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ABSTRACT

The quality of indoor lighting can influence task performance, social interaction and communication, health and safety, visual comfort, student behavior, and aesthetic judgments. These by-products of lighting are examined in this literature review in an effort to define the conditions that are associated with good lighting quality. Lighting quality has been debated among lighting professionals for two decades but with little advancement due to a lack of reliable empirical evidence. Since economic considerations have driven much lighting research, most investigations have focused on lighting for offices. This literature review focuses on office lighting applications, although lighting in other settings, such as schools, is also considered. The review begins with research on the luminous environment, including its influence on social interaction and communication (i.e., findings reveal that higher luminance induced female students to communicate more). Other studies found that both male and female university students rated higher illuminance more favorably than low illuminance, yet such illuminance had no effect on self-reported stress, well-being, or fatigue. Other areas investigated include daylight, luminance distribution and illuminance uniformity across rooms, preference judgments, discomfort, and visual display terminals. Contains approximately 175 references. (RJM)

Determinants of Lighting Quality II: Research and Recommendations

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Abstract

Lighting practitioners and laypeople alike believe that the quality of the luminous environment can influence task performance, comfort, and well-being. There is mounting concern that the quality of the lit environment will decline in parallel to lighting energy use as energy codes and standards come into effect; however, there is no consensus about what constitutes good lighting quality. Broad agreement exists that illuminance, luminance, luminance distribution, uniformity, glare control, flicker rate, and spectral power distribution are the important dimensions of the luminous environment. This literature review relates these variables to behavioural outcomes such as visual comfort, task performance, preferences, and well-being. Comparison of these studies to the recommended practices for lighting design in offices reveals little agreement. Psychologists and other behaviour scientists, although not generally accustomed to participating in the writing of codes and standards, have an important role to play the development of these regulations, in ensuring that the best possible knowledge base is applied to the establishment of working and living conditions to support people.

Determinants of Lighting Quality II: Research and Recommendations

Surveys of office employees consistently report that lighting is among the more important features of office design and furnishings (e.g., "Office lighting", 1980; Spreckelmeyer, 1993). Likewise, in the professional community of lighting designers and illuminating engineers, there is a long history of speculation that the quality of the luminous environment can influence task performance, comfort, and well-being (e.g., Miller, 1994; Wagner, 1985).

Electric lighting consumes up to half of the electricity consumed in commercial buildings (Eley, Tolen, Benya, Rubinstein, & Verderber, 1993), but this percentage will decline as energy codes come into effect (e.g., American Society of Heating, Refrigeration, and Air-Conditioning Engineers [ASHRAE], 1989; Canadian Codes Centre, 1995). These codes regulate energy consumption in new buildings and also influence current practice in renovations and retrofits. Before the 1970s energy crisis and the introduction of computers into workplaces (which require less ambient illumination than paperwork), lighting power densities of 30 W/m^2 (2.8 W/ft^2) were typical in North America. Today, values of 17 W/m^2 (1.6 W/ft^2) are usual, and lower levels are easily attained with commonly-available equipment.

The first strategy used to reduce lighting energy consumption in th early 1970s was delamping. In this practice, one fluorescent lamp was removed from a 2-lamp fixture; in some cases, alternate luminaires in a row were disabled. This reduced overall light levels (illuminance) and produced uneven distributions of light (luminance distribution). Energy was saved, but lighting quality declined. Lighting designers of the day decried this simplistic approach to conservation (e.g., Benya & Webster, 1977; Chase, 1977; Florence, 1976), and concern about the quality of the lit environment in the context of energy conservation persists today.

Despite ongoing discussion throughout the 1980s ("Illumination Roundtable III", 1984), defining and debating lighting quality remains a contentious issue among the lighting community. Panel discussions, workshops, and seminars occur at nearly every major conference. The fear that lighting quality will decline in parallel to lighting energy use is difficult to address because there is no consensus about what constitutes good lighting quality. Some believe that no agreement on this issue is possible (e.g., Erhardt, 1994). One survey found only moderate consensus among lighting practitioners about the quality of computer-simulated lighting designs; differences between cultural groups were also observed (Veitch & Newsham, 1996a).

