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**A Critical Examination of Perceptual and Cognitive Effects
Attributed to Full-spectrum Fluorescent Lighting**

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Abstract

Full-spectrum fluorescent lighting has been credited with causing dramatic improvements in vision, perception, and cognitive performance, as compared to other fluorescent lamp types. These effects are hypothesised to occur because of similarity between FSFL emissions and daylight, which is said to have evolutionary superiority over other light sources. This review, covering the period 1945-1998, critically considers the evidence for these claims. In general, poor-quality research has resulted in an absence of simple deterministic effects that can be confidently attributed to fluorescent lamp type. Promising avenues for lighting-behaviour research include investigations of cognitive mediators of lighting-behaviour relationships, and flicker rates and colour rendering effects on visual processing, appearance judgements, and affect. Good lighting solutions are more complex than lamp type specification.

A Critical Examination of Perceptual and Cognitive Effects Attributed to Full-spectrum Fluorescent Lighting

1.0 Introduction

Electric lighting is a ubiquitous part of everyday life. Even in sunny California, the daily exposure to daylight is lower than to electric lighting (Espiritu *et al.* 1994). Among electric light sources, fluorescent lamps account for 67% of the lumens world-wide (T. K. McGowan, GE Lighting, personal communication, October 18 1996). Not surprisingly, electric lighting has been identified as a source of concern and interest to people ("Office lighting" 1980; Veitch, Hine, and Gifford 1993). Fluorescent lighting, in particular, is viewed with suspicion as a cause of headaches, eyestrain, and other more serious health complaints, such as skin cancer (Lindner and Kropf 1993; Stone 1992; Veitch *et al.* 1993; Veitch and Gifford 1996).

Many believe that daylight is superior to electric lighting in its effects on work performance, mood, and health (Veitch *et al.* 1993; Veitch and Gifford 1996). Media attention has contributed to this notion, with articles and news items in prominent publications: "New York Schools Consider Installing Full-Spectrum Lighting to Help Students", "A Case of Daylight Robbery", "Natural Prozac", "Report Card on School Lighting" run the headlines (Blumenthal 1992; Cook 1994; "Light treatment" 1994; "Report Card" 1993). These articles advocate the use of full-spectrum fluorescent lamps (FSFL), which manufacturers claim simulate daylight. Visitors to the exhibitors' area at a recent American Psychological Association convention could read that one particular FSFL "is the only patented ... general purpose fluorescent lamp that simulates daylight. This simulation is a major asset toward creating the perfect interior lighted environment" (Anonymous 1988). Full-spectrum lighting beliefs have even reached the notice of comic-strip writers (Figure 1). This material leaves the impression that the use of a FSFL in offices, classrooms, and for light therapy of certain mood disorders, will have beneficial effects on behaviour, mood, and health.

Initial interest in FSFLs began with observations of plants, which appeared to grow differently under different lamp types (Ott 1973). Laszlo (1969) reported that certain species of snake, known to be difficult to maintain in zoo cages, had exhibited increased activity when the cage lighting was changed to FS sources. This report has been widely cited as supporting the healthful qualities of FSFLs (e.g., Ott 1973; Blatchford 1978). Despite the questionable generality of these observations, claims about dramatic beneficial effects of FSFLs have persisted (e.g., Blumenthal 1992; Henderson 1986; Hughes 1980; Ott 1982; Tibbs 1981).

Wurtman and Neer (1970) were among the first to suggest that the spectral composition of light sources might be an appropriate target for federal legislation to ensure the maintenance of public health. The claims for FSFLs have included reports that these lamps improve visibility, reduce hyperactivity in children, improve academic performance, reduce fatigue in office workers, and improve health generally. In 1986, the United States Food and Drug Administration (FDA) issued a "Health Fraud Notice" against one manufacturer of FSFLs 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 (FDA 1986). Nonetheless, a substantial proportion of the public accepts these claims, believing that light that mimics daylight is better for work performance and for mood (Veitch *et al.* 1993).

If these outcomes are real, and FSFLs offer superior illumination, then widespread changes in lighting practice are warranted. However, if the effects are neither clear nor powerful,

then decision makers must weigh this information against the greater cost of FSFLs (as much as 450% for one manufacturer's FSFL versus a comparable CWFL). In either case, psychologists have a responsibility to evaluate the strength of such claims about the putative causes of behaviour, and to communicate a reasoned conclusion to the public at large. This paper reviews the scientific literature concerning the claims that FSFL beneficially affects perception, cognition, and other behaviours in healthy people. A companion paper (McColl and Veitch 2000) addresses the literature concerning direct and indirect effects of FSFLs on physiology, mental health, mood, and social behaviour. Despite the confusion and controversy about these lamps and their effects, no other integrative review has appeared in the scientific literature.

This review covers the years 1945-1998. The basis for the review was a search of Psychological Abstracts, Index Medicus, Ergonomics Abstracts and the electronic databases PsycInfo, Medline, and Inspec. Journals not covered by these services, but known to be relevant, were also searched, for example *Journal of the Illuminating Engineering Society* and *Lighting Research and Technology*. Proceedings of lighting conferences, which publish brief versions of papers presented, were also reviewed. Because of the widespread public interest in this topic, it was decided to be as inclusive as possible in this review, to provide a comprehensive overview of publications on this topic.

2.0 Foundations and Definitions

A brief introduction to lighting is provided here to establish the basis of the review and to define potential confounding variables. For more detail, consult a reference work such as the *IESNA Lighting Handbook* (Rea 1993a), or the Chartered Institution of Building Services Engineers (CIBSE 1994).

2.1 Lamp Types

A wide variety of fluorescent lamp types exist. The lamps are characterised by differences in *spectral power distribution* (SPD), the radiant power per unit wavelength as a function of wavelength (Rea 1993); that is, different fluorescent lamps emit different patterns of radiant energy as a function of wavelength (e.g., Figure 2). Lamp type is described by two quantities, the *correlated colour temperature* (CCT) and *colour rendering index* (CRI).¹ Historically, the most common fluorescent lamp has been the cool-white fluorescent lamp (CWFL), which is characterised by an SPD designed to maximise achromatic visibility and has CCT=4100 K. Warm-white fluorescent lamps (WWFL), also common, are warmer in colour appearance (CCT=3000 K). Various lamps exist within these CCT classes, with varying degrees of colour rendering capability.

