effects that might be consistent with the hypothesis that full-spectrum lamps reduce neurological activation; however, they did not find other effects on neurological function that one would predict based on the differences between different lighting technologies. Other field experiments and simulations have failed to find the predicted effects. Instead, experimental evidence suggests that expectancy effects are more powerful explanations of the reports that fluorescent lighting affects muscle strength and activation. One issue that has yet to be resolved is the discrepancy between the predicted direction of these effects: Does full-spectrum light reduce activation, possibly to the detriment of performance on simple tasks, or does it prevent muscle weakness, and therefore improve performance?

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[2]Furthermore, in testing the effectiveness of the grounding, Jewett et al. reported that although the grounding of the mesh screen effectively reduced its electromagnetic field to background levels when tested in the laboratory, the background levels in an ordinary house are greater than an ungrounded Ott fixture tested in a laboratory. Thus, although the experimental manipulation was real, the net effect of surrounding the lamps with a grounded mesh screen would be negligible outside a laboratory setting, .

2.3.3 Classroom activity levels. The underlying assumption in the literature concerning children is that the use of a light source believed to simulate natural daylight will improve classroom attention and reduce problem behaviours such as the severe restlessness and distractibility characteristic of children with attention deficit disorder (ADD; also known as hyperactivity). Investigations have been undertaken using a variety of different subject populations: severely handicapped children, children diagnosed with ADD, learning disabled children in first grade, normal children in first grade, and normal children in grades 3 or 4.

Several classroom studies will be discussed in this literature review: the studies by Hathaway et al. (1992), Kuller and Lindsten (1992), Ferguson and Munson (1987), and Mayron, Ott, Nations and Mayron (1974) will be discussed in several sections. Most of the classroom studies have a fundamental research design problem: Children within classrooms are not independent subjects. The experimenter cannot, in general, randomly assign students to classes; therefore, it is probable that there are existing differences between classes in ability, experience, personality variables and rates of maturation. Furthermore, students within a single class receive more similar instruction than students in different classes. Their behaviour and development are influenced by interactions between students in the class. Even when health is the measure, students are not independent because within each classroom they expose one another to contagion.

Experimental design and statistical analyses require that each subject be independent of the others (Keppel, 1982; Kirk, 1982). In most cases in the review, the analyses did not take into account the violation of this fundamental assumption; that is, these analyses used the incorrect units of analysis. The appropriate analysis would be to use a nested design to separate the classroom effects from the student effects; this requires more classrooms in each treatment condition. Only one study in this review adopted this approach (Norris, 1979). Some of the other studies exacerbated this problem by assigning treatment conditions to separate schools and failing to control or to measure differences in parental involvement, instructional style, administrative differences (e.g., policies about absenteeism, conduct rules), socioeconomic differences and the like, which were therefore confounded with treatment differences. All of the school studies discussed in this review must therefore be interpreted cautiously.

Ott (1976) installed cameras for time-lapse photography in classrooms in an elementary school in Florida in early 1973. Two of the classrooms had cool-white fluorescent lamps; two other classrooms were fitted with full-spectrum lamps having lead foil shields wrapped around the ends of the tubes (Ott suspected that X-radiation is emitted by the cathodes of fluorescent lamps). Illuminance levels were not reported, but the replacement of cool-white lamps by full-spectrum lamps would have reduced illuminance levels by approximately 30% because of their lower output. Ott used no systematic data collection for behaviour or classroom performance and no experimental controls, but reported that in the full-spectrum classrooms "less nervousness was evident and overall performance was better" (p. 22). He reported specifically that one child in one classroom had, over three months after the installation of full-spectrum lamps in one of the original cool-white classrooms, "changed to a quieter child...he had even learned to read during the short period of time" (p.23). The possibility that the change in this child’s behaviour might have been related to any action by the teacher, the parents, or to normal maturation was not mentioned.

The discussion section of Ott’s (1976) article contained several speculative attempts to link the author’s lighting investigations, including wholly anecdotal personal observations, with: drug treatments for hyperactivity; drug and alcohol addiction; the use of artificial food colourings and flavours as putative triggers for hyperactivity; and, radiation from television sets as triggers of hyperactivity. At least one special education teacher was motivated on the basis of this article to attempt a field trial of incandescent lighting in place of the usual fluorescent lighting in her classroom (Painter, 1977). She reported a drop in hyperkinetic activity, but also stated that teachers described the room as "warm, pleasant, homelike, restful, and noninstitutional" (p. 183). The possibility that the children responded to the changed atmosphere or to a change in teacher behaviour was neither tested nor discussed. This is an example of what Henker and Whalen (1980) called "a premature bandwagon effect, with widespread publicity and classroom interventions occurring in the absence of adequate empirical justification" (p. 328).

Mayron, Ott, Nations and Mayron (1974) conducted a larger-scale trial of full-spectrum lighting in first-grade classrooms. In this study, two rooms were fitted with full-spectrum cathode-shielded lamps and with grounded aluminum mesh screen to shield against low frequency electromagnetic radiation (see below under Motor Tasks for a discussion of this issue), and two were left with the regular cool-white lamps. The report states that in the full-spectrum classrooms, the illuminance ranged from 650-850 lx, but no illuminance measurements were reported for the cool-white rooms. The lamps were replaced one-for-one, but cool-white lamps are more efficient, which makes it likely that the cool-white rooms were brighter than the full-spectrum rooms.

The measurement period lasted for six months from January to June. Time-lapse photography was used in all four classrooms and student behaviour was coded using unspecified criteria to produce a score for "total time of hyperactive behaviour". Academic achievement was also assessed at three times during the semester; the results for those data will be discussed in the appropriate section below.

The data for hyperactivity suggest that hyperactivity dropped in the full-spectrum classrooms but may have increased in the cool-white classrooms over the study period. The difference was statistically significant, but the data presented in their paper (Mayron, Ott, Nations and Mayron (1974), Figure 2, p. 36) suggest that the control and experimental rooms differed initially in level of hyperactivity: the control rooms had fewer extremely high scores than the experimental rooms. The change over time, in which the low-scoring rooms increased and the high-scoring rooms decreased, could be an example of statistical regression, in which scores tend towards the overall mean (cf. Cook & Campbell, 1979).

Other methodological flaws also prevent the inference that lighting spectral composition was the cause. There was no random assignment of subjects to classrooms, no control for differences in the teachers' behaviour, no control for the awareness of the experimental manipulations by the people doing the behavioural coding, and, as already noted, the illuminance level in the two lighting conditions probably differed.

O'Leary, Rosenbaum, Hughes (1978a) performed a systematic replication of the Mayron et al. (1974) study, using children previously diagnosed as hyperactive, controlling for illuminance level differences and expectancy effects on the part of teachers, observers, and children. They used a previously validated measure of classroom behaviour as the dependent measure of hyperactivity, and included a measure of fatigue (critical flicker fusion, discussed above). Full-spectrum and cool-white lamps were alternated, week by week, for eight weeks. There was no effect of lamp type on any hyperactivity measure. The authors report that an effect for block (each pair of weeks was one block) was statistically significant, but did not discuss it (nor did they report the descriptive statistics that would allow it to be evaluated by other researchers). This suggests, however, that hyperactive behaviour changes in frequency over time.

Mayron (1978) and O'Leary, Rosenbaum, and Hughes (1978b) exchanged views on the appropriateness of this experiment as a replication of the Mayron et al. (1974) study. Mayron held that O'Leary et al. (1978), in using a classroom of diagnosed hyperactive children, had tested a different hypothesis than his group had done in studying a regular, rather than a special-education, classroom. However, other reviewers have judged the O'Leary et al. study to be methodologically stronger (e.g., Henker & Whalen, 1980).

Norris (1979) compared warm-white, daylight, and full-spectrum lamps for effects on attending behaviours of first-grade students. Baseline observations were made of behaviour under cool-white lamps. All the data were coded using a fixed set of criteria for nonattending behaviours from videotapes of classroom activity, and inter-rater reliability was assessed as adequate.

On one of five behaviours there were statistically significant effects: the frequency with which children broke eye contact with the task was lower for warm-white lamps than full-spectrum lamps. That is, children were more attentive to the task under the warm-white lamps than under the full-spectrum lamps. Norris (1979) noted a number of differences in illuminance and colour between the classes that might have confounded the results (colour differences could mean that wall reflectances differed, further affecting the light levels on desks and displays). Also, the classes that were changed to full-spectrum lamps had initially lower levels of this behaviour, so the posttest scores in warm-white and full-spectrum scores overlapped substantially. This study does not support the contention that fluorescent lamp type has a substantial effect on classroom attending behaviour.

Wohlfarth and Sam (1982) videotaped classroom interactions in a special education classroom with severely multiply-handicapped children, some of whom were blind, under the original lighting and interior decoration conditions (including cool-white fluorescent lighting) and in a specially designed colour psychodynamic modification of both the colour of the walls (specific colours were chosen for walls and furnishings as a test of Wohlfarth's theory of how colour affects behaviour, mood, and physiology) and furnishings and of the lighting (changed to full-spectrum fluorescent lamps). Phases 1 and 3 were the standard classroom conditions; Phase 2 was a period of exposure to the modified environment. Physiological data collected in this study are discussed below. The videotape data was coded by one rater who was aware of the experimental manipulations. The behavioural data were not analyzed for statistical significance, but nevertheless the authors reported that aggressive and self-destructive behaviour dropped after Phase 1. This is attributed to the effects of the colour psychodynamic changes (the design does not permit separation of the contributions of light and colour). However, comments from the teachers provide evidence that teacher behaviour, growing familiarity with being videotaped, and general awareness of the experimental hypotheses are strong competing explanations for the data.

Learning disabled children were the focus of a classroom lighting intervention study by Schulman (1989). During the period of each day that these children spent in special education classes, some were in rooms lit with full-spectrum fluorescent light and others were in rooms lit with cool-white fluorescent light. For the rest of the day all the children were in regular classrooms with cool-white lamps. Distractibility was measured by standardized tests and by teacher ratings on both special education and regular classrooms (the teachers were aware that this was part of a study of classroom lighting). There was no possibility of random assignment to classes, and the pupils in the full-spectrum classes were somewhat younger than those in the cool-white classes.

There was no effect of lighting on the standardized tests of distractibility, but over time, distractibility declined. There was an interesting effect of lighting on teacher ratings of distractibility. Special education teachers in rooms with cool-white lighting rated the students as more distractible than did special education teachers under full-spectrum lighting or regular classroom teachers with cool-white lighting. This is more suggestive of an expectancy effect on the part of some teachers than it is of a lighting effect on the students (Schulman, 1989).

The carefully-designed classroom experiments in Victoria provided limited evidence in support of the hypothesis that full-spectrum fluorescent light reduces undesirable classroom activity in comparison to cool-white fluorescent light (Ferguson & Munson, 1987). Videotape data coded using standardized procedures, having reasonable inter-rater reliability, and analyzed using the correct model for this nested experimental design, showed that a statistically significant decrease in the frequency of students inappropriately leaving their seats occurred under full-spectrum fluorescent illumination as compared to cool-white illumination in one experiment. However, this effect did not replicate in the second experiment, and none of the other task attention or classroom conduct variables demonstrated statistically significant relationships to lighting condition. Boray, Gifford, and Rosenblood (1989) noted that the classrooms used in the Ferguson and Munson experiment had large windows (both research teams are from the same university in British Columbia), which may have either confounded or reduced the spectral differences between the classrooms, depending on their orientation, and on the time of year and time of day of the observations.

Kuller and Lindsten (1992) followed classroom behaviour in four Swedish classrooms over one school year. Two of the classrooms had windows, and two did not; one windowed classroom and one windowless classroom were fitted with full-spectrum fluorescent lamps. The other two classes had warm-white lamps. Videotapes were made four times during the year and coded using a validated method. Factor analysis was used to establish two components to the coded behaviours: Ability to Concentrate and Sociability. (A variety of other variables were also examined and are discussed in detail elsewhere in this review.) As in the other classroom studies, it was not possible to randomly assign students to classes nor to eliminate entirely the possbilities for differences between the classes in instruction or experiences over the school year.

Windows, rather than lamp type, appeared to influence the seasonal pattern in scores for Ability to Concentrate (Kuller & Lindsten, 1992). The seasonal patterns were similar in the two windowed classes, regardless of lamp type, and in the windowless classes, regardless of lamp type, although there was no overall mean difference in the ability to concentrate in one classroom type or the other. Windows also appeared to influence seasonal changes in Sociability scores. No simple effects of lamp type were evident. Moreover, both scores varied markedly over the school year. It is not clear whether biological responses to the changing seasons, social responses to the progressing school calendar, maturation factors, or behavioural responses to changing (or unchanging, in the windowless rooms) lighting conditions underlie this variation. For lighting practice, perhaps the clearest statement that can be made is that this study does not provide clear guidance as to the optimal lighting type for influencing classroom behaviour.

2.3.4 Summary. The literature survey reveals that the type of fluorescent lamp makes little difference to activity or arousal in humans. In adults, the expectation that lighting will have an effect appears to be more powerful than the lighting itself. Contrary to some early reports, full-spectrum fluorescent light is not a panacea for childhood hyperactivity, nor does it control undesirable classroom behaviours. Of the well-designed studies, only one has found a statistically significant effect, and that only on one measure of attention. Windows, rather than the type of artificial light, may be more influential for classroom behaviour in children.

2.4 Cognitive Tasks

2.4.1 Academic achievement. Many of the classroom studies already discussed have included measures of academic achievement. One difficulty with classroom measures, as already noted, is that different classes have different teachers as well as different lighting systems. This makes it particularly difficult to attribute differences in achievement to the lighting system.

Mayron, Ott, Nations and Mayron (1974) administered a standardized achievement test at the beginning and end of the six-month treatment period in the four first-grade classes (recall that two had full-spectrum radiation-shielded lighting, and two had cool-white lighting). One of the two experimental rooms had a very large number of students whose academic achievement rose dramatically over the six months; but, the other experimental room had a very small number of students with large changes. The students in the latter room appear to have begun the study at a slightly more advanced level than the former room. The two control rooms were intermediate between the experimental rooms in terms of the levels of the students at the start of the study, and in the degree of change over the six months. The authors themselves noted that the results are more likely to relate to differences between teachers than to the experimental manipulations (they also may relate to selection differences between classrooms).

In the following academic year, Mayron, Mayron, Ott, and Nations (1976) again followed the academic progress of the students. They lacked any control over the assignment of students to classes and over differences in instruction style or other teacher behaviours. No clear pattern of results emerged from classes with full-spectrum versus cool-white fluorescent lighting. To the limited extent that any pattern was discernible, the existing differences in student ability between classes probably account for it. Classes with students already at a high level of achievement tended to show less change over the test period; however, no statistical tests were conducted or reported.

The complete lack of any experimental control and the absence of details about procedure and analysis make it impossible to reach any inferential conclusions about the reasons for the academic achievement in these classrooms. The logical impossibility of causal inference was noted by Mayron et al. (1976) in the introduction to the paper. Nonetheless, the report should never have received publication. It appears to have been a platform for a 2-page discussion of unrelated research projects about the modern phenomena that the team regarded with suspicion. This discussion left the unfortunate impression that a variety of loosely related studies of both animals and humans, regarding the purported effects of electromagnetic radiation, television viewing, and biological effects of light, could provide the logical support for the conclusion that classroom lighting had caused the differences reported in the study. These unrelated studies do not, however, alter the fact that the research design in the Mayron et al. (1976) study lacked the rigorous control required to infer that differences in classroom lighting caused differences in academic achievement.