There is, however, broad agreement about the important dimensions of the luminous environment. These are illuminance, luminance, luminance distribution, uniformity, flicker rate, and spectral power distribution (cf., CIBSE, 1994; NUTEK, 1994; Rea, 1993). Lighting system characteristics such as individual control, indirect versus direct lighting, and the use of daylight are also thought to contribute to good-quality lighting. Table 1 summarises three recommended practice documents for office lighting, one each from the United Kingdom, Sweden, and North America. These recommendations are based on consensus among committee members, and are notorious for their weak link to published research (Boyce, 1987).

In a companion paper (Veitch & Newsham, 1996b), we argue that existing attempts to model or to predict lighting quality from luminous conditions have failed because of poor science: lighting research has tended to use abstract tasks for visibility measurements, a narrow range of behavioural outcomes, and inadequate specification of the population to which the data apply. We propose a behaviourally-based definition of lighting quality, in which lighting quality is defined as the degree to which the luminous environment supports the following requirements of the people who will use the space:

- visual performance;
- post-visual performance (task performance and behavioural effects other than vision);
- social interaction and communication;
- mood state (happiness, alertness, satisfaction, preference);
- health and safety;
- aesthetic judgements (assessments of the appearance of the space or the lighting).

In this paper, we review the empirical evidence that relates these outcomes to the important dimensions in the luminous environment listed above, in an attempt to define the conditions that are associated with good lighting quality. Economic considerations have driven much lighting research, with the result that the vast majority of investigations have considered lighting for offices, with relatively few investigations occurring in other settings. Accordingly, this review focuses on office lighting applications, although studies from other settings are included where their results are relevant.

Research on the Luminous Environment

Luminance

Luminance is the quantity of luminous energy propagated in a given direction by a point on a surface. Colloquially, this is what is generally meant when we speak of 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, 1993). The visual system adapts to changes in the ambient luminance by changes in pupil size and the responsivity of retinal photoreceptors. For example, pupil size decreases sharply upon going outside at high noon on a sunny day.

The long history of lighting research is dominated by investigations of the relationship between luminance and visual performance (e.g., Blackwell, 1959; Boyce, 1973; Rea & Ouellette, 1991), with the result that we understand well how light levels affect visibility. It is well established that visibility relates to four variables: luminance, task/background contrast, task size, and the age of the observer. Colombo, Kirschbaum, and Raitelli (1987) suggested that a fifth variable, blur, be added to the visual performance model.

Visibility measured using reaction times to a visual stimulus (Perry, Campbell, & Rothwell, 1987; Rea, Boyce, & Ouellette, 1987; Rea & Ouellette, 1988) and the time required to perform a number-checking task (Rea & Ouellette, 1991) have contributed to this understanding. Visibility is poor when the task luminance is low, but above a certain level of stimulation it quickly saturates. Perry et al. (1987) suggested that this change relates to a shift from rod to cone-based processing of retinal stimulation.

The relationship between contrast and visibility is similarly asymptotic. For a given adaptation luminance there is a contrast value above which visibility is almost invariant; the drop-off below this value is sharp (Rea & Ouellette, 1991).[1] The shape of this "plateau and escarpment" depends also on the size of the object being viewed, with smaller objects being most difficult to see and most adversely affected by reductions in luminance or contrast.

As age clouds the lens, retinal illuminance declines; thus, the effective adaptation luminance is lower for older adults than younger ones. For this reason, older adults generally will require better contrast, higher task luminance, or larger objects to obtain the same visibility level as a younger person. This decrement in vision is noticeable around age 40 (Guth & McNelis, 1969).

Luminous conditions that influence visibility may also affect other important variables. Rea, Ouellette, and Kennedy (1985) found that participants tended to modify their posture to maintain visual performance under luminous conditions that otherwise would reduce task visibility. This has important implications for offices and other workplaces and is worthy of more detailed examination. Awkward or slouching postures can lead to orthopaedic or other health problems that are painful and debilitating, and which are expensive for employers and society in terms of absenteeism, lost productivity, and health care costs.