Although there is no firm definition of FSFLs, here we adopt the definition of full-spectrum fluorescent lighting described by Boyce (1994): A FSFL is one that emits light in all parts of the visible spectrum and some in the ultraviolet-A region of short-wavelength, high-

¹ Color temperatures describe the color of a light source in terms of the color of a blackbody radiator, which is a theoretical object that radiates energy perfectly. CCT is the color temperature (in Kelvin) at which a blackbody radiator has the same color appearance as the fluorescent lamp (which is not a radiator) (Rea 1993a). CRI refers to the color appearance of illuminated objects under a given light source, rather than the color appearance of the light itself. It is a comparison of the color appearance of objects under the test light source with the color appearance of the same objects when illuminated by a reference (standard) light source of the same color temperature. If the match between the color appearances under the two lamps is perfect, CRI=100 (Rea 1993a).

energy radiation (UV-A, 320-400 nm), has a CCT of 5000 K or greater and a CRI of at least 90. This higher CCT than other common lamps means that they appear more blue-white. Figure 2 shows the SPDs of CWFL and FSFL for comparison purposes.

2.2 *Light Intensity*

Illuminance is the technical term for the area density of luminous flux incident on a surface; colloquially, we speak of “light levels”. Luminance is the quantity of luminous flux propagated in a given direction from a point on a surface. Colloquially, this is the brightness of an object (although this use confuses the photometric quantity and the sensation of brightness, which depends on the state of adaptation of the eye as well as the luminance of the object [Rea 1993a]). The two quantities are related by reflectance: Luminance is the product of the illuminance on the surface and the reflectance of the surface. Luminance and illuminance are both weighted functions of the spectral sensitivity curve (V_λ for photopic vision, V'_λ for scotopic vision). Irradiance is the measure of the density of radiant energy falling on a surface, and is unweighted by visual sensitivity.

The review revealed two problems with the specification of light intensity. The studies reported here all involve visually-mediated processes for which luminance is the appropriate descriptor of the stimulus. Most studies, however, reported illuminance and provided no indication of the reflectances of surfaces, which makes it impossible to determine exactly the luminous conditions experienced by participants. Had luminance been reported instead, there would have been a common metric describing the stimulus conditions, as would have been desirable for comparing studies. This problem was compounded by photometric errors that are particularly serious for comparisons of different lamp types (Ouellette 1993).²

Even within a single study, it was not uncommon for illuminance and lamp type changes to be confounded because of differing lamp efficacies. FSFLs in general emit fewer lumens per watt than other common lamp types, so that when replaced one-for-one with another lamp type the light level drops. In such cases it was impossible to determine whether any effects observed were caused by lamp type changes or by the changing luminous conditions, although some authors attempted such attributions.

2.3 *Lighting Systems and Sources*

2.3.1 *Luminaires*.

The UV component of the FSFL is said to be critical to its beneficial properties (e.g., J. N. Ott, quoted in Cameron 1986), but some lighting systems absorb UV radiation. The commonly-used plastic and glass lenses and diffusers absorb almost all the UV radiation below 400 nm (Whillock, Clark, McKinlay, Todd, and Mundy 1988), although special UV-transmitting plastics and glass are commercially available. Research reports were not consistent in the manner of describing the luminaires housing the lamps. Unless otherwise noted, all experimental conditions within a single study used the same type of luminaire and cover treatment, but in general it is not known whether this would have transmitted or absorbed the UV component.

² Common photometric measurements, both of illuminance and luminance, are made using meters calibrated against an incandescent standard. Where the standard lamp differs in the spectral power distribution from the test lamp (as fluorescent lamps do from incandescent), substantial errors in measurement can occur, and the size of the error varies for each wavelength (Ouellette 1993). Careful photometric procedures, recommended by Ouellette to minimise these errors, are expensive and technically difficult, and therefore are relatively uncommon.

2.3.2 Windows. 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 difference between fluorescent lamp types. Therefore, it is impossible to characterise precisely to which stimulus conditions subjects responded if they were in rooms with windows. 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 if the authors did not specify.

2.3.3. Ballasts. One difference between natural light sources and some electric lighting technologies is in the occurrence of flicker. Fluorescent lamps on conventional magnetic ballasts have the appearance of a constant output, but in fact their luminous output varies at twice the AC rate (thus, at 120 Hz in North America; and 100 Hz in Europe). Electronic ballasts, a relatively new technology available for fluorescent lamps, use integrated electronic circuitry to increase the rate of oscillation to the range 20-60 kHz. The degree of luminous modulation is not constant across lamp types, but depends on the nature of the lamp phosphor (which determines the lamp SPD) and the ballast characteristics (cf. Rea, 1993a). The phosphor compounds used in fluorescent lamps vary considerably in their spectral output and in the decay time for that output. In some lamps, the various phosphors have sufficient variability in decay time that the lamp output varies chromatically as well as in overall luminance. This phenomenon has been called *chromatic flicker*. Among common lamp types, those using halophosphates (F40T12) flicker least, with warm white lamps the most stable and cooler CCT lamps having higher flicker rates. Triphosphor lamps (F34T8) flicker more than halophosphate lamps (Wilkins and Clark 1990). FSFLs have a higher degree of luminous modulation than other common lamp types (e.g., Veitch & McColl 1995).

Various investigators have already found that the luminous flicker of fluorescent lights using magnetic ballasts, as compared to electronic ballasts, has effects on neural activity, visual performance, saccadic eye movements, reading, and headaches (Kuller and Laike 1998; Veitch and McColl 1995; Veitch and Newsham 1998; Wilkins 1986; Wilkins, Nimmo-Smith, Slater, and Bedocs 1989). Although it is possible that chromatic flicker adds to these effects, this is yet unknown. No one has investigated whether the increase in luminous modulation associated with lamp type exacerbates the effects that have been observed by comparing flicker rates within lamp types. If so, however, FSFLs would tend to cause more problems than other common lamp types because of their greater luminous modulation, at least when run on low-frequency ballasts. In the review, it was difficult to evaluate this hypothesis because of the lack of information provided about ballast type, although magnetic ballasts may be assumed to have been used in most studies prior to the late 1980s, when practical electronic ballasts reached the market and began to be widely adopted.

2.4 Explanatory Mechanisms

2.4.1 Evolutionary fitness. Some writers have argued that because daylight was the sole source of illumination for most of the period during which humans evolved, therefore all physiological processes should function optimally when exposed to daylight (Hughes 1980;

Thorington, Parascandola, and Cunningham 1971; Wurtman 1975a 1975b). According to this hypothesis, any deviation in daily light exposure from daylight risks causing abnormal function. Indeed, Wurtman and Neer (1970) characterised American life, with its primary light exposure being to electric lighting, as 'unplanned phototherapy' that might have unwanted, unspecified consequences (p. 395).

A subset of the evolutionary hypothesis holds that the UV component of FSFLs is critical to its biological and behavioural effects; that is, that this UV exposure in interiors is physiologically essential to health and well-being (e.g., Ott 1982; Cameron 1986). This hypothesis is principally associated with direct effects through skin absorption because adult eyes do not transmit UV (Barker, Brainard and Dayhaw-Barker 1991), although indirect effects in children cannot be ruled out, in light of the evidence of visual responses to UV radiation in children (Brainard *et al.* 1992; Sanford *et al.* 1996).