The other substantial classroom study of full-spectrum fluorescent lighting is the two-year trial by Hathaway et al. (1992; see also Hathaway, this volume). This study not only lacked control for differences between teachers, but used different schools in different communities for each of the lamp type conditions. Parental involvement; socioeconomic status; administrative policies and practices; pre-existing differences in ability, experience, and achievement; and, differences in maturation rates all are potential confounding variables in this study.

The investigators did attempt to control for existing differences in achievement by using pretest scores as a covariate in an analysis of covariance (ANCOVA). The performance measure was a standardized test of academic skills including reading, arithmetic, vocabulary, language, and work study (related scores like this should be tested first with an omnibus test using multivariate analysis of variance; cf. Gifford, this volume). The report does not provide the details of the data on the subtests for each school; nor does it specify whether the subtest scores at pretest were the covariates in the corresponding ANCOVA for the change in subtest scores from pre-to post-test. The authors report that statistically significant differences between schools were found for total achievement, language, work study, and mathematics.

The report does not provide the details for the subscale effects, but there is a table for the total achievement gains. The table shows separate t-tests for each possible combination of schools, with no correction for the inflation of error rates in these nonindependent comparisons. The authors stated that the smallest improvement occurred in the school with high-pressure sodium lighting and the greatest in the schools with full-spectrum or ultraviolet-enhanced full-spectrum lighting (ranks 1 and 2). This is a true statement, but misleading. Not only are causal attributions about lighting meaningless, but the means for the first- and second-ranked schools (full-spectrum lighting and ultraviolet-enhanced full-spectrum lighting) differed more (0.29 versus 0.08) than the means for the second- and third-ranked schools (ultraviolet-enhanced full-spectrum lighting and the cool-white lighting). The third-and fourth-ranked schools differed by as much as the top two (0.27). If the spectral qualities of the lighting caused differences in academic achievement, it is very peculiar that the ultraviolet-enhanced full-spectrum lighting and cool-white lighting schools had almost identical mean scores, both lower than the mean for the full-spectrum lighting.

This finding, incidentally, is consistent with that observed informally by Zamkova and Krivitskaya (1985). There was no systematic difference in achievement between the classrooms with added ultraviolet lamps and those with regular fluorescent lamps in the school in Leningrad.

The one experiment that has been able to control for teacher differences is the field experiment by Ferguson and Munson (1987). Rather than rely on achievement data, they used measures of attention and memory administered by the teachers in the classrooms. The teachers were aware that this was part of an experiment, but not of the hypotheses under test. There were some problems noted with the reliability of the data because of the use of classroom teachers with limited instruction in the administration of these tasks. Ferguson and Munson reported slightly lower performance on a symbol-digit substitution task under full-spectrum as opposed to cool-white lighting; however, there was evidence that this was confounded by pre-existing differences between groups. The less able students may have clustered in the classroom that was exposed to full-spectrum lighting first; these students improved by the second condition, giving the appearance of a benefit to cool-white lighting. There was no pre-test data available for use in analysis of covariance to test this speculation.

The data on school achievement does not permit any firm conclusions about lighting effects. It does, however, provide a textbook demonstration of the difficulty in conducting field experiments in school settings.

2.4.2 Effects on adults. Both field experiments in university classrooms and laboratory experiments with controlled conditions have been conducted to test the hypothesis that full-spectrum lighting enhances performance. None have found support for the hypothesis, although there is evidence to suggest that lighting conditions can influence performance on nonvisual tasks. This evidence points to cognitive mediating processes, rather than simple deterministic responses to spectral differences.

Seminar classes were conducted in a room lit either with full-spectrum or cool-white lamps, alternately week by week for eight weeks. The students rated the quality of the discussion, of the teacher's and students' ideas, and their own interest and learning during the session. Videotapes were made of the classroom interactions. There were no systematic differences in any of the ratings nor of the behaviours coded (Bartholomew, 1975; also reported in brief by Kleiber, et al., 1974).

Blais (1983) obtained permission to vary the lighting in a university lecture hall. Students were given their course examinations under either full-spectrum or cool-white fluorescent illumination (classes were divided in half and the two halves did mid-term and final examinations in counterbalanced lighting conditions). Students also predicted their examination scores immediately after each examination. There were no differences of lamp type on either actual or predicted examination performance.

In addition to the classroom experiments described above, Ferguson and Munson (1987) also performed a laboratory experiment in which university students performed a computer-based memory task in a windowless room lit with either cool-white or full-spectrum fluorescent lamps. The room illuminance was 300 lx in both lighting conditions. Each of the 36 subjects participated in both experimental conditions (order of presentation was counterbalanced). Performance on a sensitive, commonly used measure of memory did not differ under the two lamp types.

A variety of simple cognitive tasks were measured during exposure to either warm-white, cool-white, or full-spectrum fluorescent lighting in a carefully controlled laboratory experiment with young undergraduate subjects. A composite score was created from subtests involving grammar and arithmetic problems performed under time pressure. Lamp type had no effect on performance (Boray, Gifford, & Rosenblood, 1989). The subjects also were asked to assign a starting salary to a fictitious job candidate whose resume they were given to read. This variable, too, was unaffected by differences in lamp type.

The office simulation experiment reported by Boyce and Rea (1993) found no effects of lighting on ratings of a fictitious job candidate or on performance of a memory and comprehension task. This experiment used a within-subjects design so that the subjects were probably aware that lighting was the focus of the experiment; this evidently did not bias their performance in any way. This is interesting in view of the evidence that the response to interior lighting is mediated by cognitive processes like expectations or affect.

Veitch, Gifford, and Hine (1991) assessed reading comprehension and the timed grammar and arithmetic task used by Boray et al. (1989). The experiment showed no effects of cool-white versus full-spectrum fluorescent light on any measure. However, providing information about the expected effects of full-spectrum lighting did cause improvements in reading performance (and self-reported arousal scores; see above). This was true whether the information set stated that full-spectrum lighting improves performance and decreases fatigue, or whether it stated that there is no evidence to support claims about full-spectrum lighting. Two cognitive processes, demand characteristics and reactance, were offered as possible explanations for the reactions to the two information sets; alternatively, providing information about lighting may increase arousal sufficiently to affect task performance.

Baron, Rea, and Daniels (1992) varied illuminance and spectral power distribution in a laboratory setting to test the hypothesis that lighting conditions that produce positive affect (mood) would also improve cognitive performance and ratings of others. The first experiment used four fluorescent lighting conditions: warm-white, natural-white, cool-white, and full-spectrum, and two illuminance levels: 150 lux and 1500 lux. The ratings of others were simulated performance appraisals of a fictional employee; cognitive task performance was measured using a word categorization task. There was an interaction of lamp type and illuminance: for all lamps except the cool-white lamp, the performance appraisals were higher for the low illuminance condition. Performance appraisals were higher in the high illuminance condition for the cool-white lamp. There was no main effect of lamp type on the performance appraisals. For the word categorization task, subjects in the low illuminance condition included a wider range of words in specific word categories than subjects in the high illuminance condition. Low illuminance and warm-white lighting tended to be somewhat more favourably rated, but there were no systematic differences in ratings of either positive or negative affect in relation to the lighting conditions on a questionnaire measure of affect.

Two additional experiments were conducted to further explore the hypothesis that reactions to interior lighting are mediated by affective reactions. These experiments were factorial comparisons of cool-white and warm-white fluorescent lighting and low and high illuminance on a variety of cognitive and social behaviours including willingness to help, conflict resolution, and clerical task performance. Experiment 3 included manipulations known to influence affective states directly. The results tended to support the hypothesis that lighting conditions can influence performance on a variety of tasks that do not involve primarily visual processes.

The results of these experiments are provocative because not all the dependent measures showed similar effects and because the mechanisms for these effects are not known (Baron, Rea, & Daniels, 1992). The authors discussed several possibilities, each involving different nonvisual, cognitive processes (e.g., arousal, priming of specific memories or experiences, and familiarity with lighting conditions in particular settings).

2.4.3 Summary. Studies of full-spectrum fluorescent lighting effects on cognitive performance fall into two categories: studies of academic performance in schoolchildren, which tend to use quasi-experimental field study methodology, and studies of cognitive performance in adults, which are mostly laboratory experiments. The lack of control in the field studies makes causal interpretation meaningless. In the few cases that have observed performance differences between classrooms, the differences are small. More importantly, these investigations confound lighting differences with differences between classes in teacher behaviour; and with pre-existing differences between classes in ability, experience, and maturation rates. The laboratory experiments involving adult subjects attain a higher standard of experimental control. although at the expense of a strict replication of naturally-occurring conditions. These experiments have entirely failed to show any direct effect of fluorescent lamp type on cognitive behaviour. Recent evidence does provide an intriguing new direction for investigation, with the possibility that the effects of lighting on behaviour are mediated by nonvisual cognitive processes such as memory and the interpretive meaning of the lighting in a particular setting.

2.5 Summary: Behaviour and Performance

The overall picture of behavioural effects of full-spectrum lighting that emerges from this segment of the literature review does not support the dramatic reports sometimes read in the popular press (e.g., Blumenthal, 1992; Cook, 1994; "Report card...", 1993). There may be benefits to increasing the blue wavelength component in lighting for extreme, difficult tasks, but there is no evidence that this necessitates providing a spectral power distribution that would be described as full-spectrum. Any light source with a high colour rendering index, including a full-spectrum lamp, can be beneficial when extremely fine judgements about colour are required. For general appraisals of the appearance of people or spaces, there is no evidence that lamp type has any effect. As for effects on activity, arousal, or cognitive task performance, there is no compelling evidence for simple, deterministic effects favouring full-spectrum lighting. There is evidence to suggest that subtle reactions to interior lighting influence our overt behaviour, but these are not associated in any simple way with full-spectrum fluorescent lamps. Improved understanding of these processes may, ultimately, result in meaningful guidelines for design practice.

3. Mental Well-Being and Affect

The claim that full-spectrum fluorescent lighting is beneficial to mood is persistent. A substantial percentage of people hold the belief that lighting that simulates daylight makes people feel happier (Veitch, Hine, & Gifford, 1993). Furthermore, as Stone (1992) noted, the media coverage of the use of phototherapy with full-spectrum lamps to treat some psychological disorders has led some to assume that all interiors should be provided with full-spectrum lamps for the betterment of emotional well-being in the general population.

The present discussion of the relevant research is divided into two sections beginning with a consideration of the clinical issues in the treatment of seasonal mood disorders and their implications for general lighting. The second half of this section concerns full-spectrum lighting effects on mood and well-being in the general population.

3.1 Full-Spectrum Fluorescent Lighting and Mental Health

3.1.1 Clinical indications and mechanisms. Diagnoses of mental disorders are made by professionals according to criteria set out in the Diagnostic and Statistical Manual of Mental Disorders (DSM) of the American Psychiatric Association (APA). The revised third edition, published in 1987, known colloquially by its acronym DSM-III-R, is in general use. A fourth edition was published in late 1993.

Mood disorders (formerly called affective disorders) involve prolonged emotional states that "color the whole psychic life" (APA, 1987, p. 213), involving either elation or depression. These disorders include depressive episodes (when the symptoms occur in a single distinct period of time), bipolar disorders (commonly called manic-depressive illness), and depressive disorders (disorders are diagnosed according to the pattern of mood episodes). Any mood disorder may exhibit a seasonal pattern.

The best known seasonal disorder is depressive disorder with seasonal pattern; in the popular press this is what usually is meant when Seasonal Affective Disorder (SAD) is discussed. Despite the implication in media and advertising claims, these disorders are not mild cases of unhappiness that one would call "the winter blues". Severe disruption of everyday life is required for the diagnosis of a mood disorder. All diagnoses of mood disorders require that organic diseases be ruled out, as is grief accompanying bereavement (APA, 1987). The diagnostic criteria for a major depressive episode are given below to illustrate the extent of the behavioural change required for a clinical diagnosis.

At least five of the following behavioural changes are required for the diagnosis of a major depressive episode. They must have been present during the same two-week period and one of the symptoms must be either depressed mood or loss of interest or pleasure.

1. depressed mood most of the day, nearly every day
2. markedly diminished interest or pleasure in all or almost all activities
3. significant weight loss or weight gain when not dieting (e.g., more than 5% of body weight in a month); or increase or decrease in appetite nearly every day
4. insomnia or hypersomnia nearly every day
5. psychomotor agitation or retardation nearly every day (observable by others, not merely subjective feelings of restlessness or being slowed down)
6. fatigue or loss of energy nearly every day
7. feelings or worthlessness or excessive or inappropriate guilt (which may be delusional) nearly every day
8. diminished ability to think or concentrate, or indecisiveness, nearly every day (either by subjective account or as observed by others)
9. recurrent thoughts of death (not just fear of dying), recurrent suicidal ideation without a specific plan, or a suicide attempt or a specific plan for committing suicide.

(APA, 1987, p. 221)

For the diagnosis of a seasonal pattern of a mood disorder, four criteria are applied:

A. There has been a regular temporal relationship between the onset of an episode of Bipolar Disorder (Including Bipolar Disorder NOS) or Recurrent Major Depression (including Depressive Disorder NOS) and a particular 60-day period of the year (e.g., regular appearance of depression between the beginning of October and the end of November).

Note: Do not include cases in which there is an obvious effect of seasonally related psychosocial stressors, e.g., regularly being unemployed every winter.

B. Full remissions (or a change from depression to mania or hypomania) also occurred within a particular 60-day period of the year (e.g., depression disappears from mid-February to mid-April).

C. There have been three episodes of mood disturbance in three separate years that demonstrated the temporal seasonal relationship defined in A and B; at least two of the years were consecutive.

D. Seasonal episodes of mood disturbance, as described above, outnumbered any nonseasonal episodes of such disturbance that may have occurred by more than three to one.

(APA, 1987, p. 224).

Estimates of the incidence of seasonal mood disorders vary, but are generally in the range of 7-9% of the population (cf. Hill, 1992). A case can also be made for the existence of a milder disorder, termed subsyndromal-SAD, which affects 13-18% of the North American population (cf. Hill, 1992; Kasper, Rogers, Yancey, Skwerer, Schulz, & Rosenthal, 1989). In subsyndromal-SAD, there is sufficiently severe impairment of function to warrant psychiatric attention, but not all of the DSM-III-R criteria are present.

There is no generally agreed-upon mechanism to explain seasonal mood disorders. Hill's recent review (1992) noted that the link between changes in total daily light exposure, and not seasonal changes in temperature, appears well established as an environmental trigger to these disorders. Circadian rhythms are usually disrupted in these patients, and such changes are linked with the secretion of melatonin and prolactin in animals. However, studies of hormone and neurotransmitter levels in SAD patients have not clearly identified differences between the patients and healthy control subjects (Hill, 1992). Nonetheless, some interrelationship between melatonin, serotonin (its biological precursor and a neurotransmitter implicated in mood disorders in general) and SAD appears to exist. Drugs that increase serotonin release have been effective in treating SAD, and improvements in SAD symptoms are often accompanied by advances in circadian phase delays (Hill, 1992).

In healthy subjects, exposure to monochromatic (509 nm) light overnight suppresses melatonin secretion in a dose-dependent manner (Brainard et al., 1988). The brighter the light, the greater the suppression of melatonin. However, when Dollins, Lynch, Wurtman, Deng, and Lieberman (1993) varied the brightness of the cool-white illumination in workstations at which male subjects worked overnight on computer tasks, the expected (and obtained) dose-dependent suppression of melatonin secretion was not accompanied by any changes in any behaviour or mood measure. Thus, the relationship of melatonin to behaviour and mood is not clear.

This brief consideration of the clinical issues involved in seasonal mood disorders serves merely to lay the ground for the discussion of phototherapy which follows. A sizeable, but identifiable, proportion of the population may experience seasonal changes in mood severe enough to require professional assistance (a total of up to 25% by some estimates). These changes appear to be connected to changes in light exposure. The question we turn to next is, what is the evidence that full-spectrum light is important to light therapy for these people?