Illuminance

Illuminance is the technical term for the quantity of visible radiation incident on a surface; colloquially, we speak of "light levels". As discussed above, visual performance increases sharply at the low extreme of light levels, but quickly reaches asymptote; thus, as Boyce (1995) said, "To put it bluntly, what this means is that for many visual tasks, lighting is unimportant to visual performance" (p. 6). There is a broad range of acceptable light levels that provide adequate quantity of illumination, but quantity and quality are separate issues (Guth, 1970; Stein, Reynolds, & McGuinness, 1986).

Task performance. Despite the failure of the Hawthorne experiments to observe systematic effects of illuminance on performance of electrical assembly tasks (Roethlisberger & Dickson, 1939;

[1] One study found that extremely high task contrast reduced visual performance on one task, which the authors suggested might be attributable to a dazzle effect for a spatially patterned task printed in intense black on white (Stone, Clarke, & Slater, 1980).

Snow, 1927), the belief that more light leads to better work has persisted throughout this century. Illuminance recommendations rose steadily until the 1980s, mostly probably because of this belief (Pansky, 1985). The research evidence for illuminance effects on task performance, however, is mixed.

Hughes and McNelis (1978) (see also Barnaby, 1980, for another report of this study) reported that an increase in illuminance from 500 to 1500 lux caused an average 9 per cent increase in the productivity of clerical office workers doing a difficult paper-based task. If such an improvement in work performance were reliable, the economic benefit to employers would justify the increased cost of the higher illuminance level. However, Baron, Rea, and Daniels (1992) found that lower illuminance levels (150 lx) tended to improve performance on a complex word categorisation task as compared to high levels (1500). Nelson, Hopkins, and Nilsson (1983) found a puzzling effect in which performance on a tracking task (which requires hand-eye coordination) was best under 80 lux, worst under 160 lux, and intermediate under 320 lux; there were no illuminance effects on reading or spatial relations tasks.

The literature includes more instances of null results than clear-cut effects of illuminance on task performance, over a wide range of illuminance levels and for a variety of complex and simple tasks. Smith and Rea (1982) found no effect of illuminance levels on reading comprehension over a wide range (9.2 to 4540 lx). Nelson, Nilsson, and Johnson (1984) found no effect of illuminance levels of 100 and 300 lx on creative writing performance. Horst, Silverman, Kershner, Mahaffey, and Parris (1988) found no effect of illuminance levels over 100 lx (up to 800 lx) on reading and scanning tasks typical of nuclear power plant control rooms. Kaye (1988) compared task performance under 500 and 1200 lx and found no effects on proofreading or visual search tasks. Reading performance was unaffected by illuminance levels of 200-600 lx in an office simulation study (Veitch, 1990).

Meta-analytic techniques are a recent statistical development that allow the results of several independent research studies to be quantitatively and systematically combined to reach a general conclusion about a specific hypothesis. Gifford, Hine, and Veitch (in press, 1996) applied this technique to the literature on illuminance effects on office task performance. The meta-analysis was limited by the quality of the published reports on this topic: many investigations that were candidates could not be included because they included too few statistical details to allow effect sizes to be calculated. Overall, Gifford et al. found that contrasts between low (average 70 lx) and medium (average 486) illuminance levels did not produce significant effects on task performance; however, contrasts between low and high illuminance (average 1962 lx) produced a (statistically significant) average correlation of .25 between illuminance and task performance. Closer analysis revealed that this relationship may be moderated by the adaptation time. Studies that allowed more than 15 minutes to adapt to the new lighting level showed a smaller relationship between illuminance and task performance. Thus, it is likely that any relationship between these variables is transitory. People adapt to new luminous conditions, and can perform well regardless of the illuminance level.

Social interaction, communication, and arousal. One notion about the effect of illuminance is that higher light levels lead to louder conversation and more communication. Sanders, Gustanski, and Lawton (1974) observed this effect in naturally-occurring groups in a university corridor (over the range 10-270 lx). Groups of female university students conversing about fictional job candidates were louder, however, under low illuminance (400 lx) than high illuminance (1274 lx) (Veitch & Kaye, 1988). Veitch and Kaye speculated that the reason for the difference in results lies in different expectations for the settings involved. This hypothesis is consisted with Gifford's (1988) finding that intimate communication was greater with a home-like decor than a classroom decor.