McColl and Veitch (2000) consider the evolutionary hypothesis and its variants in greater detail in relation to physiological processes (including stress and arousal). Its relevance to the present review lies in the frequency of the notion that what is natural is good in anecdotal reports and media coverage of FSFL effects on cognitive and visual processes such as visual performance (e.g., Blumenthal 1992) and academic achievement (e.g., "Report card" 1994). In this review, the authors sought evidence supporting the evolutionary theory -- that lighting similar to daylight is generally superior in its effects on people -- and other theories specific to the visual, perceptual, and cognitive domains.

The chief problem with the evolutionary theory is its vagueness. It relies on the assumption that the evolutionary pressures on vision and physiological processes influenced by luminous conditions all selected for processes optimised by exposure to daylight. It assumes that, unlike other environmental conditions (e.g., temperature), humans cannot adapt to changes in luminous conditions, either using other physiological mechanisms or through behavioural adaptations. The existence of physiological mechanisms that respond to light is taken as evidence for the hypothesis, regardless of the action spectrum for the process or its relation to daylight (or moonlight) conditions.

Spectral qualities are most often cited as the most relevant light source characteristic, although intensity is also proposed as the active agent. Under this hypothesis, if one must have electric lighting then it should be as similar as possible to daylight. FSFLs emit light that is said to be similar to daylight over the visible range. Thus, using FSFLs for interior lighting should be beneficial in their effects on vision and physiology, compared to other lamps. Most writers say little directly about the relevance of this hypothesis to cognition or perception, but imply that mood, well-being, and quality of life in a general sense require lighting that is similar to daylight (e.g., Hughes 1980).

The purported similarity between FSFL emissions and daylight is tenuous at best, although it is true that the general shape of the SPD of a FSFL is more similar to daylight than the popular CWFL. Daylight varies in colour temperature from 5000 to 10,000 K depending on sky conditions, season, and time of day (Thorington 1985); an FSFL lamp can have only one CCT. Daylight is more intense than any interior lighting (offices and schools are designed to provide 200-500 lumens/m² [lux, lx] incident on a desk surface; outside, daylight is on the order of 50,000-100,000 lx. Daylight also is polarised; polarisation for interior lighting requires a special filter, and is a separate issue (see Clear and Mistrick 1996, for a review of the literature on polarisation and visibility).

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 and 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, electric light sources (which are never as intense as the most intense daylight).

These differences make the light source (whether it be solar radiation, fire, fluorescent lamps or other electric light sources) a poor specification for the effective physiological and visual stimulus for behaviour and well-being. If conditions similar to those under which evolution occurred are indeed optimal for human health and well-being, then optimal visual conditions will have to replicate those colours, reflectances, and variations, as well as the spectral power distribution. As far as we are aware, the precise visual conditions under which human evolution occurred are unknown; and in any case, it is likely that humans might have developed adaptive mechanisms to tolerate deviations from those conditions.

2.4.2 Expectancy biases. Among the best-known studies in psychological research are the Hawthorne experiments, conducted in the 1920s at the Western Electric plant in Hawthorne, Illinois (Snow 1927) to study performance of electric assembly workers working in a special test room. The results have entered the realm of psychological legend, although precisely what was observed, and why, remains poorly documented and probably misunderstood (Diaper 1990). The researchers increased light levels, decreased them, and even pretended to change the light bulbs for new ones when in fact they merely replaced them with the same ones. No matter what lighting change they made, performance apparently increased. Today, it is generally considered that several processes might explain these results: the participants were singled out to participate in an experiment in a special room; the changing lighting conditions sent a powerful signal to employees that their employer was concerned about them, to which they responded with increased effort and output; and, other aspects of the special social conditions in the test room probably also contributed to the higher output (Diaper 1990; Gifford 1997).

One lesson to be learned from this series of investigations is that lighting research is not immune to the confounding effect of participant expectancies, which can seriously bias empirical outcomes. Indeed, expectancy biases are a potentially serious problem in lighting research because the nature of the stimulus is impossible to hide to sighted subjects. Almost all field studies reported here, and many of the laboratory studies, used within-subjects research designs that cannot control for this potential source of bias. What is unknown, moreover, is the direction in which these biases might occur. A few studies have attempted to manipulate lighting-related expectancies directly, and these are discussed below.

3.0 Visual Processes

The relationship between vision and light is enshrined in two curves of spectral luminous efficiency for vision. At the light levels typical of interiors, vision is a function of the photopic system of cone photoreceptors, with maximal response at 555 nm. Night vision is dependent on the scotopic system of rod photoreceptors, which are most responsive at 508 nm (Rea 1993a). Thus, it is trivial to observe that the SPD of a light source affects vision. It will determine the colours we see and, together with the irradiance, the apparent brightness (e.g., at low light levels

a blue light will appear brighter than a red light, but the reverse will be true at high light levels). The important question for application to interior lighting is whether the SPD of an illuminant will influence our ability to see at light levels typical of interiors.

3.1 Visual Performance

Berman, Jewett, Fein, Saika, and Ashford (1990) tested the perceived brightness of a wall illuminated by one of two colour-matched lamp combinations at luminance levels typical of interiors. One of the combinations was stronger in the 508-nm band to which the scotopic system is most sensitive; the other combination was more similar to the sensitivity of the photopic system. The results indicated that both the scotopic (rod) and photopic (cone) sensitivity systems influenced brightness perception, contrary to the received wisdom that only cone contributions would influence brightness perception at interior light levels.

Berman (1992) also found that pupil size 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. The smaller the pupil, the greater the depth of field and the better the visual acuity. Thus, Berman predicted that a light source with strong emissions around 508 nm in addition to the photopic spectrum will produce optimal visual performance. Such lamps are not generally available, and the closest alternative for general use would be a FSFL.

Some experimental evidence is consistent with this theory: Simonson and Brozek (1948), comparing visual functions under three different incandescent illuminants in a within-subjects design, found that the lamp that produced the best performance had slightly greater emissions in the range 500-540 nm (scotopic), and lower emissions at the photopic peak wavelength of 550-560 nm. However, this paper does not include the statistical analyses that today would be required to support inferences about their observations. Blackwell (1985) found that the relative "spectral effectiveness" of HPS, clear mercury, and incandescent lamps all were significantly lower than the spectral effectiveness factor calculated for the FSFL, a finding also consistent with the scotopic sensitivity theory. Krtilova and Matousek (1980), summarising studies of mental workload, visual acuity and visual comfort in relation to lamp type, stated that "statistical evaluation of control tests shows best result for daylight, Daylight fluorescent [CCT=6500K, probably a FSFL] and discharge RVLX lamps" (p. 231), although they provided no detailed data.