3.1.2 Phototherapy of seasonal mood disorders. Norman Rosenthal and his team are generally credited with pioneering this field of study. Full-spectrum lamps are reported in these studies from the beginning, although no theoretical reason was stated for the choice. Clinical case studies do not include control groups, but are careful records of the outcomes of treatment trials; these began in North America around 1980 (cf. Rosenthal et al., 1984) with some success. Successful uses of light therapy with full-spectrum fluorescent light for seasonal mood disorders have also been reported by Fleischhauer, Glauser and Hofstetter (1988) in Switzerland and by McIntyre, Armstrong, Norman, and Burrows (1989) in Australia.

Rosenthal et al. (1984) presented data from a controlled crossover trial of 11 depressed patients in winter in Maryland. Light therapy using bright (2500 lux) full-spectrum lamps for three hours before dawn and three hours after dusk was effective in improving symptoms in all patients. Dim yellow light was the control condition, and was ineffective in all but one patient. Rosenthal et al.

believed that the effective mechanism was the extension of the photoperiod (the daily time of light exposure) by bright light. The dim light control was believed to be biologically inactive because of its intensity, although they did not rule out the possibility of spectral effects.

Wirz-Justice, Bucheli, Graw, Kielholz, Fisch, and Woggon (1986) compared photoperiod extension using bright full-spectrum light or dim yellow fluorescent light in a Swiss population. Both light treatments were effective, but there was evidence that the bright full-spectrum light treatment had a longer-lasting effect than the dim yellow light. The team noted that the effectiveness of yellow light might have been a placebo effect; an alternative explanation is that some subjects (who self-administered the light therapy in their homes) may have been close enough to the yellow lights to have received a brighter exposure than the researchers intended.

In 1985, Rosenthal, Sack, Carpenter, Parry, Mendelson, and Wehr reported an investigation that controlled for spectral differences. The dim light condition used neutral density filters to reduce the light transmission from the same lamps that had delivered the bright light therapy. In the initial study, light therapy was administered in both morning and evening sessions every day, but when some patients entered the follow-up period, only evening sessions were used. The bright light treatment was effective in both cases in reducing depressive symptoms to a statistically significant degree; the dim light was not.

Similarly, Hellekson, Kline, and Rosenthal (1986) reported that two hours of bright full-spectrum light was effective in reducing depressive symptoms in Alaskan patients with seasonal mood disorders, regardless of whether the treatment was administered in the evening, in the morning, or one hour each in evening and morning. The time of day at which phototherapy occurred seemed not to affect the treatment efficacy.

Contradictory results occurred in a widely-cited study by Lewy, Sack, Miller, and Hoban (1987). Morning phototherapy with bright light (full-spectrum and cool-white lamps produced the same effects, therefore Lewy et al. combined the data from the two light conditions) advanced melatonin secretion onset and produced the greatest antidepressant effect. Evening light delayed melatonin onset time and produced a smaller antidepressant effect. When phototherapy was split into morning and evening sessions on every day, the outcome was intermediate.

Isaacs, Stainer, Sensky, Moor, and Thompson (1988) failed to replicate the results of the Rosenthal et al. (1985) study for the dim light condition. Full-spectrum fluorescent light therapy was effective in improving depressive symptoms. The improvement occurred regardless of whether the administration was an extension of the photoperiod using either bright or dim full-spectrum light, or if it was a four-hour period of bright light phototherapy at midday. However, the bright light conditions showed a small trend towards greater improvement of symptoms than the dim light condition. Isaacs et al. concluded that the mechanism of action of phototherapy may not involve a phase-shift effect dependent on melatonin secretion.

Variation in the spectral composition of phototherapy lights was the independent variable in a therapeutic trial by Brainard, Sherry, Skwerer, Waxler, Kelly, and Rosenthal (1990). In this experiment, the researchers controlled the photon density of the three light conditions (blue, full-spectrum white, and red), apparently on the theory that the number of photons incident on the retina is the dose-determining measure for phototherapy. This inevitably produced differences in all other photometric and radiometric values for the three conditions (for example, the photopic illuminance for the full-spectrum light was 2236 lx, for blue 638 lx, and for red 603 lx).

The outcome of this experiment did not clearly demonstrate the superiority of any of the three phototherapy conditions. The scores on a standard measure of depression, administered after a week of phototherapy for two hours morning and evening, were not different for the three light conditions. However, the number of patients who experienced a drop of 50% or more in their depression scores was greatest for the full-spectrum condition. Thus, the more conservative measure of depression did not reveal a treatment effect, although the number of people responding to treatment suggests that white light, rather than blue or red coloured light, is more efficacious (Brainard et al., 1990). This effect could, alternatively, be a function of the differences in apparent brightness that would have existed between the differently coloured light sources. The patients' reported expectations of the outcomes for the different light therapy sources did not differ, which implies that this result is not a placebo effect.

The role of melatonin in phototherapy of seasonal mood disorders was cast into further doubt by a British trial in which bright full-spectrum light therapy of either two or six hours per day had equal effect on plasma melatonin suppression, yet the antidepressive effect was clearly greater in the six-hour condition than the two-hour condition (Winton, Corn, Huson, Franey, Arendt, & Checkley, 1989). The two-hour phototherapy condition appeared to have little more effect on depressive symptoms than the dim red light control condition, although the team did not report the statistical test to confirm this relationship.

All of the preceding studies used full-spectrum fluorescent lamps. Other lamps can also produce successful antidepressive effects:

Kripke, Rische, and Janowsky (1983) found a small but immediate improvement in scores on a standardized measure of depressive symptoms following one hour of treatment using bright warm white fluorescent lamps. The control comparison was one hour of dim red light exposure. Bright incandescent lamps were successful in improving symptoms of seasonally depressed patients in an open trial (Yerevanian, Anderson, Grota, & Bray, 1986).

Bielski, Mayor and Rice (1992) reported a carefully-controlled study that compared full-spectrum and cool-white fluorescent sources in a 2 x 2 crossover design. This is one of few reports that reported both spectroradiometric and photometric measurements. For the full-spectrum condition, illuminance was 2690 lux and the irradiance, measured spectroradiometri cally, was 675 $\mu W/cm^2$. For the cool-white condition, the illuminance was 3013 lux and irradiance 600 $\mu W/cm^2$. Thus the cool-white condition might have appeared slightly brighter, but the full-spectrum condition delivered slightly more radiant energy. In both cases, acrylic lenses removed UVB emissions below 325 nm.

Phototherapy sessions in the Bielski et al. (1992) experiment were two hours long, administered every morning for seven days. Subjects were treated with one light source for one week, withdrew from light therapy for one week, and crossed to the other light source for one week. The dependent measures were standard measures of depression and atypical depressive symptoms, administered by a trained clinician with no knowledge of the treatment assignments of the subjects. The data were analyzed appropriately using repeated measures analysis of variance and are reported in full. The only statistically significant effect in this experiment was for the light therapy treatment itself. Depressive symptoms were relieved after light therapy. The light source used for the therapy made no difference to the treatment outcome. This outcome is consistent with that observed by Lewy et al. (1987), who reported all data in one group because the lamp type had no differential effect on the dependent measures.

Bielski et al. (1992) noted two limitations to their findings. The sample size was small, which reduced the statistical power of the study. A larger experiment might have been able to find a treatment effect. Alternatively, it is also possible that both lamp types had a placebo effect on depressive symptoms. Bielski et al. noted that researchers in this field have yet to develop a plausible placebo control for nonspecific effects of phototherapy.

Phototherapy studies typically have included examination for ophthalmic side effects of prolonged exposure to bright lights and have failed to observe any. Nonetheless, concern has been expressed that if the light source emitted significant ultraviolet radiation, there may be undesirable long term side effects. The relative efficacy of phototherapy with and without the ultraviolet portion of the spectrum has attracted research attention in recent years.

Lam, Buchanan, Clark, and Remick (1991) used specially prepared eyeglasses that either transmitted wavelengths below 400 nm, or blocked them, to alter the spectral composition of light reaching the retinas of subjects receiving light therapy from full-spectrum lamps shielded with ultraviolet transmitting diffusers. In a third condition, the eyeglasses were tinted to reduce the light intensity from 2500 lux to 500 lux. The dim light had no antidepressant effect. The bright UV-light condition showed statistically significant improvement in both typical and atypical depressive symptoms; the UV-blocked light showed significant improvement only in the ratings of atypical symptoms. However, the authors cautioned that the small sample size weakened the power of the comparison.

The same team later conducted a larger trial of ultraviolet radiation in phototherapy using light boxes containing cool-white fluorescent lamps and special UVA lamps (Lam, Buchanan, Mador, Corral, & Remick, 1992). Again, the subjects wore eyeglasses that either transmitted or blocked wavelengths below 400 nm, although there was no dim light condition. The bright light phototherapy significantly improved both the typical and atypical depressive symptoms, but there was no difference between the UVA and UVA-blocked conditions.

It is clear that phototherapy with bright light is an effective non-pharmaceutical treatment for seasonal mood disorders. Furthermore, few adverse effects have been noted in any study, although most studies report that a small number of subjects fail to maintain the treatment regimen for one reason or another. The mechanism underlying the treatment effect is unknown, and debate continues concerning the ideal time of day and duration for phototherapy sessions (Hill, 1992). There is no evidence to support the claim that full-spectrum fluorescent light, or any other lamp type, produces superior treatment outcomes for SAD.

3.1.3 Phototherapy and eating disorders. In the early popular reports about full-spectrum light, anecdotal effects on plants and animals were used to support the argument that full-spectrum fluorescent lamps are superior to other types (e.g., Ott, 1973). Laszlo (1969) reported his observations of zoo snakes whose cage lights were changed to full-spectrum lamps. He reported increased feeding in species known to be difficult to maintain in captivity following a change from cool-white lamps.

The effects of lighting on eating behaviour in humans have been limited to one case study and one controlled study of the effects of phototherapy for bulimia nervosa having a seasonal pattern. Lam (1989) reported that a patient given bright full-spectrum phototherapy improved in mood and had fewer binge-eating episodes than during a crossover trial with dim full-spectrum light.

Lam and his colleagues followed this case study with a controlled trial (Lam, Goldner, Solyom, & Remick, 1992). Patients with bulimia nervosa with or without a seasonal pattern underwent light therapy using bright cool-white light of 10,000 lux for 30 minutes in the early morning or dim red light at 500 lux for 30 minutes each morning. There was an overall treatment effect of the bright cool-white light indicated by improved mood and reduced binge/purge episodes and relapse under the dim red light. The improvement was greater for the patients whose bulimia showed a seasonal pattern. Lam et al. (1992) observed that it is not clear whether the reduction in binge/purge episodes is secondary to the improved mood. Several of the patients had concurrent diagnoses of seasonal depression, which muddied the interpretation of this outcome.

Regardless of the precise mechanism, it is worth noting that phototherapy shows promise as a treatment for bulimia nervosa. Further investigation is necessary, but present evidence does not suggest that the effectiveness of the therapy is necessarily dependent upon the use of full-spectrum fluorescent light.

3.1.4 Phototherapy and the general population. The availability of a simple, relatively inexpensive, nonpharmaceutical treatment for a clinical condition is a boon. If the treatment were also effective in nonseasonal mood disorders or if it improved mood in people generally, many people would benefit. The generalization from the special clinical population to other people underlies many of the claims made by advertisers of home phototherapy units. What evidence is there to support this generalization?

In the study by Yerevanian et al. (1986) discussed above, nonseasonally depressed patients served as the control group. The nonseasonally depressed patients did not benefit from the phototherapy with bright incandescent light.

Lahmeyer (1988) examined physiological effects of bright light exposure in two people previously diagnosed as having seasonal depression and three people with no personal or family history of psychiatric disorders. The treatment did appear to affect the patients differently than it did the control subjects. Evening bright light prevented the normal drop in temperature and in heart rates in the patients. It also delayed sleep onset in the patients, and both experienced subjective activation. In the control subjects, bright light prevented the evening temperature drop in one person but not the others, and there were no effects on heart rate. Two of the control subjects had delayed sleep onset after bright light exposure, but less so than the patients. None of the control subjects reported any subjective effects of bright light exposure. These results are limited by the small sample size; moreover, the two patients were not in depressive episodes during the study. The study suggests, but does not conclusively demonstrate, that healthy people and people with a history of mental disorders, respond differently to phototherapy.

More systematic studies using nonclinical populations have also found different effects from the studies of patients meeting the DSM-III-R criteria for mood disorders with seasonal pattern. Kasper et al. (1989, Study 1) found no changes in mood or activity following morning exposures to either bright or dim light. Study 2 examined people with no reported seasonal mood difficulties and those who reported mild symptoms of seasonal mood disorders (subsyndromal-SAD). Light therapy was effective in the subsyndromal subjects, but caused no change in psychometric ratings for the normal subjects.

This finding was replicated in another study in which phototherapy caused mood and behaviour improvements in subjects having the full syndrome or subsyndromal-SAD, but had no effect on normal subjects (Kasper, Rogers, Madden, Joseph-Vanderpool, & Rosenthal, 1990). The sample size in this study was not large and it is possible that a larger, more sensitive study might be able to detect a treatment effect in normal subjects. However, small sample sizes have not prevented the detection of treatment effects in the clinical studies of phototherapy discussed above. If there is an effect in the general population, it is not as powerful as in the people suffering from clinically-diagnosed seasonal mood disorders.

Another way to examine the distinction between the sufferers of seasonal mood disorders and normal individuals is to assess their responses to ordinary indoor lighting. One investigation to date (Heerwagen, 1990) has taken this approach, examining room brightness preferences and mood scores in people who met the minimal criteria for seasonal mood difficulties, whether full-blown or subsyndromal, in comparison with matched controls. The tests were conducted seven times over 8 months from October to June, in Seattle, Washington. The subjects who showed seasonal patterns in mood symptoms consistently preferred brighter rooms than the matched controls. These subjects also had lower mood than the matched controls. The absence of seasonal variation in the mood scores over the study is a problem for the interpretation of the data, although it is possible that the study concluded too early in the year for spontaneous mood improvement to have been observed.

Kasper et al. (1989) proposed a theoretical model of seasonal mood disorders in which a portion of the population is more vulnerable to a lack of light than others. Heerwagen's (1990) study suggests that this group might be identifiable. For these people, it is possible that providing more light in everyday interiors could operate as a preventive. Further investigation, including a replication of Heerwagen's study, are required before this suggestion leads to design changes.

3.1.5 Summary. The American Psychiatric Association recognizes that certain mental disorders have seasonal patterns; the best-known of these is popularly called Seasonal Affective Disorder. Most patients diagnosed with this condition experience recurrent depressive symptoms in the winter months. Phototherapy with very bright light has proven to be an effective, non-pharmacological treatment for this disorder. There is no evidence that the spectral qualities of the light source contribute to the efficacy of the treatment. A proportion of the population (estimated as high as 25%) experiences less severe symptoms that some researchers have labelled "sub-syndromal SAD". These individuals also have benefitted from bright light phototherapy. Outside of these special populations, there is no benefit to be realized by the use of phototherapy. Phototherapy of mood disorders is an effective treatment, but has no implications for general lighting practice.

3.2 Affect and Full-Spectrum Fluorescent Lighting

3.2.1. Mood effects. Although claims that full-spectrum fluorescent light will improve mood have been many, relatively few studies have systematically examined the effects of full-spectrum lamps on mood. Smith and Rea (1979) did not include a full-spectrum lighting condition, but their experiments with cool-white fluorescent, metal halide, and high pressure sodium lights failed to find any differences on feeling ratings such as "bad-good", "tense-relaxed", "sleepy-alert", "tired-rested", "comfortable-uncomfortable", and "discouraged-satisfied". The literature search for full-spectrum lighting investigations of mood effects identified four field experiments, one with schoolchildren and three with adults, and three laboratory experiments with adult subjects.