Gifford (1988) studied the quantity of general and intimate written communication in relation to illuminance and decor. He reported trends in which both types of communication were increased under higher illuminance (60 and 900 lx), and concluded that arousal theory can account for the outcome. The theory is that higher illuminance levels induce greater arousal and, in this case, more communication. Biner (1991) demonstrated that 1650 lx illuminance increases general arousal in comparison to 30 lx; but Kaye (1988) found that lower illuminance was associated with increased self-reported arousal (500 vs 1200 lx).

Evidence suggests that the lighting-arousal relationship is complex, and depends on other environmental and situational conditions. Kallman and Isaac (1977) found that noise and illuminance interacted, such that in quiet conditions (40 dB(A) ambient noise), 270 lx increased arousal relative to 10 lx; in noisy conditions (70 dB(A) white noise), there was no effect of light on arousal. Delay and

Richardson (1981) found that increasing illuminance (0.33 to 170 lx) decreased arousal for women in a linear fashion, but showed a quadratic function for men in which the greatest arousal was for the highest illuminance level.

The lack of clarity in this area may be attributed to the weakness of arousal theory. 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, as was the case in the studies cited here. Greater clarity about lighting-arousal effects would result if researchers tied their investigations to properly grounded theory.

Preference and mood effects. Many illuminance studies have included mood or satisfaction ratings in order to determine which lighting conditions are preferred. Creating conditions that people prefer, that satisfy them, or that make people comfortable, is one goal of lighting design. Implicit in this goal, at least for workplaces, is the assumption that these conditions are conducive to work.

Limited evidence exists regarding this notion. Baron et al. (1992) tested the hypothesis that lighting conditions that produce positive affect will influence cognitive task performance and social behaviours. The results did not clearly demonstrate that the lighting conditions (combinations of illuminance and lamp spectral power distribution) caused positive affect, but the pattern of results over the three experiments was consistent with other research concerning the effects of positive affect on behaviour. In contrast to other investigations (discussed below), lower illuminances were generally associated with positive affect. Further research is needed to demonstrate clearly that positive affect mediates lighting-behaviour relationships, and to identify the luminous conditions that create positive affect.

Preferences for illuminance levels are generally higher than the recommended levels. Despite known cultural differences in illuminance preference (Belcher, 1985), this is true regardless of culture. For example, Leslie and Hartleb (1990) found that American university students chose an average illuminance of 1557 lx for a reading task, which is 1000 lx higher than the recommended level for such a task and age group (Rea, 1993). Similarly, 1500 lx was rated most highly for clerical office work at a time when the American standard was 1000 lx (Barnaby, 1980/Hughes & McNelis, 1978).

Begemann, Aarts, and Tenner (1994) (see Aarts, 1994, for a detailed report) found that Dutch office workers added an average of 800 lx of artificial light, regardless of daylight or weather conditions; the Dutch illuminance standard for offices is 500 lx. British office workers were more satisfied with a horizontal illuminance of 800 lx than with the then-standard 400 lx (Saunders, 1969). Boyce (1973) also reported that higher illuminances were preferred by all participants in a British sample, regardless of their age, over the range 160-1600 lx task illuminance. One exception to this pattern is a pilot study involving French office workers, in which illuminance preferences were consistent with recommended practice (Berrutto, Avouac-Bastie, Fontoynont, & Belcher, 1994).

A variety of mood checklists have been employed to assess affective response to illuminance conditions. The one consistent finding is that higher illuminances are preferred over lower ones. Nelson et al. (1983) found that their highest illuminance level, 320 lx, was lower than their male participants preferred for office work; there were no effects of illuminance on other mood or satisfaction measures. In a separate experiment, Nelson at al. (1984) found that increasing illuminance from 100 to 300 lx decreased men's scores on three mood measures (concentration, activation, and good mood), but increased women's scores on these measures. Higher illuminance (1200 lx) was rated more favourably than lower illuminance (500 lx) by both male and female university students, but had no effect on self-reported stress, well-being, or fatigue (Kaye, 1988).