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 by 18-45-year-old participants who experienced all luminous conditions. Variations in spectral composition were achieved by varying the combinations of fluorescent lamps that provided the light around the task (the *surround*), which was presented on a computer screen. In one condition the lamps consisted of three red and one pink lamp (having a ratio of scotopic-to-photopic luminance of 0.24); in the other condition, one green-blue lamp (incorporating Sylvania phosphor #213) was used (having a scotopic-to-photopic luminance ratio of 4.31). 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, which is consistent with the theory. These effects

were replicated with older subjects (61-66 years of age), although the effect sizes were smaller (Berman, Fein, Jewett and Ashford 1994). The effect was eliminated when pupil size was controlled using Mydriacyl eyedrops, and enhanced when participants with natural pupils wore glasses that blurred the stimulus (Berman, Jewett, *et al.* 1996).

The results from Berman's experiments are consistent, but it is not clear that pupil size is the mediating mechanism for the enhanced visual performance with the scotopically-enhanced lamps. There was no correlation between pupil size and performance in the initial studies (Berman *et al.* 1993 1994). Fotios and Levermore (1995) also found improved visual performance under a white incandescent lamp with a high colour temperature (stronger blue component than a regular incandescent lamp), but the size of the effect was not consistent with a prediction based on Berman's theory. However, Berman, Fein, Jewett, Benson, and Myers (1996) reported that word-reading accuracy was greater with smaller pupils, when pupil size was controlled by luminance differences in a scotopically-rich fluorescent lamp.

Other laboratories, using both within- and between-subjects research designs, have failed to find effects of SPD on visual performance or visual acuity in the luminance range typical of interiors (Boyce and Rea 1994 [also presented in brief by Rea 1993b]; Chance 1983; Halonen 1993 [also published as a technical report by Halonen, Eloholma, and Lehtovaara 1993]; Hathaway 1995 [technical report by Hathaway, Hargreaves, Thompson and Novitsky 1992]; Kuller and Wetterberg 1993; Rowlands, Loe, Waters, and Hopkinson 1971; Veitch and McColl 1995; Vrabel, Bernecker, and Mistrick 1995).

One potential explanation for the conflicting findings is subject expectancy biases; individual differences in visual acuity are large, so most researchers control for this source of variance by using within-subjects designs that make the independent variable obvious. However, consistent results have been obtained using within-subjects designs to study effects predicted by other visual performance models (e.g., Rea and Ouellette 1991), such as contrast (e.g., Boyce and Rea 1994) and photopic luminance effects (e.g., Halonen 1993; Rowlands *et al.* 1971), which are equally evident stimulus conditions. If inconsistent results were caused by expectancy biases arising from knowledge of the hypotheses, surely these other investigations would also show conflicting findings.

Luminous flicker affects visual performance (Veitch and McColl 1995; Wilkins 1986) across the range of 100/120 Hz to 20 kHz, with lower flicker rates reducing visual performance. In addition, differences in chromatic flicker between lamp types might contribute additional variance in visual performance. Although there is no direct evidence that chromatic flicker influences visual performance, indirect evidence suggests that it might be important, at least for sensitive populations. Wilkins and Wilkinson (1991) developed a tint for eyeglasses to reduce the degree of chromatic modulation from fluorescent lamps, and Wilkins and Neary (1991) demonstrated visual and perceptual benefits of tinted glasses for people with a history of perceptual distortion and reading difficulties. These findings suggest that chromatic flicker might confound the literature in this area, given the wide variation in lamp types and methodologies used in these investigations, some that are subject to flicker (fluorescent and high-intensity discharge) and some that are not (incandescent). Differences in chromatic flicker associated with lamp type would obscure the effects of lamp SPD on visual performance. For example, FSFLs are scotopically rich (to use Berman's terms), which might improve visual performance. However, depending on the specific FSFL used, there could also be an increase in chromatic modulation if the lamp is run using magnetic ballasts, which might decrease visual

performance.³ Studies in this area should take care to minimise such confounding effects and should report the techniques used to do so. Further direct tests of the chromatic flicker hypothesis are also warranted.

3.2 Visual Comfort

Evidence that SPD affects measures of visual fatigue or discomfort (a construct with no firm definition) is inconsistent. Berman, Bullimore, Bailey, and Jacobs (1996) reported that electromyographic responses indicating discomfort were greater for a scotopically-deficient light source, and subjective ratings of discomfort on a global scale were greater for the same source at high luminances (ballast type, and hence flicker rate, is unknown). Kuller and Wetterberg (1993) averaged severity ratings on a list of symptoms to form a visual discomfort index. FSFLs caused more visual discomfort than WWFLs, and visual discomfort was lower on the second testing occasion (lamp type was a within-subjects variable; illuminance levels were varied between-subjects). The increased visual discomfort for FSFLs is contrary to their predictions, although consistent with the notion that flicker causes visual discomfort (the ballasts were magnetic, with luminous modulation at 100 Hz). Veitch and McColl (1995) developed a 16-item visual comfort scale based on commonly reported symptoms such as blurred vision, irritated eyes, and headache, and found no effects of spectral distribution or flicker rate on visual comfort ratings after a short exposure time using a between-subjects comparison for lamp type (in which participants are unaware of the existence of other experimental conditions using other lamps). The sample size for this comparison, however, was small.

Maas, Jayson, and Kleiber (1974; also discussed in a trade publication by Kleiber, Musick, Jayson, Maas, and Bartholomew 1974) examined the after-effects of 4-hour study hall sessions under equivalent levels of CWFL or FSFL in luminaires equipped with "standard translucent covers" (which would have absorbed all UV radiation), in a within-subjects experimental design. The presence or absence of windows or daylight was not noted. Only one of three objective measures of visual or neurological fatigue (and none of the subjective measures) showed a statistically significant effect: a smaller decrease in critical flicker fusion (CFF)⁴ scores in the FSFL condition than in the CWFL condition. They interpreted this finding, and other trends, as clear evidence for the superiority of the FSFL condition. However, O'Leary, Rosenbaum, and Hughes (1978) obtained the opposite result: Hyperactive children had lower CFF rates, indicating greater visual fatigue, following weeks of FSFL lighting than following weeks with CWFL in their windowless classroom. In both cases, flicker was uncontrolled (there were no practical high-frequency ballasts at the time these investigations were conducted), and could have confounded the results in these studies.