Both colour and light were independent variables in the investigation of <u>colour psychodynamics</u> by Wohlfarth and Gates (1985). The details of the colour manipulation are not important to the present discussion; there was a control condition and an experimental condition of specially chosen colours. The two lighting conditions were cool-white fluorescent light and full-spectrum fluorescent light. Four schools were involved in this study. One was unmodified, having control colours and cool-white lighting. One school was refurnished and repainted with the experimental colours, but kept the cool-white lighting. One school was relamped with full-spectrum lamps but retained its original colours. The fourth school was modified both in colour and lamp type. Blood pressure and mood measures were made; the blood pressure data are discussed below in the section on physiology and health.

This report shows several of the problems noted by Gifford (this volume), among them an inappropriate design for the statistical analyses in this nested design; an absence of control for socioeconomic differences and for differences in maturation rates, instruction, and local events during the study period. Few details of the mood data are provided; in fact, the source of the scale itself was not included in the report. Wohlfarth and Gates (1985) reported that only the school with both colour and light modifications showed measurable changes in mood scores between baseline and experimental phases. It is impossible to evaluate this claim because the authors failed to provide any descriptive statistics for the mood variables. This paper provides no clarification of the effects, if any, of changing fluorescent lamps on student mood.

Bartholomew (1975) reported details of a classroom study at a university (also discussed above). The same study was also reported in less detail by Kleiber et al. (1974). Students in a seminar class did their regular work under either full-spectrum or cool-white fluorescent lighting and subsequently rated the atmosphere of the room, the quality of the class, and their reactions to the class. For the measures of mood, alertness, activity, and interest in the class, there were no differences attributable to the classroom lighting.

Office workers participated in a field study by Erikson and Kuller (1983). One floor of the building was relamped with full-spectrum lamps and a second floor retained its "standard fluorescent ceiling fixtures" (lamp type unknown). After four and ten months under one or the other lighting condition, the 55 subjects completed a 36-item mood questionnaire, which was reduced to five scales using factor analysis. Reliable results from factor analysis require at least eight times as many subjects as there are questions (Tabachnick & Fidell, 1983), so it is unlikely that these five factors would emerge in a replication of the study.

None of the statistical details appear in this conference paper, but the authors reported (based on analysis of the factor scores) that it appeared that mood declined in the full-spectrum group from December to June, but not in the standard group. Erikson and Kuller (1983) suggested that in December, the full-spectrum lighting improved mood in comparison to the standard, but that it had no differential effect in June when there was exterior daylight available. However, the meaning of this result is unclear without the details; for example, the report implies that overall mood in December was better in the full-spectrum group than in the standard group, but does not provide data to substantiate this statement.

In Berry's (1983) electronic assembly field study of work efficiency and mood effects on employees, subjects completed a standardized mood measure during the baseline (cool white), experimental (full-spectrum), and second baseline conditions. There were no statistically significant differences between the scores on this scale as a function of the change in the lighting.

In three separate laboratory studies, undergraduate volunteers have been randomly assigned to one experimental condition for one, brief session. The experiments were carefully designed to eliminate alternative explanations and to allow strong inferences to be made about any treatment effects observed. However, the short-term nature of these studies precludes any conclusions to be drawn from them about the effects of prolonged exposure to any light source. Boray, Gifford, and Rosenblood (1989) compared warm-white, cool-white, and full-spectrum lamps. Veitch, Gifford, and Hine (1991) compared full-spectrum and cool-white lamps. Baron, Rea, and Daniels (1992) compared warm-white (CCT=3000K), natural-white (CCT=3600K), cool-white (CCT=4200K), and full-spectrum (CCT=5000K) lamps. No lamp type effects were found on mood measures in any of these experiments.

Laboratory interest in mood effects of full-spectrum fluorescent lighting continues, but dramatic effects elude researchers. Kuller and Wetterberg (1993) reported a laboratory mock-office experiment (also discussed elsewhere in this review) in which the independent variables were lamp type (full-spectrum versus warm-white) and illuminance (450 lx and 1700 lx). There were no effects of either variable on mood scores computed from 36 bipolar rating scales [this study also used factor analysis with an inappropriately small number of subjects (36 subjects completed the ratings in each of two sessions)]. The researchers did report that mood changed over the day-long sessions to a more social, more bored, and more negative state.

3.2.2 Subjective fatigue. Maas, Jayson and Kleiber (1974; also discussed in brief in Kleiber et al., 1974) compared full-spectrum and cool-white lamps in a study hall, and measured fatigue with both subjective and objective measures. Students were invited to take their own study materials to the experimental room for a four-hour study session on four days during which they worked twice under each lighting condition. The report does not include statistical details for any of the measures, but the authors reported that only one of the 34 subjective reports varied systematically with the light. Because of its similarity to other scales that had not shown any difference, they dismissed this as a chance outcome. There were three objective measures of visual fatigue; these were discussed above under the heading "Visual Performance".

In addition to the dependent variables already discussed, Kuller and Wetterberg (1993) asked the participants in their experiment to rate their visual discomfort by rating a list of symptoms (e.g., visual fatigue, eye pain, itchiness, tears, blurred vision) on a scale from 1, no discomfort, to 3, high discomfort. It is not clear precisely how many symptoms were rated, but the scores were averaged to form a visual discomfort index. The internal consistency reliability of this index was not reported; therefore, it is impossible to tell how well the scale measured visual discomfort,. There was a significant three-way interaction of illuminance, lamp type, and test occasion (each subject experienced both lamp types on different days, both at the same illuminance level) that the authors did not interpret. Two main effects were significant: on the second occasion, visual discomfort was lower; and, full-spectrum lamps caused more visual discomfort than warm-white lamps.

3.2.3 Summary. Investigations of full-spectrum lighting, when used for general illumination, have failed to find robust effects on mood in either children or adults. Although three studies of the eight cited here have reported lamp type effects on a measure of affect (Erickson & Kuller, 1983; Kuller & Wetterberg, 1993; Maas et al., 1974), none provide compelling evidence because of omissions or errors in statistical testing or reporting. Indeed, Maas et al. dismissed their finding as a chance outcome based on their use of a large number of nonindependent comparisons. Erickson and Kuller had too few subjects for a robust use of factor analysis. Kuller and Wetterberg did not provide a detailed accounting of their measurement of visual discomfort. Overall, the research literature does not demonstrate that full-spectrum lighting has any effect on mood in either adults or children.

3.3 Summary: Mental Health and Affect

In some clinical applications, phototherapy can have important effects on symptoms. Despite continuing debate about the effective mechanisms, a few questions have answers. Bright light appears to be consistently effective, and the spectral power distribution of the light source has no effect. People with nonseasonal mood disorders and in the general population are unaffected by phototherapy regimens.

In both field and laboratory studies of full-spectrum fluorescent lighting effects on mood, there is no strong evidence for such effects. Those articles that do report effects are difficult to evaluate. This literature weighed together with the absence of phototherapy effects on mood ratings of normal individuals leads to the conclusion that there is no compelling reason to believe that full-spectrum lamps for general interior lighting can improve mood or well-being for most people.

Although Kuller and Wetterberg (1993) did not find that illuminance affected mood in healthy subjects, this finding is not consistent with other recent research. Grünberger, Linzmayer, Dietzel, and Saletu (1993) used bright (2500 lx) and dim (500 lx) conditions of full-spectrum fluorescent light and found that overall mood was higher over the intermittent exposure (random periods totalling 4 hours of exposure to each condition over an 8-hour period) in the bright light group as compared to the dim light group. Grünberger et al. did not describe the lighting conditions that existed between the experimental exposures; therefore the total light exposure of these subjects remains unknown. It is unclear how this effect, if it can be replicated, might be applied to lighting practice in everyday interiors;

however it may be the case that the intensity of illumination, and not its spectral properties, can contribute to mood-and well-being. A detailed examination of the literature on this subject is beyond the scope of this review of the full-spectrum lighting literature.

There has been no research into the possibility of individual differences in sensitivity to spectral differences in illumination, although there is reason to suspect that individual differences in lighting preferences exist (Heerwagen, 1990). This area of research holds untapped potential. Small subgroups in the general population might experience large effects that disappear when effects in the majority are examined. These subgroups may be sensitive to the spectral properties of illumination or to other factors, including its intensity, variability, or flicker rate (cf. Lindner & Kropf, 1993; Wilkins et al., 1989).

4. Physiology and Health

4.1 Biological Effects of Light

Initial interest in full-spectrum fluorescent lighting began with observations on plants (Ott, 1973). Ott pioneered time-lapse photography, and he found that his success in filming certain types of plants depended upon the type of fluorescent lamp under which he cultivated them. This is not surprising when one considers that plants create chemical energy from light in photosynthesis. Different photosynthetic pigments are known to have different action spectra: that is, each pigment requires a particular spectral power distribution of illumination for the most effective photosynthetic action. Every year we witness the variety of photosynthetic pigment combinations in various plants as we watch the changing and various colours of leaves in autumn.

The biological differences between plants and mammals are many, so that to generalize from one to the other is unreasonable. We should not expect that the specific conditions conducive to plants will be the same as those required for humans.[3] The fundamental question, however, is a reasonable one: What are the biological effects of light on people? This opening section describes the general mechanisms through which light affects human biology; succeeding sections describe specific processes in which full-spectrum fluorescent light has been investigated or implicated.

Three routes have been identified through which light can affect mammals. First, light may affect individual cells directly. Second, light is absorbed by the skin and other tissues and can exert effects on various chemical processes that affect the whole organism. Third, light is absorbed through the visual system and causes information to travel through the neural pathways.

4.1.1 Direct effects on cell cultures. The shorter, more energetic wavelengths of ultraviolet radiation below 290 nm have long been known to have germicidal action. Lamp manufacturers produce fluorescent lamps for this special purpose, having emission peaks in the UVC range around 265 nm. These are not general-duty lamps for interior lighting, but are designed for use in special devices for sterilization. The implications for preventing the spread of disease are obvious.

Lamps with emissions in the visible range of the spectrum can affect both bacterial and mammalian cell cultures in vitro. Buchbinder, Solowey, and Phelps (1941) demonstrated that cultures of streptococcus bacteria grown in glass Petri dishes were killed by exposure to visible light. The light sources were daylight, direct sunlight, and a type of fluorescent lamp identified in the report as a "daylight" fluorescent lamp. In all three cases, significant culture death occurred in comparison to control plates kept in darkness. Ultraviolet light is unlikely to have been the causative factor because the glass covers on the plates would have absorbed almost all of the UV emissions from these light sources.

Himmelfarb, Scott, and Thayer (1970) examined the bactericidal effects of two types of fluorescent lamps (cool-white and full-spectrum) on two species: Staphylococcus aureus and Serratia marcescens. The full-spectrum source was effective in killing S. aureus cultures, whereas the cool-white source appeared not to have this effect. Neither lamp was effective on cultures of S. marcescens. In this case, the culture plates were uncovered and any ultraviolet component in the light

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[3] Indeed, the Illuminating Engineering Society of North America recognizes this fact and provides a separate chapter in its Lighting Handbook (Rea, 1993a) on the subject of lighting for plants.

would have been effective, so that the killing effect of the full-spectrum source may have been attributable to invisible UVA emissions (below 400 nm).

Eisenstark (1970) reported that certain light-sensitive mutants of Salmonella typhimurium were killed by exposure to various sources of visible and ultraviolet radiation including a 500 W quartz-iodine projector lamp, a cool-white fluorescent lamp, and an incandescent floodlamp. The sensitivity depended upon the strain, with the wild type being least affected by light. Of greater interest is the fact that bacterial mortality persisted even when the experiments were repeated with filters that removed any UV component with a wavelength lower than 365 nm.

The findings of bactericidal effects of light may have implications for settings where disease prevention is desirable, although these studies show that visible light does not kill every bacterial strain. It could be argued that what has been demonstrated is that the survival rates of certain bacterial cultures depend upon the physical conditions in which they are kept. It is hardly news that there are some conditions that are lethal to some organisms.

Similarly, laboratory conditions must be carefully maintained for the successful culture of human and other mammalian cells. Daylight lamps (not full-spectrum according to the definition adopted here) caused cell death in human cell cultures grown in a special medium, but not when the cells were in phosphate-buffered saline solution (Wang, 1975). Wang argued that researchers should attend more carefully to the lighting conditions in their laboratories to prevent unintended variability in results of experiments using such cultures.

Kennedy, Ritter, and Little (1980) examined mutation rates in mouse embryo cell cultures as a function of exposure to cool-white fluorescent light, as compared to cultures incubated in dark. When the Petri dishes were covered with Plexiglas covers, there was no effect of light on mutation rates. When the dishes were uncovered, the survival rate was lower (more cells died) and the mutation rate was higher in light-exposed dishes. The experimenters concluded that the effective portion of the spectrum was the ultraviolet component that had been screened out in the Plexiglas-covered dishes. This finding has implications for laboratory practice, and also for the issue of ultraviolet radiation effects on humans, which is discussed in greater detail below.

4.1.2 Direct effects on living systems. Mammalian bodies are transparent to visible light. Gagong, Shepherd, Wall, Van Brunt, and Clegg (1963) found that visible light could be detected deep in the brain of animals as large as sheep. The quantity of light was inversely proportional to the size of the animal, and the measurements were identical in both living and decapitated brains.

Light absorption by the skin itself produces the familiar responses of suntan and sunburn -- protective and pathological responses, respectively (Wurtman, 1975a). Over time, ultraviolet radiation exposure causes the skin to thicken; skin cancers can be the result of excessive exposure to ultraviolet radiation, particularly the more energetic rays at shorter wavelengths (UVB, 290-320 nm).

Light absorption through the skin stimulates chemical reactions in the blood and in other tissues (Wurtman, 1975a). Pathological responses are possible, as in photosensitivity diseases. A complete survey of all the possible photosensitivity diseases is beyond the scope of this review, as there are over 40 and their etiology is poorly understood. Diagnosis and therapy of each reaction depends on the determination of the precise wavelength that induces the response in the patient (Harber, Whitman, Armstrong, & Deleo, 1985). The section below on photosensitivity discusses this problem as it relates to interior lighting.

The metabolism of vitamin D_3 is the best known of the beneficial photochemical processes (Wurtman, 1975a). The chemical precursor of vitamin D_3, 7-dehydrocholesterol, absorbs ultraviolet radiation in the skin and subcutaneous tissue and is transformed into the active vitamin.

Vitamin D is essential to the regulation of calcium metabolism and to the maintenance of bones and teeth. The vitamin-D deficiency disease, rickets, has long been known to be curable through exposure to sunlight (Wurtman, 1975a). In modern times, the success of vitamin D_2 (a related, biologically active chemical) in curing rickets has led to its use as a food additive in milk and grain products in North America and some European countries.

However, there is evidence that most of the vitamin D activity in the blood, even in a population that consumes vitamin D_2 in food, is in forms that can only be formed in the body by light exposure (Wurtman, 1975a). A certain degree of regular exposure to ultraviolet radiation appears to be necessary to health; however, the specific wavelengths and dosages required remain unknown (cf. Wurtman, 1975a).

Light also is biologically effective in the treatment of neonatal hyperbilirubinemia (neonatal jaundice), a disorder common to premature babies. These infants are born before their livers are fully developed, and they lack the means to metabolize bilirubin, a product of the decomposition of haemoglobin in dead red blood cells. The problem is particularly serious in infants whose blood type is incompatible with that of their mothers because the incompatibility causes red blood cell destruction at a higher than normal rate. If untreated, hyperbilirubinemia causes irreversible brain damage including mental and motor retardation (Wurtman, 1975a).