A few studies provide exceptions to the finding that higher illuminances are preferred. Kimmel and Blasdel (1973) found that student ratings of library lighting installations showed a preference of 425 lx, which was lower than they expected. Horst et al. (1988) found that ratings of the ease of working, desire to work under the lighting condition, and comfort, increased from 10 to 200 lx illuminance, and then remained stable. Increasing illuminance for these control room tasks from 200 up to 800 lx did not alter these subjective ratings.

There is considerable individual variability in illuminance preferences. Tregenza, Romaya, Dawe, Heap and Tuck (1974) observed that individuals consistently chose the same desktop illuminance levels, but the variance over all participants was high. Heerwagen (1990) found that people with Seasonal Affective Disorder or the milder, subsyndromal form of this mood disorder, consistently preferred higher room illuminance levels than matched, normal controls. Begemann, Beld, and Tenner (1996) reported that two male participants whose illuminance preferences were observed over a year showed a consistent difference in the preferred level, one preferring a very low level and one a high level. The reason for this difference is unknown.

Leslie and Hartleb (1990) found a trend that suggests possible sex differences in illuminance preference (the few female participants preferred much lower levels than the male participants). However, Butler and Biner (1987) found sex differences in preferred light level only for two (of 43) behaviours: washing dishes and leaving a parking garage. Knez (1995) conducted two experiments in which illuminance and lamp type were varied, and mood and task performance measured for both male and female participants. In one experiment, females rated the lighting as more intense and glaring than males, regardless of the actual conditions; however, this finding did not replicate.

The literature is equivocal concerning age differences in illuminance preference. Boyce (1973) did not find that age influenced illuminance preferences. Older clerical workers, however, did show stronger preferences for higher illuminance than younger ones (Barnaby, 1980/Hughes & McNelis, 1978). Age-related increases in illuminance preference would be consistent with known age-related decrements in vision, but it may be that the overall preference for higher illuminance masks this effect.

Task type influences illuminance preference. Lower illuminance levels are preferred for offices where VDTs are used, than are preferred for paper-based, horizontal tasks (e.g., Shahnavaz, 1982). Visually demanding tasks (e.g., reading, studying) have higher preferred light levels than tasks that are intimate or relaxing (talking with a friend, listening to music) (Butler & Biner, 1987). Biner, Butler, Fischer and Westergren (1989) found that lighting level preferences vary with the social situation as well as the task demands, particularly for tasks with relatively few visual demands.

Biological and health effects. The role of light in the regulation of circadian rhythms is well known (e.g., Hill, 1992). Light exposure suppresses melatonin secretion; melatonin induces sleep. In healthy subjects, exposure to monochromatic (509 nm) light overnight suppresses melatonin secretion in a dose-dependent manner (Brainard et al., 1988). This knowledge has led to the demonstration that bright light exposure can facilitate shift workers' adjustment (Czeisler, Johnson, Duffy, Brown, Ronda, & Kronauer, 1990).

The use of interior illumination for biological effect remains somewhat controversial. Bernecker et al. (1994) exposed healthy subjects to 200, 1600, or 3200 lux using a luminous ceiling from midnight to 1:30 a.m., and found that the bright light exposure did suppress melatonin secretion in comparison to the 200 lux control condition. However, the trend to increased suppression with increased light intensity was not statistically significant (possibly because of a small sample size). Dollins, Lynch, Wurtman, Deng, and Lieberman (1993) varied the illuminance in workstations at which male subjects worked overnight on computer tasks, and obtained the expected dose-dependent suppression of melatonin secretion, but it was not accompanied by changes in any behaviour or mood measure. Night nurses who were exposed to short doses of bright light at work (the nature of the work precluded continuous exposure) showed some signs of better adjustment to the schedule, but there was no sign of the expected physiological changes, so circadian phase shifting could not provide an explanation of the results (Costa, Ghirlanda, Minors, & Waterhouse, 1993).

The application of these findings to day-shift workers is still less clear. Begemann, Beld and Tenner (1995) have speculated that the changes they observed in illuminance preferences over the course of the working day relate to differences in alertness. That is, that individuals prefer higher illuminances at the time of day when the circadian cycle dips, so that illuminance maintains an acceptable alertness level.