The lack of agreement about the visual fatigue/visual discomfort construct is another

³ Wilkins and Clark (1990) observed very little chromatic modulation from FSFLs, but other experts have said that older FSFLs using halophosphates might have had significant chromatic flicker as well as luminous flicker (T. McGowan, personal communication, March 5, 2000). We were unable to obtain data concerning luminous or chromatic modulation of currently-available fluorescent lamps. Recent developments in lamp technology have resulted in considerable change in the phosphors used in most lamp types, so this issue will be unresolved without new data.

⁴ CFF is the frequency at which a flickering light appears to be a constant stimulus. Some investigators treat CFF as a trait, having a typical level for each individual that indicates the sensitivity of the visual system (e.g. Kuller and Laike 1998). Others, following Simonson and Enzer (1941), interpret changes in CFF as responses to environmental conditions, being a measure of visual fatigue [e.g., Maas *et al.* (1974) and O'Leary *et al.* (1978)].

likely explanation of the inconsistent results: Each investigation might be measuring different outcomes, but using the same labels. Moreover, there is no clarity about the mechanism being invoked: fatigue in the visual system, the ocular musculature, or some other process.

In addition, only one of the studies cited here included controls for participant expectancy biases (Veitch and McColl 1995); consequently it is possible that such biases have obscured real differences associated with fluorescent lamp type. If such biases operated here, it is at least clear that the expectancies do not uniformly favour FSFL.

4.0 Perception

4.1 Colour Perception

Although FSFLs, with CRI=90, improve colour discrimination performance compared to CWFLs (CCT=4100, CRI=62) (Boyce and Rea 1994), this effect is not a unique property of a FSFL. High CRI lamps exist for many fluorescent lamp types. Boyce and Simons (1977) directly compared hue discrimination under various types of lamps in a series of eight experiments. CRI, but not lamp type (CCT), was a good predictor of mean error scores.

Moreover, fluorescent lamps of all colour temperatures with a CRI lower than 69 are prohibited lamps under energy-efficiency legislation in the US (the Energy Policy Act) and in Canada (Energy Efficiency Act) (e.g., Osram-Sylvania 1995), and have not been available for sale in those countries since December 31 1996. The literature is silent on the effects of newer lamp types on colour perception. Both T8 and T5 lamps use a triphosphor coating that produces a very peaky SPD, although the overall perception is of a white light (of a specified CCT). The lamps are designed to produce a high CRI for the given CCT, but this is not the same as a good colour discrimination ability.

4.2 Judgements of People

If one accepts the evolutionary hypothesis, and believes that the daylight simulation of an FSFL is superior to other lamp types, then one would expect that FSFL would give a more flattering, more "natural" appearance to people, and that viewers would prefer such an appearance. However, only one experiment included an FSFL condition to test this hypothesis. Boray, Gifford and Rosenblood (1989) asked groups of psychology undergraduate students to judge the appearance of live models under equal illuminance of either WWFL, CWFL, or FSFL in a windowless room (i.e., between-subjects design). None of the ratings for attractiveness or friendliness of the male and female model differed significantly in relation to the light source.

Other evidence, although not including a specific FSFL condition, points away from the hypothesis that FSFL leads to improved appearance. Judgements using skin colour were the most accurate discriminations between lamp types in a paired-comparison trial (Rea, Robertson, and Petrusic 1990); in this experiment, discriminations improved with practice and were most accurate for the CWFL, which was the least-preferred lamp. The most-preferred lamps had lower CCTs (whereas, FSFLs have a higher CCT than CWFLs). This result is consistent with the United Kingdom Medical Research Council standard for fluorescent lighting in patient areas in hospitals: CCT around 4000 K and a high CRI (MRC [1965], cited in Lovett, Halstead, Hill, Palmer, Sonnex, and Pointer 1991). The initial 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).

4.3 Judgements of Spaces

The evolutionary hypothesis predicts that spaces lit with FSFLs should be judged as more attractive and appealing than when lit with other electric lamp types because of their alleged similarity to daylight and consequent "natural" appearance; furthermore, people should express a preference for rooms lit with FSFLs over other lamp types. Although a few studies report this effect, on closer examination it becomes apparent that colour rendering properties, rather than SPD, are the more likely explanation.

For example, Kolanowski (1990) found that that elderly people preferred FSFLs to WWFLs. The most frequently given reason for the preference was that the FSFL appeared brighter, although illuminance was equated at 300 lx for both conditions. Moreover, ocular transmittance at lower wavelengths (more prominent in FSFLs than WWFLs) declines with age (Rea 1993a), which should lead to the opposite result. However, the specific WWFL used in this study appears to have had a low CRI, comparing it against published tables for that class of lamp (Kaufman and Christensen 1984), whereas the FSFL had a high CRI. Perhaps participants rated the latter as brighter if colours appeared more true.

Participants in Berry's field experiment (1983) reported similar reasons for their preferences for FSFL over CWFL. They cited a variety of reasons, including the belief that the experimental lamps were brighter (in fact, this experiment was confounded by lower illuminance in the FS condition than the CW condition), that they were "easier on the eyes", and improved visual clarity. Here too, the FSFL condition used a lamp with higher CRI than the CWFL condition.

These reports are consistent with a frequently-cited study on the effects of lamp type on "visual clarity" (Aston and Bellchambers 1969), often cited as evidence in favour of daylight-simulating or FSFL lamps. The experiment involved adjusting the illuminance in a model room lit by a "Kolor-rite" lamp (CCT = 4000 K, CRI = 92; Note: this lamp would not meet our definition of an FSFL because of its lower CCT) until the model room appeared equal in overall clarity [defined as "the satisfaction gained by you personally, discounting as far as possible any obvious difference in colour and brightness" (Aston and Bellchambers 1969, p. 260)] to a standard model room lit with either white, WW, or daylight lamps (3900 K), all of which gave poor colour rendition. Each participant completed all comparisons. For all three pairs, the Kolor-Rite lamp was judged to give equal overall clarity of appearance with less light, and the authors concluded that "subjective adequacy is more easily attained with sources having a spectral emission similar to that of daylight" (p. 261). Similar results were obtained in full-scale rooms in a follow-up experiment by Bellchambers and Godby (1972). However, the superiority of the Kolor-Rite lamp might have been caused by its colour rendering capabilities, which were superior to those of the other lamps, and not its correlated colour temperature.

Laboratory evidence is consistent with the CRI explanation. Light sources with higher CRI are preferred over those with lower CRI, but the colour temperature of the lamp was unimportant (Boyce 1977; McNelis, Howley, Dore, and Delaney 1985; Wake, Kikuchi, Takeichi, Kasama, and Kamisasa 1977). Boyce (1977, Experiment 2) replicated Aston and Bellchambers (1969), finding that high-CRI lamps at CCT=6500 K (a FSFL) and CCT=4000 K both gave higher subjective ratings than either white or daylight lamps with lower CRIs, and were judged to give an equally satisfying appearance at a lower illuminance. There was no intrinsic benefit to

the FSFL. These studies used within-subjects designs, meaning that expectancy biases cannot be ruled out; however, reporting and statistical analysis problems also mar these reports.