Complete blood transfusions were once the only means of removing the jaundiced blood; however, phototherapy is now the standard treatment (Wurtman, 1975a). Exposure to light bleaches the bilirubin irreversibly into a form that can be excreted. There is a history of debate concerning the most effective lighting type for the treatment of neonatal hyperbilirubinemia, which is touched upon briefly below.

Some writers (e.g. Ott, 1973; Wurtman, 1975a, 1975b) have suggested that other plasma or tissue reactions may also be affected by light in the same manner as bilirubin metabolism. However, Abramov (1985) cautioned against the indiscriminate use of phototherapy because of the possibility that the side effects may be undesirable rather than therapeutic. These possibilities are discussed in greater detail below.

4.1.3 Indirect effects through visual pathways. Vision is the system that we consider most often in relation to light. Light enters the eye through the pupil and strikes the retina, the area of specialized cells on the inner back surface of the eye. There is evidence that these cells are the only photoreceptive cells in mammals (Wurtman, 1975a; or see Wurtman, 1975b for a less technical discussion); a photoreceptive cell is one that is capable of transducing light energy into a neural signal.

Light information travels along different pathways depending on its function. The neural pathway for visual information goes from the retina via the optic nerve, the optic chiasma, and the lateral geniculate body, and thence to the visual cortex where complex circuitry allows us to perceive features and to interpret those patterns. A classic, accessible review of sensory and perceptual processes in vision is provided by Gregory (1977).

A second pathway that exists only in mammals transmits light information from the retina to the suprachiasmatic nucleus in the anterior hypothalamus. A complete elucidation does not yet exist of the biological processes thus affected (Wurtman, 1975a; Hill, 1992). The suprachiasmatic nucleus send signals to the brain, the spinal cord, and the pineal gland.

The pineal gland secretes melatonin, which has been implicated in the regulation of periodic biological processes such as circadian rhythms, although its precise role remains unknown (Hill, 1992). Light activation of the pineal gland inhibits the release of melatonin. Melatonin induces sleep and causes the release of serotonin, a neurotransmitter implicated in the etiology of some depressions. Activity levels vary cyclically in inverse relation to melatonin secretion (Kalat, 1984).

Melatonin also influences the secretions of the pituitary, adrenal glands, and gonads and it is believed that this is the means by which light and dark cycles influence other periodic biological processes, such as ovulation. For example, Wurtman (1975a) summarized several studies of mammalian species reared under continuous illumination. The female animals matured sexually at an earlier age than animals reared on a cyclic lighting schedule and did not then ovulate cyclically, but persistently. Zacharias and Wurtman (1969) found that girls blind from early in life reached menarche at an earlier age than sighted girls.

Hill (1992) suggested that premenstrual depression, which one would expect to have a hormonal basis, has characteristics of both seasonal and nonseasonal depression. Depression is more common in women than in men. The processes that cause each form of depression may be related and may also relate to neural processes that begin with periodic exposure to light.

4.1.4 Summary. The biological effects of light on human health fall into three general categories. First, the bactericidal effects of certain wavelengths on certain species can prevent disease by eliminating the causal agent. Second, light absorption through the skin produces both local and systemic responses. Local responses include suntan and sunburn; systemic responses include vitamin D metabolism and degradation of serum bilirubin in cases of neonatal jaundice. Third, light incident on the retina produces neural signals that influence hormonal processes. These neural signals travel a separate pathway from the visual signals. Hormones produced by the pineal gland are believed to regulate circadian rhythms, adrenal gland secretions, and ovulation. These biological processes are poorly understood, but may underlie disorders involving sleep-wake cycles and seasonal or periodic mood and behaviour problems.

4.2 Full-Spectrum Fluorescent Lighting Effects on Health

4.2.1 Global indices of health.

A. School attendance. Before turning to the examinations of specific biological systems, we consider the 20-year history of field investigations into the effects of full-spectrum fluorescent light on illness rates in children. Comparable studies on adults do not exist, probably because the data are less easily accessed than school attendance records. Most investigations have included many different behavioural and health measures, and so the same reports will in some cases have been cited above.

Mayron, Ott, Nations and Mayron (1974) reported that there were no differences between the control (cool-white) and experimental (full-spectrum) classrooms in terms of attendance rates or trips to the school nurse. (The principal goal of the study was to examine classroom behaviour and attendance, and it is discussed in greater detail above.)

Wohlfarth (1984) tested his theory that an appropriate mix of light source and surface colours is important to behaviour and health. He used four elementary schools in Alberta, with standard and experimental lighting conditions crossed with standard and experimental colour conditions (see discussion above). The design is a 2 x 2 factorial nested analysis of variance, but main effects and interaction effects were not examined. The appropriate analytic strategy would have been to report both the means and standard deviations of the number of absences per classroom and to have used each classroom as a unit of analysis, nested within schools (see above).

Instead, Wohlfarth used simple counts of the number of absences in each school over the entire academic year and appears to have used the variability between schools as the estimate of measurement error, although it is not clear from the report. (For example, the report does not state the number of students nor the number of classrooms in each school, leaving open the possibility that there were higher counts of absences in schools with more students.) The missing information makes a thorough evaluation impossible.

Even accepting the analyses performed by Wohlfarth (1984) does not give a clear interpretation of the findings. It appears that absences were lower in the schools with colour modifications, regardless of the type of lighting installed. Lamp type itself had no relationship to absence rates.

Wohlfarth had an additional manipulation in the school with full-spectrum fluorescent lighting and standard colours: One classroom had additional ultraviolet radiation added to the full-spectrum source. This classroom had fewer absences than the classroom with full-spectrum lighting only. However, one contagious illness can affect the overall rate for an entire class and would exaggerate differences between classes. Treating individual students as the unit of analysis violates one of the assumptions of a valid statistical significance test because the observations are clearly not independent. It would make a treatment effect appear to exist when it did not (Type I error). Trials with several classrooms, randomly assigned to receive additional UV radiation, or not, would be necessary to adequately test the hypothesis that the additional ultraviolet radiation was the causative factor in reducing school absence rates, expressed as days absent per student per class.

The same research design problem exists in a study reported in brief form by London (1987). The raw numbers of sick days suggest that the classrooms with full-spectrum fluorescent light were healthier than other classrooms. However, the analysis of the data did not take into account variability between illness rates in the classrooms. London also, as Wohlfarth (1984) had done, failed to treat classrooms as the unit of analysis.

Kuller and Lindsten (1992) studied eight- and nine-year-old children in classrooms with and without windows and with either cool-white or full-spectrum fluorescent light in southern Sweden. The dependent measures included a variety of physiological measures and performance measures discussed elsewhere in this review. They, too, did not consider classrooms as the unit of analysis, as such a design properly requires. Therefore, it is noteworthy that there were no significant differences between the classrooms in the analysis of overall sick leave rates. Neither natural daylight availability nor full-spectrum fluorescent light had any effect on overall sick leave.

In the recent study in Alberta schools (Hathaway et al., 1992; Hathaway, this volume), four types of lighting were examined for effects on children over a two-year period, starting at approximately age 9. A variety of problems with the experimental design were noted above with respect to other variables and these apply here also. The statistical analyses in this study also failed to use the appropriate level of analysis; data at the individual level were used, rather than at the classroom level. In the case of the attendance data, the data were analyzed using t-tests on all possible pairs of schools, without correction for the experiment-wise error rate. This is incorrect because the comparisons are not independent (cf. Keppel, 1982; Kirk, 1982).

Hathaway et al. (1992) concluded on the basis of their analyses that the school with high-pressure sodium vapour lighting had poorer health than the other schools. Lacking the original data for classrooms, this outcome cannot be re-evaluated. In any case, it is worth noting that the mean monthly attendance rate for all students in the school with ultraviolet enhanced full-spectrum fluorescent lighting and the school with cool-white fluorescent lighting were identical (95.9%). The school with full-spectrum fluorescent lighting without UV enhancement had a fractionally higher monthly mean, 96.2%. Therefore, these results do not support the hypothesis that full-spectrum fluorescent lighting -- with or without additional ultraviolet radiation -- improves student attendance rates.

B. Headaches and neurological functions. Berry (1983) conducted a field experiment in an electronic assembly plant; the study was described in greater detail above. Three of the 16 participants in the experiment stated that they had experienced fewer headaches at work during the experimental (full-spectrum) period of the study. One, however, reported more headaches during this time. Light levels varied between the baseline (A) and experimental (B) phases (full-spectrum lamps usually emit fewer lumens per watt than their cool-white and lite-white counterparts); therefore the causal factor behind these informal reports remains unknown.

Similarly, Dutczak (1985) was unable to control the illuminance level in the conditions of her case-control study of lamp type effects on a severely handicapped epileptic girl. The girl experienced fewer seizures at school when the school was lit with full-spectrum fluorescent lamps (year 2) than when it was lit with cool-white fluorescent lamps (year 1). At all times, the lighting in her home was cool-white fluorescent lighting. The number of seizures at home increased from year 1 to year 2. The illuminance levels were not reported, but the author noted that the classroom was considerably less bright with full-spectrum fluorescent lamps. The change in the number of seizures could relate to spectral differences between the lamp types, to the change in illuminance level, or to some unknown factor that changed the temporal pattern of seizure activity (e.g., time of day effects).

In the mock office setting in Kuller and Wetterberg's (1993) laboratory experiment, electroencephalogram readings of delta, theta, beta and alpha waves were taken in both the morning and afternoon of the full-day sessions. Other physiological measures from this experiment will be discussed below. The independent variables were lamp type (full-spectrum and warm-white) and illuminance (450 lx and 1700 lx). Kuller and Wetterberg hypothesized that different brain wave patterns would result from different intensities and spectral qualities of illumination. They predicted specifically that bright light would tend to cause cortical arousal in comparison to the dim light. They made no specific prediction as to which of the two lamp types would cause greater arousal, only that a difference would exist.

The results demonstrate the difficulty of interpretation of putative indices of arousal. Delta waves, associated with sleep, were higher at low illuminances (as predicted) but not related to lamp type. Theta waves, associated with sleepiness, apparently were not influenced by illuminance, but there was a small effect in which full-spectrum lamps were associated with more theta activity (ie., more sleepiness). Alpha waves are indicative of a state of relaxed wakefulness, and the results for this variable showed an interaction of lamp type and illuminance. Alpha waves were greatest when full-spectrum lamps were dim and when warm-white lamps were bright. Beta waves, which reflect activity, did not consistently relate to lamp type or illuminance, but to an interaction of the two. The afternoon increase in beta waves (ie., the greatest increase in activity) was reported to be greatest in dim full-spectrum light.

From this complex pattern of results it is impossible to say which of the two lamp types was more arousing. Full-spectrum lamps were associated in one case with sleepiness, and in another with increased activity. Moreover, results that were predicted, such as increased beta activity under high illuminance, did not occur. Brain-wave potentials do not appear to be a consistent or reliable index of the vague concept of activation or arousal.

C. Cardiovascular function. Adult females exposed to full-spectrum or warm-white fluorescent light for a four-hour session displayed a variety of effects on cardiovascular functions (Chance, 1983). This experiment is confounded in that lamps were replaced on a lamp-for-lamp basis. The proper measure of light intensity for this study would be one of radiant flux density, which is not weighted by the standard visual function, V_λ. These data were not measured (nor were illuminance levels, which are weighted by the standard visual function). Therefore, it is very likely that the independent variable, lamp type, was confounded by differences in radiant energy.

Chance's (1983) results included interesting interactions between lamp type and duration of exposure in that when the exposure was to full-spectrum light, resting systolic and diastolic blood pressure dropped from hour 1 to hour 3, then rose again slightly at hour 4. Under warm-white fluorescent light, there was a slight but consistent rise in systolic and diastolic blood pressure from hour 1 to hour 4. Both measures were always lower in the full-spectrum condition. In a complex interaction of lamp type, time, and treatment order, the pulse pressure measure was also lower in the full-spectrum lamp condition (this is predictable from the blood pressure measures).

The experiment included physiological measures during and after exercise on a stationary bicycle. Four of fifteen measures (each analyzed separately using t-tests) showed significant differences between lamp type conditions. Heart rate after six minutes of exercise was lower under full-spectrum lamps. Predicted maximal oxygen uptake, a measure of fitness, was higher under full-spectrum lighting. Subjects cycled longer in the full-spectrum condition than the warm-white condition. Final pulse pressure was higher in the full-spectrum than the warm-white condition. Chance (1983) described these results as favouring the full-spectrum condition, and interpreted the pattern as an indication that the full-spectrum lamp caused less stress than the warm-white lamp.

One curious aspect of Chance's (1983) report is absence of a discussion on the different directions of the effect on pulse pressure. In the resting state, pulse pressure was lower under full-spectrum lamps and was interpreted as better. After exercise, higher pulse pressure under full-spectrum lamps was interpreted as favourable to that condition. The fact that direction of the outcome differed suggests that the effect is not robust; taken together with the confounding effect of illuminance, these results are not compelling.

Wohlfarth and Sam (1982) examined colour psychodynamic decorative changes to walls, floor coverings, furnishings, and lighting in relation to behaviours and physiological responses of seven severely physically and mentally handicapped children, two of whom were blind. The original lighting was cool-white fluorescent; in the experimental condition this was changed to full-spectrum fluorescent lighting at the same time as the decorative changes were made. The behavioural data from the study were discussed above in section 2.3.3, "Classroom activity levels". As regards the measures of blood pressure and heart rate, the results are unclear. No statistical analyses were published and no reanalysis is possible without standard deviations in addition to the published means.

The published report (Wohlfarth & Sam, 1982) provides tabular data of mean values showing that diastolic blood pressure was relatively invariant for all children in all phases and for their two teachers. For the teachers, systolic blood pressure and heart rate did not seem to vary systematically over the three phases. For the seven children, systolic blood pressure seemed to be highest during the initial baseline phase, but dropped from day 1 to day 10. It remained at approximately the same lower level throughout the 13 days of the experimental phase (colour psychodynamic decoration and lighting) and during the 15 days of the second baseline phase (when conditions were restored to the original). Heart rate data paralleled the systolic pressure data. The blind children responded in a similar manner to the sighted children.

Wohlfarth and Gates (1985) published a report on a different set of variables measured during the study originally reported by Wohlfarth (1984) and described above. In the 1985 publication, data regarding blood pressure and mood measures were reported. Blood pressure measurements were made in both mornings and afternoons, fall and spring, in teachers and randomly selected students. The authors chose to analyze the difference scores between the fall and spring measures. The only statistically significant differences were on afternoon measures in children. In the school with both colour and light changes systolic blood pressure increased more from fall to spring than in the schools where only light or only colour were changed, or where there was no change. The differences were very small.

Two cardiovascular measures of arousal were included in the battery of psychophysiological variables measured by Kuller and Wetterberg (1993) in a well-controlled laboratory experiment. Average heart rate and cardiac arrhythmia were each measured at two times of day. As discussed above, the authors expected that bright light would be physiologically arousing and that the two lamp types would produce different levels of arousal. Neither prediction was supported: There were no differences in either cardiovascular measure as a function of illuminance nor of lamp type.

In conclusion, the evidence that full-spectrum fluorescent light has a beneficial effect on cardiovascular function is weak. The one experiment with rigorous research design failed to find any effects; two other studies have provided inconsistent results with no clear interpretation.

4.2.2 Direct effects on living systems. In this section, we consider the effects of full-spectrum fluorescent light mediated by direct effects of light absorption by skin and other tissues.