Some writers advocate the availability of higher illuminance as critical to the maintenance of good health (e.g., Begemann et al., 1996; Brainard & Bernecker, 1995). It is true that in the Western world, daily light exposure is low (e.g., Espiritu et al., 1994; Koller, Kundi, Stidl, Zidek, & Haider, 1993). Espiritu et al. (1994) suggested that inadequate light exposure is associated with depressed mood, although they were unable to demonstrate a clear causal link. It is possible that such a mechanism could account for the illuminance preferences discussed above, but the evidence is not yet strong enough to support increased illuminance standards. The energy costs of such a change would be considerable; moreover, the levels that have biological effect are high enough that there is a risk of increasing the incidence of glare problems, unless care is taken with design (Bernecker et al., 1994).

Luminance and Illuminance Uniformity across Tasks

Two photometric quantities are relevant to the description of the uniformity of local (task) luminous conditions: minimum-to-maximum illuminance ratio across the work surface (desk), and the ratio of task to surround luminance. As with all photometric measures, they are interrelated. If the illuminance ratio is very low (very nonuniform lighting), then the task:surround luminance ratio will also differ from 1:1 (except under very unusual circumstances of task and surround reflectances). However, task:surround luminance ratio depends on the reflectances of both the desk and task, as well as on the illuminance. Luminance uniformity and illuminance uniformity will be discussed together because they are not independent quantities.

Visual and task performance. The conventional wisdom has been that uniformity of illumination is optimal. Saunders (1969) found that illuminance ratios lower than 0.7 caused a substantial increase in dissatisfaction, although the drop in satisfaction from 1.0 to 0.7 was small. Luminance ratios of 1:1 are considered optimal in North America, with 3:1 (i.e., task brighter than surround) being acceptable (Rea, 1993). These values are nominally based on research results (Guth, 1970).

However, closer examination of the literature suggests that these limits are flexible. Early pilot data for a horizontal visual performance task (Landolt rings), with a very small sample size, showed no short-term effect of luminance ratios on visual performance (Biesele, 1950), and very small differences in long-term visual performance over the luminance ratio range 10:1 to 1:1. The relationship was not symmetrical around 1:1. When the surround was brighter than the task, visual performance dropped more rapidly.

Rea, Ouellette, and Tiller (1990) varied task:surround luminance ratios by varying the reflectance of the surround while keeping the task reflectance constant, for a variety of background luminance and task contrast conditions, using a horizontal paper-based numerical verification task. They found that the task:surround luminance ratio had a very small effect on visual performance, and no effect on ratings of the readability of the task. As expected, background luminance and task contrast both affected visual performance and readability ratings.

The advent of computers in offices changed the primary task from the horizontal to the vertical plane and raised new research questions about acceptable luminance ratios between the computer screen and paper documents. Early visual display terminal (VDT) screens were dark, with luminous characters. Kokoschka and Haubner (1985) examined the speed of data entry for a wide range of task:screen luminance ratios and found no effect up to 20:1. The data suggested that more extreme ratios might reduce performance.

Illuminance uniformity across the desk has less effect on task performance than previously believed. Slater and Boyce (1990) varied the minimum:maximum ratio between 0.2 and 0.8, but found no effect on a variety of paper-based clerical tasks. They noted that this was not unexpected, because calculation based on the Rea and Ouellette (1991) relative visual performance model showed that all the illuminance conditions were sufficient to see the tasks.

Preference, comfort, and acceptability. Desktop illuminance uniformity became a more important issue with the change from general lighting schemes to combinations of ambient and task lighting. The acceptability of such systems was of great interest. Boyce's (1979) evaluation of various types of then-current task lighting suggested that the acceptable installations would provide a uniform distribution over a large area of the desk surface. This was consistent with then-current knowledge (e.g., Saunders, 1969).