In some simple comparisons of lamp types, both field studies and laboratory simulations, there is no preference for FSFL over other lamp types. In some cases, there are no differences in ratings of room appearance, size, or preference (Bartholomew 1975 [also described by Kleiber *et al.* 1974]; Boray *et al.* 1989; Boyce and Cuttle 1990; Kuller and Wetterberg 1993). Cockram, Collins, and Langdon (1970) found by field survey that a daylight lamp (4300 K) was preferred for office work both day and night, and the FS source (6500K) was never preferred either by lighting experts or by occupants.

Illuminance, rather than lamp type, also might influence appearance ratings. Baron, Rea, and Daniels (1992, Experiment 1) found differences in the perceptions of a laboratory viewed under one of four lamp types: WWFL, natural-white, CWFL, or FSFL. It appeared that the CW condition was less pleasing overall and that the WW condition was somewhat more favourably rated, but the ratings did not vary systematically with correlated colour temperature. The low illuminance conditions were generally rated as more pleasing, but the high illuminance conditions were rated as brighter and higher in clarity. Boyce and Rea (1994) found that bright polarised FSFL and bright unpolarised CWFL did not differ in room appearance ratings, but both were preferred over dim polarised FSFL (this study used a within-subjects design). Knez (1995; or see Knez 1993, for more detail) found main effects of illuminance on ratings of the appearance of lighting that were consistent in two between-groups experiments comparing 300 lx and 1500 lx CWFL and WWFL (low-CRI lamps in Experiment 1, high-CRI lamps in Experiment 2). Higher illuminance was rated as brighter. There were no lamp type effects on the appearance ratings in either experiment, nor in a partial replication (Knez and Enmarker 1998).⁵

5.0 Cognition

5.1 Performance Effects

The evolutionary hypothesis holds that general cognitive performance should be best under lighting similar to daylight. In this section, research into main effects is considered; below, we consider evidence that lighting effects on task performance are cognitively mediated by other processes.

5.1.1 Performance effects in children. Academic achievement is the typical measure for children's cognitive performance. One problem common to almost all such field studies is the impossibility of controlling for selection and maturation biases because random assignment of students to classes is usually not permitted, and for the possibility of bias from history effects such as differential instruction. The lighting literature is particularly noteworthy for its failure to discuss these issues (Gifford 1994). Nested designs are infrequently used, although they are the appropriate design when the same treatment is applied to an entire classroom unit. In cases in which different lamp types are installed in different schools, differences in socioeconomic status,

⁵ Knez has also found evidence of gender effects in judgments of room lighting, but with inconsistent directions. Women in his studies have rated room lighting as *cooler* with a lower-CCT lamp type (around 3000 K) than a higher (around 4000 K), whereas men rate the 4000 K condition as cooler (the men's rating is consistent with common parlance which would label the 4000 K lamp a cooler light source) (Knez 1995, Knez and Enmarker 1998). Knez and Enmarker (1998) also found the complementary effect for ratings of the warmth of the lighting: women rated 3000K as less warm than 4000K.

school policy, teacher behaviour, and history are particularly difficult to control. Random assignment of classrooms to treatment conditions cannot control for these effects in the studies cited here, which had only one or two classrooms per condition.

The field studies and field experiments generally fail to find systematic effects of FSFL (nor favouring any particular electric lamp type) on academic performance (Ferguson and Munson 1987; Hathaway 1995; Mayron, Ott, Nations and Mayron 1974; Mayron, Mayron, Ott, and Nations 1976; Zamkova and Krivitskaya 1985). In the best of these studies, Ferguson and Munson (1987) controlled for the long-term effects of different instruction by examining measures of attention and memory administered for their study by the teachers in the classrooms, and conducted both within-subjects (crossover) experiments and between-subjects experiments in different classrooms. They did not find evidence that classroom illumination type affected these outcomes.

5.1.2 Performance effects in adults. Both field experiments in university classrooms and laboratory experiments with controlled conditions have been conducted to test the hypothesis that FSFL directly enhances cognitive task performance. This is true of studies using both within-subjects and between-subjects comparisons, suggesting that the null results are not the consequence of participant expectancy biases.

Two field experiments in university classes failed to show effects of lamp type. Student ratings of the quality of the discussion, of the teacher's and students' ideas, and their own interest and learning during the session, and behavioural measures of classroom interaction, did not differ in a seminar room lit with either FSFL or CWFLs (Bartholomew 1975; also reported in brief by Kleiber, *et al.* 1974). In a lecture hall, performance on course examinations and student predictions of their exam performance were unaffected by the lamp type (Blais 1983).

Three laboratory experiments comparing lamp types also failed to find effects on cognitive task performance. Ferguson and Munson (1987) performed a laboratory experiment in which university students performed a computer-based memory task in a windowless room lit with 300 lx of CWFL and FSFL (counterbalanced within-subjects comparison). Performance on a sensitive, commonly used measure of memory did not differ under the two lamp types. Boray *et al.* (1989) examined composite scores from subtests involving grammar and arithmetic problems performed under time pressure under either FSFL, WWFL, or CWFL in a between-subjects design. Lamp type had no effect on performance (Boray *et al.* 1989), nor on a job candidate evaluation task. Similarly, the office simulation experiment reported by Boyce and Rea (1994) found no effects of lighting on ratings of a fictitious job candidate or on performance of a memory and comprehension task.

5.2 Cognitive Mediators

5.2.1 Expectations. One possibility is that anecdotal reports of beneficial effects following the installation of FSFLs are an expectancy effect in which occupants respond as they have been conditioned to do by advertising and promotional material. This type of expectancy is different from the participant expectancy biases discussed above, which emerge in consequence of participants becoming aware of the changing independent variable and forming their own hypotheses as to the behaviour the experimenter wishes them to emit. In this case, the expectancy is a consequence of specific information about the alleged effects of FSFLs on behaviour.

Veitch, Gifford, and Hine (1991) tested this hypothesis, finding no direct effects of lamp type (FSFL vs. CWFL) on reading comprehension nor on a timed grammar and arithmetic task. However, providing information about the expected effects of FSFL did cause improved reading performance and increased self-reported arousal. This was true whether the information set stated that FSFL improves performance and decreases fatigue, or whether it stated that there is no evidence to support claims about FSFL. 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 might increase arousal sufficiently to affect task performance. However, Veitch (1997) conducted a replication study that found neither information sets nor lamp type effects on performance or mood, despite a larger sample size, double-blind experimental control, and a more vivid information set using a video presentation. If the anecdotal reports about beneficial changes following FSFL installation illustrate the action of expectancies created by advertising or promotional material, the process by which this occurs is difficult to create in a laboratory setting.