A. Vitamin D and calcium metabolism. The role of light in the production of vitamin D is not in dispute. The relevant question in this review is whether full-spectrum fluorescent lamps are more efficacious than other types of lamps in stimulating production of this essential nutrient. For most people, the question may be moot because sufficient natural daylight exposure is available to them. However, for special populations such as the institutionalized chronically ill, the elderly, shift workers, and those living in extreme polar latitudes, artificial sources of light may be the only available source for light-stimulated vitamin D metabolism.

Vitamin D is important to the absorption of calcium in the intestine. Neer et al. (1971) reported a study of calcium absorption involving subjects in a special population, elderly residents of a veterans' home in Massachusetts. Some of the same data, with additional data from a second year, were published by Neer, Davis, and Thorington (1970). The 1971 report is discussed here because this presentation includes greater detail concerning the methodology.

The participants were divided into control and experimental groups and followed for three phases (Neer et al., 1971). Phase 1 was a baseline period during which subjects adopted a special diet. During phase 2, the experimental subjects were exposed to full-spectrum fluorescent lamps for 8 hours each day at an illuminance level of 5000 lux. The luminaires allowed the transmission of the ultraviolet component of the full-spectrum sources (Thorington, Parascandola, and Cunningham [1971] reported that this arrangement would give an appropriate ultraviolet dose at a low enough intensity to prevent any danger of erythemal response). The control subjects were exposed to 300-500 lux of cool-white fluorescent lighting for the 8 hours. It is not clear whether these luminaires would have allowed ultraviolet transmission or not, for they are described only as "representing their normal light environment" (Neer et al., 1971, p. 256). During phase 3, both groups returned to the same routine as in phase 1.

During the second phase of the study, calcium absorption (as measured with a standard fecal assay) was significantly greater in the experimental than in the control subjects (Neer et al., 1971). The result was the same in the second year (Neer et al., 1970). Seasonal variations also were noted. In phase 3, the control group levels rose to equal the experimental group levels and both groups were as high in calcium absorption as the experimental group had been in phase 2 (Neer et al., 1971). The authors suggested that the increase in day length by the early spring, when phase 3 occurred, could explain this result. The subjects were free to go outside or to sit near windows when not exposed to the special lighting arrangements and exposure involved in phase 2.

This study does show that bright artificial illumination using full-spectrum fluorescent lamps can improve intestinal calcium uptake. However, the illumination levels involved were 10 times greater than the usual level in the building. It may be that intensity, not spectral composition, was the causative factor for this effect. Th experimental design does not permit these variables to be separated. Nonetheless, Wurtman (1975b) has argued that this finding should lead to an increase in general interior illumination levels as well as to a shift in the spectral composition of light sources. Hughes and Neer (1981) have argued that such findings should be paid greater attention in providing a healthy environment for elderly populations at risk for osteoporosis and other calcium-deficiency disorders, although the precise mechanisms of action are not entirely known.

Calcium is critical to the maintenance of healthy bones and teeth. The hypothesis that full-spectrum fluorescent light might prove beneficial to dental health was tested in the golden hamster in Sharon, Feller, & Burney (1971). In this experiment, the fluorescent lamps were replaced one-for-one, although the full-spectrum lamps were in luminaires having ultraviolet transmitting lenses, whereas the cool-white lamps were in luminaires having standard acrylic lenses. The illuminance levels ranged from 1700 to 2700 lux under full-spectrum lamps and from 2700 to 3700 under cool-white lamps; the authors reported that the computed irradiances were approximately equal, at 900 μW/cm^2[4]. Half of the hamsters ate a diet high in sugar, and half ate regular lab chow.

There was an interaction of diet and lamp type. Under the cool white lamp, the animals with the high-sugar diet had a larger number of dental caries after 15 weeks than the animals under the full-spectrum lamp with the high-sugar diet. The animals with the regular diet showed no difference in the number of dental caries regardless of lamp type. Full-spectrum lamps prevented caries only in those animals fed a diet that predisposed them to develop caries (Sharon et al., 1971). The animals with the most caries also had smaller submandibular glands, which led Sharon et al. to hypothesize a mediating role for salivary function, which may mean that the effect is indirect.

Feller, Edmonds, Shannon, and Madsen (1974) followed this experiment with an examination of lighting effects on dental caries in the cotton rat. Three lamp type conditions were used: full-spectrum fluorescent, cool-white fluorescent, and incandescent sources. In the full-spectrum condition, the illuminance was 3600 lux (computed irradiance approx. 1350 μW/cm^2), whereas in the cool-white condition the illuminance was 4200 lux (computed irradiance approx. 1400 μW/cm^2). The light level was lower in the incandescent condition: illuminance was 380 lx (irradiance 360 μW/cm^2 measured at 290-700 nm). The animals were fed a diet low in sugar, to provide a more sensitive test of the relationship between light levels and caries than the earlier work in golden hamsters.

Feller et al. (1974) found that the incidence of caries was identical in the incandescent and full-spectrum lighting conditions, but significantly more and more serious caries occurred in the cool white group. Incandescent lamps have almost no ultraviolet emissions; therefore, the reason for the caries in the cool-white lamp group cannot be related to a deficiency of ultraviolet radiation relative to the full-spectrum lamps. Both incandescent and full-spectrum sources have relatively greater output in the red range of the visible spectrum than cool-white sources, which raises the possibility that this is the relevant range of wavelengths causing this effect. However, the intensity of the light was considerably lower in all wavelengths in the incandescent lamp condition than the other conditions.

In humans, studies of the effects of full-spectrum lighting on dental caries have used children as subjects. Mayron, Ott, Amontree and Nations (1975a; the same data were also published in Mayron, Ott, Amontree and Nations, 1975b) examined the incidence of caries in first-and second-grade children whose classrooms had either radiation-shielded full-spectrum fluorescent lamps, or unshielded cool-white fluorescent lamps. [The shielding is hypothesized to remove any (undocumented) low-frequency electromagnetic radiation that might be emitted from the fluorescent lighting system]. There were two classrooms in each condition.

At the end of the school year, the proportion of students with caries in the classrooms lit with full-spectrum lamps was lower than the proportion of students with caries in the classrooms lit with cool-white lamps. This pattern was not attributable to chance, nor to existing differences between the groups. All children were from the same community and drank fluoridated drinking water. There were no data collected concerning the brushing or eating habits of the students, nor is it known whether

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[4] The irradiances were computed by Sharon et al. from the manufacter's data. The authors did not report the wavelength range that was used for the computation. This omission makes it impossible to compare this value with irradiances reported elsewhere, for the values will differ depending on the precise wavelengths for which irradiance was calculated. The same limitation applies to the values reported below for the study by Feller et al. (1974).

there were any differences between the classes in hygiene instruction. Within any one school, however, such differences should be small.

Hathaway et al. (1992) included dental caries as a measure in their study of lighting effects on schoolchildren. Unfortunately, they were unable to include the students in the school with cool-white lamps in their data analysis because a large number had had fissure sealants applied. (Fissure sealants prevent caries.) They do not report having conducted any statistical tests on the incidence of caries on students in the schools whose data they present. The data are presented in the form of average decayed surfaces or average decayed teeth, per student, in each group or school. It appears that students in schools having ultraviolet enhanced full-spectrum fluorescent light had fewer caries, on average, than students in schools not having ultraviolet enhanced light.

There is reason to suspect, however, that the Hathaway et al. (1992) dental results do not relate to lighting. There is no information about the variability of caries incidence across the schools and therefore no way to assess the probability that this is a random variation. There is no information about the prior incidence of dental caries in any of the schools; only the incremental increase in incidence over the two-year study period is indicated. It is quite possible that the students may have differed from the start in their likelihood of developing dental caries.

Uncontrolled external variables such as nutrition, fluoridated water, tooth-brushing, flossing, and regular fluoride treatments from a dentist are known to be strong influences on dental health. Although the researchers attempted to check that diet was not a factor, the use of self-reported journals with young children as a means of assessing nutrition is fraught with error. The variability of these data are high (see Hathaway et al. 1992, p. 25), which may reflect real variability between children in their dietary intake. or it may reflect a difficulty in completing the nutrition diaries. There may additionally have been differences between the schools in the children's brushing habits, frequency of dental checkups and care, parental encouragement of dental hygiene, or classroom teaching about hygiene, all of which may have influenced the outcome.

In conclusion, the data concerning vitamin D-related systems is unclear. Calcium absorption in elderly men can be stimulated by bright full-spectrum light (Neer et al., 1971), but it is not clear that the spectral properties of the light fully account for the effect. There is no consistent finding concerning the effects of full-spectrum fluorescent light on dental caries. In animals, there is evidence that lighting can influence the development of tooth decay (Sharon et al., 1971; Feller et al., 1974), but the reason for the effect is unknown and it does not consistently favour full-spectrum fluorescent light. In children, there is some evidence that full-spectrum fluorescent light may help to prevent dental caries (Mayron et al., 1975a), but a sound replication that includes tight control for extraneous variables is needed.

B. Neonatal hyperbilirubinemia. Phototherapy for the treatment of this condition is well established. In vitro studies show that the action spectrum of bilirubin peaks in the blue range between 400-500 nm (cf. Thorington, Cunningham, & Parascandola, 1971; Furst, Stinton, Moore, & Harris, 1978). However, there is continuing disagreement in the medical literature concerning the effective components of the treatment; consequently, the implications of this treatment for general lighting practice are not clear. The flavour of these debates, and not an exhaustive review, is presented here because of space limitations.

As early as 1971, Thorington et al. observed that in comparing illuminants used in phototherapy, it is inappropriate to use photometric units to report light intensity. Photometric units are weighted units based on the standard sensitivity function for the human eye under photopic conditions of vision. Those wavelengths to which the human eye is most sensitive (around 555 nm) are weighted more heavily. Phototherapy is not a visual process. Therefore, it is more appropriate to compare the output of various light sources in terms of radiant energy, when discussing the therapeutic light dose, and in photometric units when discussing visual effects on medical personnel. The ability of the lamp to deliver adequate colour rendition for medical staff to detect changes in skin colour is another variable to consider in the choice of a phototherapeutic lamp. Although it would be possible to design a phototherapy unit that would allow medical staff to switch to a different illuminant in order to check on the patient, such a design was not described in any report identified in this review. The search for a single phototherapy illuminant has required a balance between the competing interests of therapeutic effectiveness and colour rendition qualities.

Thorington et al. (1971) presented calculational data illustrating that narrow-band lamps (having output peaks in the 400-500 nm, or blue, range) with the highest theoretical effectiveness for in vitro photodegradation of bilirubin have the lowest effectiveness in producing brightness sensations at photopic levels (although Berman (1992) would argue that scotopic sensitivity effects on pupil size would lead to the opposite prediction [see above]). By definition, a narrow-spectrum lamp lacks the wavelengths necessary to provide good colour rendition. The daylight lamp that they used in their calculations, a full-spectrum lamp by our definition, had high values both for the theoretical degradation of bilirubin and for the production of brightness sensations. They concluded that for the well-being of both the patients and the medical staff in nurseries it would be ideal to use a full-spectrum source for phototherapy of neonatal hyperbilirubinemia.

Lamp manufacturers have responded to the medical community by developing a range of special lamps for phototherapy. Furst et al. (1978) compared various combinations of fluorescent lamps used for phototherapy in terms of their radiant energy output, annual costs, and informal reports from medical personnel. Their anecdotal reports indicated that a combination of equal numbers of a full-spectrum lamp and a special blue lamp was best accepted by the medical personnel in terms of apparent brightness and colour rendition. This combination had high emissions in the important blue region of the spectrum, but also provided a high value in the broader visible spectrum. Its annual costs for lamp purchase and labour (not including energy costs) at that time gave it third place in the ranking of five combinations (current technology and labour costs are quite different). It was 1.8 times more costly than the lowest-cost alternative, and 0.17 times as costly as the most expensive alternative. No data were provided concerning the relative treatment efficacy of the five combinations.

Investigations of the treatment efficacy of various lamp types used for phototherapy of neonatal hyperbilirubinemia have achieved no consensus. Some of the experiments are difficult to evaluate because they failed to control for differences in the radiant energy produced by different lamp types.

For example, when Yasunaga, Rudolph, and Felemovicius (1975) replaced on a one-for-one basis the fluorescent lamps in phototherapy units, the photometric measurements showed the cool white source to be the most intense; however, this source would have been the weakest in terms of the energy emitted in the range considered effective for phototherapy. The other sources were three full-spectrum lamps from different manufacturers and one blue lamp designed specifically for phototherapy. Their experiment was confounded because both the intensity of the radiant energy and the presence of light outside the 400-500 nm band varied between the lamps. The team found no statistically significant difference in the therapy duration necessary to reach a criterion serum bilirubin level.

Nonetheless, they concluded that "results demonstrate the superiority of broad spectrum fluorescent lights resembling the natural outdoor light at 5500 Kelvin" (Yasunaga, Rudolph, & Felemovicius, 1975, p. 179). They based this conclusion on the fact that the mean therapy duration was considerably lower for one of the three full-spectrum lamps than it was for the cool-white lamp. Furthermore, they noted that the blue fluorescent lamps then in use tended to age more rapidly than other lamp types, and required more frequent replacement.

The Yasunaga, Rudolph, and Felemovicius (1975) report provides data that allow a calculation of the rate of decrease of serum bilirubin levels. For the blue lamp, this rate was 0.06 mg/dL/hour; for all other lamp types, the rate was 0.07 mg/dL/hour. When the data are presented in this fashion, the apparent superiority of full-spectrum lamps disappears.

Comparison of this study with others is difficult because of the absence of radiant energy measurements. More recent studies, which have controlled radiant energy and for which the measurements are known, demonstrate the continuing difficulty in identifying the ideal phototherapy lamp. Warshaw, Gagliardi, and Patel (1980) studied phototherapy at an irradiance of 6 $\mu W/cm^2/nm$ using a fluorescent source (lamp type unknown, described only as "conventional white fluorescent lights") and a tungsten-halogen lamp. The rate of reduction of bilirubin under both lamps was comparable: 0.16 mg/dL/hour under tungsten-halogen, and 0.14 mg/dL/hour under fluorescent. This difference was not statistically significant. The phototherapy duration varied from 7 to 83 hours with mean 30.7 hours, and was not different for the different lamp types.

Vecchi, Donzelli, Migliorini, and Sbrana (1983) compared narrow-band green fluorescent lamps with daylight fluorescent lamps, controlling irradiance at 3.14 $\mu W/cm^2/nm$. This experiment obtained statistically significant results favouring the green light when the data were analyzed separately for their three separate trials. The rate of reduction in serum bilirubin was very variable in the various groups; in Group I, Green lamps produced a rate of 0.16 mg/dL/hour and Daylight a rate of 0.10 mg/dL/hour. In Group II, Green produced a rate of reduction of 0.10 mg/dL/hour and Daylight 0.08 mg/dL/hour. It is unclear whether the apparent superiority of Green lamps over Daylight would hold if the data were re-analyzed as one large trial. Most of the babies reached the criterion after 24 hours of phototherapy, with the rest receiving 48 hours of phototherapy.

In conclusion, the use of phototherapy to reduce serum bilirubin levels is established. The action spectrum for bilirubin in vitro is known, but the effective wavelengths or combination of wavelengths in vivo is not. Various investigations have obtained successful treatment with widely varying levels of radiant energy. There appears to be no consensus in the medical community on the ideal choice of lamps, nor of their intensity, for therapy of this disorder. Ennever (1990) summarized this situation, saying:

> Next to the nomenclature of the various bilirubin photoproducts, probably nothing is more confusing to the concerned clinician than the conflicting conclusions of countless controlled clinical comparisons of color. Initially blue was "best", then green seemed promising, and now it appears that blue is back. In clinical practice, white has always been the most popular, because no one likes to work around green or blue light...No real improvement in the delivery of phototherapy has occurred in the three decades since its initial description...Most investigations have concentrated on comparing lamps of different colors, whereas intensity, a far more important parameter, has generally been ignored (pp. 476, 477, 478).