However, more recent data suggests that illuminance uniformity across the desk is not an inflexible requirement. The participants in the Slater and Boyce (1990) experiment also rated the evenness of the lighting, its acceptability, and its comfort. Based on these results they concluded that for tasks that are primarily in the centre of the desk, illuminance ratios as low as 0.5 would be acceptable for most people. Bernecker, Davis, Webster, and Webster (1993) obtained ratings of visual comfort for a variety of task lighting conditions. They obtained the same rankings of their five luminous conditions with several measures of visual comfort, but this ranking was not related to the illuminance uniformity across the desk surface. Rather, the luminous conditions of all the work surfaces, vertical and horizontal, were important. Bright surfaces without excessive glare were most highly rated.

Luminance Distribution and Illuminance Uniformity across Rooms

Lighting designers may consider luminance distribution, the pattern of light and dark across vertical and horizontal surfaces, to be synonymous with lighting quality. "Hide the source, light the walls; don't cause glare problems" is how one well-known designer summarised his views on lighting quality for offices at a seminar on office lighting (M. Kohn, May 3, 1996, Ottawa, Canada).

All lighting creates a pattern of light and dark across space, which our visual system detects and interprets. If the pattern allows occupants to see what they want and creates the desired atmosphere, then one might say that it is of good quality. The challenge for researchers, however, is to develop means of describing the pattern in measurable quantities and to relate those quantities to important outcomes for people. As yet, we are unable to do so in any precise way.

Task performance. The use of luminance distribution to influence task performance rests largely on the speculation that by making the task brighter than the room around it, one can cause attention to focus on the task. Hopkinson and Longmore (1959) reported that attention on a vertical visual task was best when the task was locally lit, than when it was lit from general illumination alone. A small, high-brightness light source below the task attracted more short off-task glances, whereas a larger, low-brightness source appeared to be less distracting. The effect, which they called "human phototropism" may also extend to movement; there is limited evidence that people will turn and move in the direction of bright light, whether it be to the right or to the left (Taylor & Sucov, 1974).

LaGiusa and Perney (1973, 1974) applied this principle to demonstrate that school pupils' attention to instructional material was improved by spot-lighting the visual aid used by the teacher. This improved the amount of time spent attending to the task (as judged by an independent observer) and performance on a vocabulary task (LaGiusa & Perney, 1973) in a short-term test involving two classrooms. The effect was replicated with a within-subjects design over a year's exposure to the novel lighting set-up (LaGiusa & Perney, 1974).

Studies of adults' task performance are not entirely consistent with the hypothesis that nonuniform lighting improves performance. Adults did complete more arithmetic calculations (on paper) in an office with nonuniform lighting, using incandescent desk lamps, than when the office was lit with uniform fluorescent lighting or very nonuniform coloured ("psychedelic") lighting (Taylor, Sucov, & Shaffer, 1975). However, there are investigations in which no effect was found: Illuminance level differences on the desk, associated with varying the light distribution in an office, did not affect (paper-based) clerical task performance in a comparison of 10 different general and local/general combined lighting installations (McKennan & Parry, 1984). Nor did varying task document brightness for participants typing text into a VDT influence typing performance (Yearout & Konz, 1989). Slater, Perry, and Carter (1993) varied the illuminance ratio across an open office with two desks between 0.29 (very nonuniform) and 0.98 (very uniform), but found no effect on a paper-based clerical coding task.

Aesthetic impressions. The classic work in this area is Flynn's investigations of the appearance of various luminous conditions in conference rooms. Flynn and his colleagues initially obtained ratings on 34 semantic differential scales in response to six lighting configurations (Flynn, Spencer, Martyniuk, & Hendrick, 1973), and separate ratings of the similarity or difference between pairs of lighting configurations. They used factor analysis to reduce the semantic differential scales to three interpretable factors: perceptual clarity, evaluative impressions, and spaciousness. Multidimensional scaling was used to identify three dimensions ("lighting modes") that accounted for the judgements of similarity or difference: uniformity, brightness, and overhead/peripheral. Later, they presented a technique for relating the lighting modes to the factors (Flynn, Hendrick, Spencer, & Martyniuk, 1979).

Although Flynn et al. (1979) clearly intended their work as an interim report, lighting modes and subjective impressions based on this work have been included in subsequent editions of the IESNA Lighting Handbook with little modification (Kaufman & Christensen, 1987; Kaufman & Haynes, 1981; Rea, 1993). For example, relaxation is said to be cued by nonuniformity, particularly nonuniform wall lighting. Perceptual clarity is said to be reinforced by higher horizontal luminances in a central location. Spaciousness is cued by uniform lighting and bright walls.