5.2.2 Affect. Baron (1990) has proposed that environmental conditions that create positive affect will improve cognitive performance and mood, and increase the likelihood of prosocial behaviours. Pleasant fragrances have this effect (Baron 1990; Baron and Thomley 1994). The theory that positive affect has beneficial effects on cognition, memory, and social behaviour has strong support within experimental social psychology (Fredrickson 1998; Isen 1987), and there is no reason in principle why this mechanism should not be triggered by lighting conditions. One might expect that, if the evolutionary hypothesis holds true, that the daylight-simulating properties of FSFLs would be preferred over other lamp types, creating a state of positive affect; or alternatively, the higher CRI of FSFLs might create more pleasing appearance to people and objects, contributing to positive affect. However, attempts to support the theory by varying fluorescent lamp type have produced equivocal results to date. Although some evidence suggests the action of this mechanism, there is little consistency to the findings linking specific lighting conditions and specific affective states.⁶

Two field studies reported small effects said to favour FSFL, but lack sufficient detail for the reader to evaluate their data. Wohlfarth and Gates (1985) exemplifies a poorly-controlled, poorly reported field experiment in schools. This 2 (FSFL or CWFL) x 2 (interior decoration) factorial experiment lacked controls for selection, maturation, and differences in instruction between schools. The authors reported that only the school with both experimental interior decoration and FSFL showed measurable improvement in mood scores between baseline and experimental phases. It is impossible to evaluate this statement because the report provides no descriptive statistics. Erikson and Kuller (1983) reported a field study in an office building. After four and ten months under FSFL or "standard fluorescent ceiling fixtures" (lamp type unknown), 55 participants completed a 36-item mood questionnaire, which was reduced to five scales using factor analysis. [Reliable results from factor analysis require at least ten times as many subjects as there are items (Kerlinger 1986)]. The authors reported that in December, the FSFL improved mood in comparison to the standard, but that it had no differential effect in June when there was exterior daylight available. However, the conference report provided no detailed

⁶ Physiological effects such as light-entrained circadian rhythms, and applied effects such as light therapy for seasonal mood disorders, are discussed by McColl and Veitch (2000). The influence of lighting on affect in healthy individuals is included here because of its relevance to the literature on cognitive task performance.

statistics.

Other research groups have not found lamp type effects on mood in laboratory and field experiments that compared a variety of fluorescent lamp types (Bartholomew 1975; Berry 1983; Boray *et al.* 1989; Kuller and Wetterberg 1993; Veitch *et al.* 1991; Veitch 1997). FSFL did not produce improved mood in any of these experiments, which include both within-subjects and double-blind between-subjects designs and a range of exposure times (e.g., field studies with 14 working days' exposure to each type [Berry 1983]; laboratory studies from 2 hours [Veitch 1997] to one working day in length [Kuller and Wetterberg 1993]). Moreover, wider differences in spectral power distribution (CWFL, metal halide, and HPS lamps, compared within-subjects) did not affect feeling ratings such as "bad-good", "tense-relaxed", "sleepy-alert", "tired-rested", "comfortable-uncomfortable", and "discouraged-satisfied" (Smith and Rea 1979).

Baron *et al.* (1992) varied illuminance and SPD in a laboratory setting to test the specific hypothesis that lighting conditions that produce positive affect would also improve cognitive performance and ratings of others. Although the overall result tended to support the hypothesis in that some findings followed the pattern expected for a manipulation of positive affect, the authors were unable to state conclusively that the pattern (over three experiments reported together) was attributable to the mediating role of positive affect. There were almost no conditions in which lighting conditions had direct effects on positive affect ratings. The authors provided several possibilities for alternative hypotheses, including arousal, familiarity, and setting-specific expectations.

For the present purpose, the most relevant result is that FSFL (a condition in Experiment 1 only) was not associated with positive affect, nor did it produce the best performance or social behavioural results (Baron *et al.* 1992). Experiment 1 used four fluorescent lighting conditions: WWFL, natural-white, CWFL, and FSFL, and two illuminance levels: 150 lx and 1500 lx. (CRI values for the lamps were not reported). There was an interaction of lamp type and illuminance: For all lamps except the CWFL, performance appraisals of a fictitious employee were higher for the low illuminance condition. The performance appraisals were higher in the high illuminance condition for the CWFL, but there was no main effect of lamp type. For a word categorisation 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 WWFLs 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.

The two attempted replications of Baron *et al.* (1992) have not included FSFL conditions, therefore the literature is lacking further direct evidence of the role of FSFLs in creating positive affect. However, these studies are important as tests of the positive affect hypothesis. If lighting-induced affective states do influence cognitive performance, this would provide a useful organising principle and new direction for FSFL investigations.

Knez (1995) reported two experiments in which mood scales were administered before and following laboratory exposure to dim or bright (300 lx or 1500 lx) CWFL or WWFL (between-subjects), during which participants performed cognitive and memory tasks. The design was between-subjects, with control for most potential confounding variables and designed to increase the sensitivity of mood measurements by examining change scores over a longer exposure time. Change scores did not yield significant effects of lamp type or illuminance on mood, nor were there main effects of lamp type, illuminance, or gender on the cognitive tasks.

However, in Experiment 1 (in which the lamps were high-CRI) there was a significant interaction of lamp type x gender on negative affect, in which women's negative affect increased over the 85-min exposure to CWFL, but decreased during exposure to WWFL, regardless of illuminance. For men, WWFL increased negative affect whereas CWFL did not. There was no such effect for Experiment 2 (in which the lamps were low-CRI), but there was an interaction of SPD x illuminance on positive affect, in which positive affect dropped more in bright CWFL than dim CWFL, and more in dim WWFL than in bright WWFL. The suggestion that dim WWFLs and bright CWFLs can reduce positive affect is similar to the observations reported by Baron *et al.* (1992). Various two- and three-way interactions of lamp type, illuminance, and gender were reported for the cognitive tasks, but none of them were the same for both experiments 1 and 2. Knez (1995) interpreted the pattern as being consistent with the notion that affect mediates the behavioural response to lighting, in that the best performance for each gender group appeared to be in the luminous conditions that produced the best affective response (least negative or most positive).