Some evidence suggests that phototherapy for hyperbilirubinemia has effects on other processes. In a comparison of narrow-band blue lamps with broad-spectrum daylight fluorescents (not a full-spectrum lamp), Sisson, Slaven, and Hamilton (1976) reported finding reductions in plasma riboflavin and, in some infants, a reduction in the activity of the enzyme glucose-6-phosphate dehydrogenase, under both lamp types. Under the broad spectrum lamp there was also some reduction of the plasma concentration of certain amino acids. The authors concluded that phototherapy light penetrates more deeply than the superficial tissues of the skin.

Abramov (1985) discussed preliminary data on the visual functions of children who had as infants received phototherapy, in comparison with other jaundiced infants who had not received phototherapy. The eyes of the phototherapy babies had been shielded during phototherapy, but the control babies had not been protected from the high ambient illumination in the neonatal intensive care units. Some of the "control" children demonstrated unusual failures on colour screening tests. This unexpected result led Abramov to warn that caution should be exercised when using light in a therapeutic fashion, because the side effects are largely unknown.

Treatment regimes for medical conditions do not necessarily provide clues to preventives. For example, antibiotics are effective against bacterial infection, but do not prevent infection. Nontherapeutic administration of antibiotics may, in fact, increase the risk of lethal infection by selecting for resistant strains of the bacterial species. Similarly, radiation therapy is effective for some cancers; but excessive exposure to the same radiation causes other cancers. In the absence of a clear understanding of the biochemical processes underlying the effectiveness of phototherapy for specific medical conditions, it would be irresponsible to use medical treatments as the basis for widespread changes to general lighting practice.

C. Ultraviolet radiation exposure. Ultraviolet emissions from interior lighting are controversial. As Stone (1992) observed, some members of the public fear that fluorescent lights can cause cancer. Others believe that evidence such as the studies discussed above points to a need for small doses of ultraviolet radiation to be provided in interiors to protect against demineralization of bones (Wurtman, 1975b). Public concern about the diminishing ozone layer and increased atmospheric transmission of ultraviolet radiation has led to what one researcher has called "near mass-hysteria over exposure to ultraviolet" (W. Hathaway, quoted in Blumenthal, 1992, p. B2).

The question of ultraviolet radiation is relevant to this review because, as given above, part of the definition of a full-spectrum fluorescent lamp is the presence of near-ultraviolet emissions. Ott (1973, and quoted in Cameron, 1986) has argued that this is a critical component of the simulation of natural daylight. He has said (quoted in Cameron, 1986) that the early full-spectrum lamps did not maintain their ultraviolet emissions as long as the visible emissions because the phosphor responsible for the ultraviolet emissions decayed faster than the other phosphors in the tube. He is personally convinced of the importance of regular exposure to ultraviolet radiation (Ott, 1973, 1982), and in consequence of this technical problem he developed a lighting system in which the ultraviolet component is provided by a separate tube that can be replaced as necessary without the replacement of the white-light tube.

Other writers in the popular press note that there is conflicting opinion concerning ultraviolet radiation in interiors. Willey (1992) noted that in New Zealand it was possible in 1991 simultaneously to read advertisements from lighting industry members that extolled products because of their ultraviolet emissions and others that championed the product's ability to eliminate ultraviolet emissions. Both manufacturers, he stated, cited published research to support their advertising claims.

In one recent North American newspaper article (Blumenthal, 1992), full-spectrum lighting was said to be recommended for classrooms because evidence indicates that its increased ultraviolet radiation is beneficial to student health and performance (the Hathaway et al. (1992) study, described elsewhere in this paper, was cited). In the same article one engineer quoted as a proponent of full-spectrum lighting (which includes the ultraviolet component) is described as favouring lighting designs that include diffusers to "reduce glare and ultraviolet emissions" (p. B2).

The central issue here is whether ultraviolet radiation provided by general interior lighting is important to human health. We have already noted the importance of ultraviolet radiation to the provision of Vitamin D. What evidence, pro or con, is there for health effects of interior ultraviolet radiation?

Hathaway et al. (1992; also Hathaway, this volume) included two full-spectrum lighting conditions in their experiment. In one school, the full-spectrum lamps were housed in luminaires that incorporated Plexiglas lenses. These lenses would have absorbed any ultraviolet emissions from the lamps. In two other full-spectrum schools, specular reflectors were added to the luminaires and plastic lenses were replaced with aluminum louvres. These procedures would have ensured that both the visible and ultraviolet portions of the spectral emissions were emitted into the room.

The authors of this report note that the students receiving interior ultraviolet radiation had fewer dental caries than the students in the other schools. Other treatment effects were reported, and are discussed elsewhere in this review, but these did not clearly favour the schools having ultraviolet radiation in the full-spectrum emissions. This fact taken together with the problems with both the statistical analyses and the interpretation of the results of the Alberta Schools study, make it impossible to conclude that additional ultraviolet radiation in classrooms has effects on the health or development of children.

One problem is that we do not know the necessary minimum daily dose of ultraviolet radiation [although recommended daily allowances for Vitamin D exist and necessary doses for erythemal response (skin reddening) and sunburn exist that are guides for maximum daily exposure]. If it is possible to obtain sufficient ultraviolet exposure from brief exposures to natural sources, then additional ultraviolet exposure from general interior lighting may be irrelevant for adequate vitamin D metabolism in most people.

The total emissions of UV radiation from fluorescent lamps are low, even from full-spectrum lamps. The levels in the Neer et al. (1971) study were approximately equivalent to 15 minutes of direct sunlight at noon in summer in Boston, but eight hours of exposure at a high intensity were required to obtain that dose. Some writers have suggested that regular exposure to such low levels of ultraviolet radiation could have a health effect preferable to the effect of brief, high-intensity bursts from direct sunlight exposure (e.g., Ott, interviewed in Cameron, 1986).

There is evidence to suggest that ultraviolet radiation provided by interior fluorescent lighting may facilitate immune function. Allen and Cureton (1945) exposed 11 young men to brief doses of ultraviolet radiation (the light source and intensity are unknown) and compared their physical fitness and health to 10 comparable men who had not been exposed to ultraviolet radiation. Twenty colds were contracted by the control group, and 10 colds were contracted by the experimental group. The groups were not segregated in any way except for the brief exposures to ultraviolet radiation, so that both groups appear to have had equal opportunity to be exposed to disease during the 10-week experiment. (Regarding the physical fitness data, the results as reported do not permit any conclusion to be drawn about the differential effects of the UV exposure).

Skin cancer as a result of fluorescent light exposure is a matter of some public concern (Stone, 1992). Calculations of the ultraviolet dose from interior fluorescent lighting as generally implemented have concluded that in general -- not specifically to any particular lamp type -- the average annual dosage of ultraviolet radiation received from interior fluorescent lighting is approximately 5 % of the dose received from natural daylight exposure over the year at 50° - 60° latitude (Whillock et al. 1988). The exposure from full-spectrum lamps is designed to be higher than the conventional (cool-white) sources, particularly in the low-energy UVA range (320-400 nm).

The epidemiological studies have not been specific as to the type of fluorescent lamp involved. In fact, as Elwood (1986) noted, it has generally proved impossible even to specify whether the fluorescent lamps were shielded by acrylic diffusers or not; if they were, then the ultraviolet exposure of people in those spaces was negligible because of the absorptive properties of acrylic. It is perhaps not surprising that reviews of the epidemiological data have concluded that the evidence does not support the hypothesis of a relationship between fluorescent lighting and malignant melanoma (Muel, Cersarini, & Elwood, 1988; Elwood, 1986).

Another perspective on this issue is provided by risk assessment calculations. For basal and squamous cell carcinomas, which develop on exposed areas of skin, the risk of death in middle-aged adults from occupational exposure to fluorescent lighting is 1 in 2.5 million per year (Stone, 1992). For malignant melanoma, a more dangerous but more rare cancer that develops in both exposed and unexposed areas, the risk has been calculated as 1 in 1.6 million per year, assuming that every case is caused by ultraviolet radiation exposure (Muel et al., 1988).

These risks are very low in comparison to cancer risks associated with genetic variability, geographic location, or natural sunlight exposure. Muel et al. (1988) concluded on behalf of the International Commission on Illumination (CIE) that this risk does not warrant changes in lighting practice or regulatory control, but that the existence of a causal link between malignant melanoma and fluorescent lighting cannot be ruled out entirely pending further research.

It is known that a small number of people experience skin reactions to light. Most frequently, the active wavelengths in these diseases are in the ultraviolet range (e.g., Harber et al., 1985). Cases are known to exist in which fluorescent light sources at intensities used in interior lighting have elicited photoallergic contact dermatitis and solar urticaria (Brown, Lane, & Magnus, 1969; Kobza, Ramsay, & Magnus, 1973; Harber et al., 1985). The same light sources that can elicit photosensitive reactions may also be prescribed as preventives: Daily exposure to low intensity visible light for short periods has been successfully used to induce tolerance in solar urticaria patients (Ramsay, 1977).

Systemic lupus erythematosus (SLE) patients are sensitive to natural sunlight, particularly in the UVB range. Rihner and McGrath (1992) conducted a survey of SLE patients. They reported a substantial number who recalled having experienced symptom flares after exposure to fluorescent light. Sontheimer (1993), however, disputed this finding, saying that the typical UV exposure from fluorescent lighting under common circumstances and the SLE symptom risk related to such exposure are both lower than claimed by Rihner and McGrath. Sontheimer speculated that the survey method used to identify fluorescent-light-induced SLE symptoms may have been biased, and may have led some patients to misattribute the cause of symptom flares.

The incidence of photosensitive diseases is not high. The most common abnormal skin response to sunlight is polymorphous light eruption, which may affect 10% of the population after a sudden, intense sun exposure such as the first sunbathing session in spring or during a midwinter vacation (Prawer, 1991). However, for those who suffer the more serious forms, the consequences may be great, including the possibility of hypotension and unconsciousness (cf. Ramsay, 1977). Before any widespread change in interior lighting increases the quantity of ultraviolet radiation in interiors, the possible effects on this subpopulation require further investigation.

The UVB exposure from natural daylight is said to be on the increase in step with decreasing atmospheric ozone, and the public is cautioned in every weather forecast to avoid excessive exposure to outdoor UV. There has been speculation that modern life leads to an ultraviolet radiation deficit because of the high proportion of the day spent indoors (e.g., Ott, 1973; 1982, also quoted in Cameron, 1986), but there is little evidence to suggest that the general population suffers from any UV deficiency. There is, however, reason to believe that some individuals would suffer if interior ultraviolet radiation levels were increased. Except for the studies by Neer et al. (1971), there is no empirical evidence relating to populations for whom natural daylight sources of ultraviolet radiation are unavailable.

4.2.3 Indirect physiological effects.

A. Melatonin, cortisol, and adrenocorticotropic hormone secretion. The use of phototherapy to treat seasonal affective disorder, a clinical psychological disorder in which melatonin secretion has been implicated, was discussed above. Here, we consider the question of whether the use of full-spectrum fluorescent lighting for general illumination has effects on the production of melatonin and the so-called "stress hormones", cortisol and adrenocorticotropic hormone (ACTH), in the general population. Increased levels of cortisol and ACTH are thought to be suggestive of responses to external stressors (Kalat, 1984). Cortisol levels also vary diurnally, reaching a peak in early morning (Hollwich, 1980).

One report of experiments into lamp type effects on cortisol and ACTH secretion reported interesting effects, but too few details to replicate the study (Hollwich & Dieckhues, 1980). They did not give procedural details, but stated that they exposed sighted adults to 14 days of cool-white illumination at 3500 lux followed by 14 days of natural daylight. A second group (which may or may not have been the same participants as the first) experienced 14 days of full-spectrum fluorescent light followed by 14 days of natural daylight. The authors performed t-tests on the difference between the hormone levels at the start and end of each of the two 14-day periods, separately for the subjects in the two lamp type condition. They concluded that both ACTH and cortisol concentrations had increased during the cool-white fluorescent light exposure and decreased under the natural daylight exposure, but that no systematic variation had occurred in the full-spectrum-exposed subjects.

Hollwich and Dieckhues (1980) concluded that exposure to cool-white fluorescent lighting produced a stress response reflected in the higher cortisol and ACTH levels, but that full-spectrum lighting produced no effect relative to natural daylight. This conclusion may not be warranted because of problems in both the procedure and the statistical analyses. It is not clear, for instance, on what basis subjects were assigned to the full-spectrum or cool-white conditions (the report implies that these were treated as two separate experiments). The effects may have been confounded by treatment order: perhaps the levels rose for one group during the first half of the treatment and dropped as the end of the experiment approached. That is, the "stressor", rather than being the light source, could have been the fact of participating in an experiment. Furthermore, there is no information about the illuminance level of the natural daylight source. Except on heavily overcast days, natural daylight is generally brighter than 3500 lux, raising the possibility that the observed effect is an illuminance level effect and not a light source effect.

Regarding the statistics, it would have been more appropriate to perform a one-way repeated measures multivariate analysis of variance (MANOVA) on the data, provided the subjects were randomly assigned to the cool-white or full-spectrum treatments. This would have increased the power of the comparison by correctly using each subject within the lamp type trials as his or her own control, and would have controlled for the lack of independence of the observations at the various points in time and of the two intercorrelated hormone levels. This design and experimental analysis would have allowed a statement to be made about the relative effect of cool-white versus full-spectrum lamps on cortisol and ACTH levels.

Erikson and Kuller (1983) installed full-spectrum on one floor and cool-white fluorescent lamps on a second floor in an office building in Sweden. They measured urinary melatonin and cortisol levels on the first and last day of the study: once in December, and once in June. Their report provides few details about the 55 subjects, their work, or their offices, other than to describe the two floors as "almost identical" and the type of work in the offices as "the same".

There were no significant differences between the subjects on the two floors on any of the hormone level measures. The conference paper in which the data were reported does not provide detailed descriptive statistics so that it is impossible to assess whether or not the study was sufficiently powerful to detect an effect if one were present. The offices on both floors had windows, which Erikson and Kuller (1983) speculated might have obscured the results by reducing the difference in ambient illumination between the floors.

Kuller and Lindsten (1992) examined cortisol levels in schoolchildren in their field experiment, which was described in some detail above. In this study, morning levels of urinary cortisol were sampled four times in the school year. They reported that contrary to expectations, the students in the classroom with windows and warm-white fluorescent lamps had the highest absolute cortisol levels. They speculated that this is not a lighting effect but a reflection of social or other differences between the classrooms.

The results included a significant three-way interaction between season, lamp type, and windows, in that the children in the windowless classroom with warm-white tubes showed a delay in the annual pattern. All of the other classrooms displayed the minimum cortisol level in December, but this classroom reached minimum in February. Kuller and Lindsten (1992) hypothesized that the effect of an absence of natural or artificial daylight in that classroom was a delay in the annual variation in cortisol production. They did not, however, report the two-way interaction between lamp type and season. If this explanation were true, then it would be reasonable to expect that both the windowless classrooms would show a delay in that even the full-spectrum lamps are not a complete replacement for natural daylight. Moreover, as was noted above, classroom studies more properly should use the classroom, not the individual, as the unit of analysis.