Knez and Enmarker (1998) reported a partial replication and extension of Knez (1995), Experiment 1, using only high illuminance (1500 lx). They expanded one of the outcome measures, to examine the effects of changes in positive affect on performance appraisals of fictitious male and female bank employees, hypothesising that positive affect might create a halo effect that would be reflected in more favourable ratings. The basic design and methodology were the same. In this experiment, there was a trend (it did not reach statistical significance, $p=.06$) towards a gender x SPD interaction effect on positive affect: the warmer lamp type decreased positive mood more for women than the cooler lamp type; positive mood dropped more for men in the cooler lamp type than the warmer. As regards negative affect, there was a statistically significant gender x SPD effect: for women, the warm lamp type increased negative affect more than the cooler one, whereas for men the cooler lamp type increased negative affect more than the warmer one. This pattern of results is opposite to Knez (1995), in which the best affect was observed for women in the warmer lamp type (WWFL) and for men in the cooler (CWFL). There were no effects of lamp type on cognitive performance either directly or in gender interactions; SPD x gender interactions had been observed in Knez (1995), although not consistently in Experiments 1 and 2. The lamp type manipulation did not affect the performance appraisal task results.

Thus, the present status of affect theory as applied to lighting is questionable. If positive affect does mediate lighting effects on behaviour, it is not clear that changes in fluorescent lamp type elicit predictable changes in affective states, nor that these changes in affective states are sufficiently large to influence cognitive performance or judgements. As regards FSFL specifically, the preponderance of evidence does not link it to improvements in positive affect nor to cognitive or social behaviour changes of the type colloquially attributed to it. One possibility is that the similarity between FSFL and daylight is too small to have the hypothesised effects: Daylight varies continuously, seasonally and diurnally, in intensity and chromaticity, whereas an FSFL is a static installation similar to a north view with no direct sunlight. Daylight's predictable variability and its information about the passage of time or weather conditions might influence affect, and thereby other behaviours, but we lack information to test this hypothesis. Another alternative hypothesis remains the possibility that CRI, rather than SPD, is the critical variable (as appears true for perceptual judgements), but no direct tests have been made of this hypothesis either.

6.0 Future Research Directions

In general, the lighting research community has done a poor job of applying basic standards for research design, statistical analysis, and reporting when studying the effects of FSFLs on vision, perception, and cognition. Illuminance and lamp type are frequently confounded in this literature, as are chromatic and luminous modulation and lamp type; sample sizes are often too small to detect small effects or to support multivariate statistical analyses; and, reports often omit important details about the statistics used as well as crucial details about lamps and lighting conditions. Authors in many studies that included small or equivocal results have interpreted their findings as supportive of claims about FSFL, apparently dismissing contrary and null results, and have almost never discussed the practical implications of the effect sizes they observe. The over-reliance on within-subjects experimental designs makes it difficult to rule out participant expectancy biases as explanations for certain results. In this welter of results it is impossible to conclude that FSFLs have powerful effects on these behavioural outcomes; indeed, it is difficult to conclude that fluorescent lamp type itself is an interesting research question (cf. Boyce 1994). Despite these serious limitations on present knowledge, the review has revealed several avenues that deserve researchers' attention.

Spectral effects on visual performance are an open question at this time. Careful, controlled laboratory experiments using special lamp combinations tend to support Berman's (1992) scotopic sensitivity theory. However, experiments and field studies with more naturalistic viewing conditions and white lamps of varying SPD have failed to find comparable effects. In this domain lies much of the best research relating to FSFLs, but the discrepancies between researchers require further research to achieve resolution. Chromatic and luminous flicker remain potential confounding variables in some of this literature, and worthy of more attention.

Theories involving cognitive mediators, such as positive affect theory, offer new directions for lighting research that have yet to be thoroughly explored (Boyce 1998). Although it does not appear that lamp type is a potent influence on affect -- nor that FSFL is intrinsically beneficial to affect -- illuminance effects might be more important. For example, intermittent exposure to high illuminance (2500 lx vs. 500 lx) improved mood in one experiment (Grünberger, Linzmayer, Dietzel, and Saletu 1993). Further advances should be pursued, taking into account the evidence that illuminance preferences are task- and situation-specific (Biner, Butler, Fischer, and Westergren 1989; Butler and Biner 1987), and subject to individual differences (Heerwagen 1990).

One lamp characteristic that might be important is colour rendering. Lamps that permit fine colour discrimination are preferred over other lamp types (e.g., McNelis *et al.* 1985) and might improve the subjective sense that one can see clearly (Aston and Bellchambers 1969; Bellchambers and Godby 1972). These findings suggest that high-CRI lamps might induce positive affect, with favourable consequences for cognitive and social behaviours. No direct test of this hypothesis yet exists in the literature, comparing high- and low-CRI lamps of the same CCT (because CRI is determined relative to a standard that differs for different CCT classes, comparisons of CRI for lamps with differing CCT are meaningless). As discussed above, the effects of triphosphor lamps on colour discrimination (as distinct from colour rendering index) are also worthy of further study.

Thus, although the evidence favouring FSFLs is weak, the prospects for interesting and useful lighting research are several. Developments along these lines have implications for future

lighting practice and for the development of new lighting technologies, to ensure that workplaces, schools, and institutions are lit using equipment that enables smooth visual, perceptual, and cognitive functioning.

7.0 Conclusions

Proponents of FSFL advocate this light source because of its purported similarity to daylight, which they claim has evolutionary significance for human well-being. Overall, the evolutionary hypothesis is not supported by the evidence reviewed here. With a few exceptions, the best studies show that there is generally no intrinsic benefit to a full-spectrum fluorescent lamp in comparison to other common electric light sources. The general absence of such evidence is unsurprising given the weakness of this vague notion, resting on questionable assumptions about the specific luminous conditions that might have influenced the development of physiological or psychological processes (for instance, considering the source spectrum rather than reflected from surrounding surfaces), and the very limited similarity between the static luminous characteristics of FSFLs and the highly variable characteristics of daylight. That is, even if it were true that daylight conditions were optimal for human life, the luminous conditions of an FSFL installation are not at all like chromatically varying, luminously varying, daily and seasonally cyclic daylight conditions as seen by reflection from widely varying surroundings.

As a practical matter, ergonomists, along with lighting designers, architects, facilities managers and other lighting specifiers, should end their search for the ideal fluorescent lamp for all circumstances. Lamp type and CRI choices should be made with an eye to their suitability for the task, the building, the local culture, and the lighting system performance, including energy efficiency and aesthetic judgements. Where problems with lighting installations are a source of complaint, examine the installation's conformity with existing codes and standards for lighting (e.g., CIBSE 1994; Rea 1993a; Swedish National Board for Industrial and Technical Development 1994), noting that none specify specific fluorescent lamp types or CCT values as universal lighting solutions. Although these consensus-based documents are known to be imperfect, they represent the best current wisdom of experts (Boyce 1996). These sources, not dramatic claims about simple solutions, are more likely to lead to the best application for fitting environments for people.

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Figure 2. Spectral power distribution curves for generic FSFL (top) and CWFL (bottom) lamps. © Illuminating Engineering Society of North America 1993. Used by permission.