Urinary cortisol and melatonin levels were measured before, during, and after the one-day exposure to either bright or dim warm-white or full-spectrum light in the laboratory experiment by Kuller and Wetterberg (1993). The light exposure was designed to mimic a normal day in an interior, windowless office. Individual differences in the levels of cortisol were large, but there was no effect of illumination intensity or spectral composition on this hormone. For melatonin, there was the expected diurnal variation in which early morning levels of melatonin were high, and afternoon levels were low; but there also was no effect of illumination intensity or spectral composition on melatonin secretion.

In conclusion, there is weak evidence that full-spectrum fluorescent light may have effects on cortisol and ACTH that are more similar to natural daylight than cool-white fluorescent light effects on these variables. Children whose classrooms do not provide natural daylight may have different seasonal variation in urinary cortisol levels. However, other variables such as social factors and extraneous events also have profound effects on cortisol levels; individuals differ widely in cortisol levels, as seen in the Kuller and Wetterberg (1993) investigation. The methodological problems cited in the investigations discussed here make it unclear whether or not the small differences in the secretion of these hormones are, in fact, related to differences in light source spectral power distribution.

B. Endocrine and gonadal growth and development. These experiments are conducted on animals for practical and ethical reasons. Groups of animals are reared under one light source or another, and organ weights are the indices of growth. The organs are weighed after the animals have been killed. Indirect measures of gonadal maturation are used in studies of human beings, and these are discussed in section C below.

The effects of light source spectral power distribution on endocrine and gonadal growth are inconsistent from one study to another, and between the sexes of the animals in a single study. In rats raised under either full-spectrum or cool-white light, Wurtman and Weisel (1969) found that in both sexes, the spleens were significantly smaller in the animals raised under full-spectrum lamps. In the male rats, the weight of testes and adrenal glands were higher in the rats raised under full-spectrum lamps. In female rats, the weight of the ovaries, heart and pineal gland were greater for those rats raised under full-spectrum lamps. However, the females matured sexually at the same time regardless of the lamp type. For female rats, there was no effect of lamp type on the weight of the adrenal glands; for male rats, the weights of the heart and the pineal gland were both unchanged by the lamp type to which they were exposed. For both males and females, body weight was unchanged by lamp type.

Ozaki and Wurtman (1979) compared rats raised under high-pressure sodium lamps (a high-intensity discharge lamp with CCT = 2100 and CRI = 21, having a spectral power distribution characterized more by peaks at certain wavelengths than by continuous emissions) with rats raised under full-spectrum fluorescent lamps. Male rats in this experiment had higher body weights and heavier adrenal glands (proportional to body weight) if they were raised under high-pressure sodium lighting. This effect was replicated in a second trial. For the females, however, in the first study only body weight was greater for the high-pressure sodium group. This effect did not replicate; in the second study, only the adrenal gland measure showed a significant effect in which the high-pressure sodium group had a higher mean than the full-spectrum fluorescent lighting group. Sexual maturation time was unchanged by the lamp type.

Thus, in rats, in one case the results demonstrated apparently greater growth under the full-spectrum source in comparison to a lamp that has been called unnatural and discontinuous in its spectral power distribution. In a second study using a different comparison, the "unnatural" and "discontinuous" source produced heavier body and organ weights in some instances.

Sharon et al. (1971), in addition to examining the incidence of dental caries, examined overall body weight, gonad weight, and submandibular gland weight of golden hamsters exposed to cool-white or full-spectrum fluorescent light. All of the animals were male. In addition to the dental caries outcomes discussed above, Sharon et al. found that overall body weight, gonad weight, and submandibular gland weight were greater in the animals that had been exposed to full-spectrum fluorescent light. This replicates the gonad weight effect that Wurtman and Weisel (1969) found in rats, and finds an overall body weight effect that the earlier experiment did not.

The interpretive difficulty is heightened by an experiment on mice reported by Saltarelli and Coppola (1979). Body and organ weights were obtained for male and female mice raised under one of five lamp types: full-spectrum, cool-white, blue, pink, or black ultraviolet. The irradiances of the light sources were equated and other standard experimental controls were implemented. For male mice, there were no differences between the full-spectrum and cool-white lamps on any measure but there were some effects on kidney, pituitary, and prostate weight in which other lamp types were associated with higher weights. There were no lamp type effects on pineal, thymus, thyroid, pancreas, spleen, testes, or seminal vesicle weights.

In female mice, Saltarelli and Coppola (1979) found lamp type effects only on adrenal, thyroid, and pineal glands. Blue and black-UV lamps increased adrenal weight relative to full-spectrum lamps. Cool-white lamps increased thyroid weight relative to full-spectrum lamps. Pink lamps and full-spectrum lamps decreased pineal gland weight compared to black-UV and blue lamps. The female mice showed no lamp type effects on pituitary, kidney, thymus, pancreas, spleen, liver, or ovary weights.

All of these experiments share an assumption that artificial lighting may be deleterious. Some of these reports state explicitly the belief that the outcome found under the full-spectrum source should be considered the natural outcome. For example, Ozaki and Wurtman (1979) reported that in the study by Wurtman and Wiesel (1969), "light from cool-white fluorescent bulbs was shown to retard gonadal growth compared with that of animals maintained under a light source that more closely simulated sunlight" (p. 339).

None of these experiments, however, included a condition in which the animals were reared under a light regimen similar to that experienced in the wild by that species. Therefore, we do not know how the obtained rates compare with the normative rate of development for any of these species. Even if the outcomes of the experiments demonstrated a clear pattern of spectral power distribution effects on endocrine or gonadal growth or overall development -- which they do not -- we would still be in the dark as to the meaning of these effects.

C. Growth and development in humans. Two of the classroom studies discussed above included measures of growth and development. Hathaway et al. (1992) examined height, weight, and body fat changes in all students and the age of onset of menarche in the girls in the study schools. As noted before, this study cannot be described as conclusive because of problems with the research design and data analysis.

The outcome for the age of onset of menarche illustrates difficulties of interpreting this study in addition to those already discussed. Random assignment of students to schools was impossible, as is commonly the case in school studies. There was no pretest period in which data were collected to determined whether or not there were differences between the schools in maturation rates (a selection by maturation interaction; cf. Cook & Campbell, 1979). Any such differences would be confounded in the interpretation with differences in lighting.

In the case of the incidence of girls reaching menarche, genetic and nutritional factors are known to be potent influences, but any pre-existing differences on these other variables between the schools are unknown. Hathaway et al. (1992) predicted the probability of menarche for each school based on province-wide data, and compared the actual to the expected probability. They interpreted as lighting effects the lower-than-predicted percentage reaching menarche in the high-pressure sodium school and the higher-than-expected percentages in the full-spectrum and UV-enhanced full-spectrum schools (the schools called "full-spectrum" used lamps in luminaires with acrylic lenses that absorbed UV emissions; the "UV-enhanced full-spectrum" schools used lamps in luminaires with egg-crate or parabolic louvres that allowed the transmission of UV radiation as well as visible light). However, local differences in genetic background, or subtle local differences in nutrition not detected by the simple measure used (see above) could equally well explain the data. Moreover, it is not clear that an earlier onset of menarche is a desirable outcome.

In the case of the health data, the statistical analyses --like those for the general health and dental data -- are inappropriate because they do not use the classroom as the unit of analysis and because they attempted to draw conclusions based on nonindependent statistical tests. Examination of the descriptive data reveals the problem with this practice. Based on a comparison of all possible pairs of schools, with no correction for the lack of independence of these comparisons, the authors concluded that the smallest gain in height over the two study years occurred in the school with high-pressure sodium lighting. Their t-test procedure gave a significant difference between the high-pressure sodium school mean and the cool-white school mean (10.2 cm [SD = 3.6] versus 11.9 cm [SD = 2.7]), and of the high-pressure sodium mean and the UV-enhanced schools' mean (10.2 cm [SD = 3.6] versus12.3 cm [SD = 2.9]), but not between the high-pressure sodium mean and the full-spectrum school mean (10.2 cm [SD = 3.6] versus 12.0 [SD = 3.9]).

That is, the significant differences occurred only for those groups with considerably smaller standard deviations, even though all the means cluster within 2 cm of each other (that is, less than the standard deviation of any group). Similar difficulty attends the interpretation of the results of the weight and body fat data. Reanalysis of these data using the appropriate nested model would likely reveal that there is no statistically significant difference between the groups on any of the general health measures. Furthermore, like the menarche outcome, it is not clear than a larger increase in body weight or body fat is necessarily a desirable outcome in the long term.

The conclusion that proper statistical analyses of the Hathaway et al. (1992) data would reveal that classroom lighting has little or no effect on growth and development measures is consistent with the outcome obtained by Kuller and Lindsten (1992). The children in this study were approximately the same age as those in the Hathaway et al. (1992) study, and the Malmo school, at 55°N, only slightly farther north than Edmonton, Alberta (54°N). There were no statistically significant effects of lamp type or classroom windows on annual body growth in the Swedish children.

In conclusion, there is no convincing evidence that differences in the lamp type used in classroom lighting exert meaningful effects on the growth and maturation of children.

4.2.4 Summary. There is little research evidence to support the contention that full-spectrum fluorescent lighting affects physical health. The literature reviewed here is, generally speaking, poor in quality. The only process in which important effects may exist is in the metabolism of Vitamin D and, indirectly, on calcium absorption and dental caries. However, even in this instance the best outcomes may relate as much to the intensity of light (e.g., Neer et al., 1971) or to some other unknown aspect of illumination (e.g., Feller et al., 1974). Some evidence suggests that a lack of natural daylight can cause changes in seasonal patterns of cortisol secretion (Kuller & Lindsten, 1992), although the meaning of this finding is unknown. In the absence of data that show overall lamp type effects on health, growth, or development, claims that any such effects exist are premature.

4.3 Summary: Physiology and Health

There is no dispute that light affects animal and human physiology and health. Both direct and indirect pathways for this influence are known, although not well understood. In certain cases, such as neonatal hyperbilirubinemia, this knowledge has led to a simple, noninvasive treatment for disease. However, the present issue is whether the use of full-spectrum fluorescent lamps for general interior illumination influences human physiology and health. The present review did not find compelling evidence for such effects. Indeed, this body of research demonstrates nearly every research methodology problem listed by Gifford (this volume), including problems with the experimental design, statistical analysis and reporting, and inappropriate generalization to different species and populations.

One unresolved issue is what a given change might mean if it were observed. Increases in body weight and body fat, or younger sexual maturation, may not be desirable. In other instances, what may be desirable for one group -- such as increased interior ultraviolet radiation for people who are unable to obtain this nutrient from natural sources -- may be undesirable for others, such as the sufferers of photosensitivity diseases. Further investigation will be necessary for determination of such value choices.

5. Conclusions

Despite the efforts of many scientists and the publication of dozens of scientific reports, our knowledge of the effects of lighting on human behaviour, mood, and well-being is poor. As regards the effects of light on health and physiology, our understanding is better, but we still do not understand many of the specific mechanisms underlying effects that are known to exist. It is clear from this review that in most areas, the quality of the research is so poor that it is impossible to say definitively whether or not full-spectrum fluorescent lighting has any effect on the behaviour or outcome in question. However, the best evidence available points away from differences in spectral characteristics of light sources and towards intensity, variability, flicker, and more complex interactions of people and physical conditions as explanations of the effects of the lit environment on performance, mood, and health. The lighting research community does not suffer a lack of research questions to investigate.

Lighting researchers, seeking general statements about the effects of lighting on all people, have tended to ignore the possibility that different people may have different sensitivities to the lit environment. A subset of the population may be particularly sensitive to the presence or absence of certain portions of the visible spectrum, or to oddities in the distribution of light. Medical professionals have long known that this is true because of the existence of photoallergic reactions that are wavelength-specific; but other disciplines have not looked for similar effects on other important variables.

One difference between natural light sources and some artificial lighting technologies is in the occurrence of flicker. Fluorescent lamps on conventional magnetic ballasts have the appearance of a constant output, but in fact vary by as much as 60 per cent in output at a rate of 120 Hz (in North America; 100 in Europe). This flicker is not perceptible by most people, but can be detected by the visual sensory system. Interestingly, the effects of flicker should be greater for full-spectrum lamps than other common fluorescent lamps because of their relatively higher proportions of phosphors with emissions in the blue portion of the visible spectrum. The output from these phosphors decays more quickly than red phosphors; therefore, the depth of the oscillation is greater in these lamps than in others (Wilkins & Wilkinson, 1991).

Some evidence suggests that certain people experience headaches and other neurological outcomes because of the temporal flicker of fluorescent lights on magnetic ballasts(e.g., Lindner & Kropf, 1993; Wilkins et al., 1989). Electronic ballasts, a relatively new technology, use integrated electronic circuitry to increase the rate of oscillation to the range 20-60 kHz, which is too fast to be detected by the sensory system. Wilkins et al. (1989) found that the incidence of headaches was lower when this type of ballast was in use.

Some previous writers (e.g., Wurtman, 1975b) have invoked evolution as an argument in favour of light sources that mimic natural daylight. The argument is that because natural daylight was the sole source of illumination for most of the period during which humans evolved, then physiological processes should function optimally when exposed to natural daylight. Any deviation from this may result in abnormal function.

The logic of this argument, however, does not withstand close scrutiny, for humans have successfully adapted to a wide variety of environments with a wide variety of natural daylight conditions. Moreover, light exposure is not principally to direct rays from a light source, but to reflected and filtered light (Corth, 1983). The spectral composition of the daily light dose depends on the colours and reflectances of walls, ceilings, floors, furniture, plants, ground and on the transmittance or reflectance of windows, water, eyeglasses or contact lenses, and the eye itself. The intensity of the daily light dose will depend upon weather conditions, latitude, day length, window coverings and upon the intensity of interior, artificial light sources. Attractive though it may be to suppose that we could directly alter health, well-being, and behaviour with the simple prescription of a specific lamp type or light source, the fact remains that the light source itself is but one factor in a complex equation. The relationship between lighting and human behaviour is unlikely to be a simple, deterministic one.

Optimists will see an opportunity here. The literature reviewed here does point to interesting, complex interactions of people and their physical environment. The daily light dose does not come from a specific source, but from exposures that vary as one moves from room to room, looking at objects of different colours and moving from indoors to out, and changing rhythmically over the days and seasons. Variability, not uniformity, characterizes our light exposure; and yet, many interiors are designed to provide uniform appearance both of objects and of lighting. We know very little about what effects this practice might have in either the long or the short term.

In opposition to the view that humans react passively to interior lighting is the experimental evidence that mental processes triggered by lighting mediate the differences in observable behaviours (e.g., Baron, Rea, & Daniels, 1992; Biner, Butler, Fisher, & Westergren, 1989; Veitch, Gifford, & Hine, 1991). This research domain within lighting research is new. Many different cognitive processes may explain differences in the effects of different lighting installations: arousal, expectations, and prior situational experiences are only a few possibilities. It is intriguing to think that our emotional or intellectual appraisals of our physical conditions influence our behaviour and, possibly, our health. Further exploration of these connections will require multidisciplinary co-operation between environmental psychologists, health psychologists, and cognitive psychologists as well as the participation of the interdisciplinary lighting community.

The relationships between environment and human behaviour are of more than academic interest. When a researcher publicizes a dramatic finding on a subject of public concern, such as the provision of safe, abundant electricity, or the quality of the educational experience for children, the media seize upon it. In turn the general public demands action from responsible parties to provide the best conditions possible. The cost of poorly-conceived and poorly-reported research is not only the dollar and time cost to the research team and project sponsors; it costs society the lost opportunity of learning the truth about ourselves, and about how to improve the quality of life for individuals.

We do not yet know the truth about how to provide high-quality lit environments for human activities; we cannot even define what we mean by "high-quality". Past research can inform us of the pitfalls to avoid in future research, and there are many pointers to the lighting variables that may be most important. There is a challenge before the lighting community. Is there the will to rise to it?

6. References

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