The research group at the Bartlett School of Architecture at University College London undertook a similar series of experiments beginning concurrently with Flynn's work. In their first paper, Hawkes, Loe and Rowlands (1979) reported that perceptions of 18 lighting configurations for a windowless two-person office could be described along two independent dimensions: brightness and interest (nonuniformity). They were unable to obtain an interpretable result in their multidimensional scaling analysis.

The team extended its work to experiments in which lighting was varied in offices both in laboratory mock-up and in the field, and sought to correlate photometric quantities with assessments of lightness and complexity. Rowlands, Loe, McIntosh and Mansfield (1985) concluded that the difficulty in this work lies in identifying the areas of the visual field that influence the assessments of the space. They had obtained significant correlations, but the direction of the effects differed across settings. Using luminance mapping instrumentation, the team later found that judgements of lightness and interest were described by the luminance contrast and average luminance, respectively, within a horizontal band 40 degrees wide and centred at eye height of a seated viewer (Loe, Mansfield, & Rowlands, 1994).

The Bartlett work suggests that brightness and interest (nonuniformity) are independent constructs, but others seek relationships between them. Perry et al. (1987) speculated than nonuniform luminance distributions might lead to the perception of gloom if they cause an adaptation shift from rod to cone retinal processing. However, two research groups have not obtained results consistent with this speculation. Shepherd, Julian and Purcell (1989, 1992) asked participants in their experiments to rate the appearance of the lit environment using an adjective checklist. The data analysis used non-parametric techniques to identify the adjectives used commonly to describe each lighting scene. Their data indicate that there is a common experience of gloom associated with lighting conditions at low adaptation luminances, particularly when the vertical luminances are low (Shepherd et al., 1989). This finding was replicated and extended to a larger range of luminous conditions (Shepherd et al., 1992). Low surround luminances, mesopic adaptation luminance, high task illuminance with a dim periphery, and conditions that obscure details in the periphery were associated with gloom, but not all nonuniform distributions produced gloom as predicted by Perry et al. (1987).

Luminance distribution effects on brightness perception have been obtained by both brightness matching and self-report techniques (Tiller & Veitch 1995a, 1995b). A small enclosed office with a nonuniform distribution produced by parabolic louvered luminaires was perceived as 5-10% brighter than an identical office with a uniform distribution produced by flat-lensed troffers. The average luminance was the same in both cases, but the variability differed. Reports from the participants about their judgements suggested that it was the contrast between bright and dark portions of the wall that led to the brighter appearance of the nonuniform room.

Satisfaction and preference judgements. Aesthetic judgements concern the appearance of the space; satisfaction and preference judgements include an emotional (affective) component: how the space makes the viewer feel. Satisfaction is the state of feeling that one's needs are fulfilled; by implication, conditions that produce satisfaction or comfort are those that one prefers. For some writers, this judgement defines lighting quality (e.g., Bean & Bell, 1992; Hawkes et al., 1979).

It is clear from many studies that vertical surfaces are key to satisfaction. People prefer brighter walls to dark ones. Collins, Fisher, Gillette, and Marans (1990) concluded that the low ratings given by office occupants to the combination of indirect furniture-mounted fluorescent luminaires with undershelf task lamps was related to the high task illuminance and low peripheral brightness of the workstation. When the same systems furniture was lit with a direct system, vertical luminances were higher and so was satisfaction.

Ooyen, Weijgert, and Begemann (1986; also republished as Ooyen et al., 1987) studied preferences for various luminance distributions at a fixed task illuminance of 750 lx by varying the reflectance of room surfaces. They concluded that wall luminance is the principal contributor to the experience of the room, with wall luminance preferences varying depending on the type of task (reading paper, conference, or VDT work). Wall luminance, of course, largely determines the vertical illuminance at the eye of a person looking at the wall. Thus, the findings of Ooyen et al. (1986) are consistent with those of Iwata, Hatao, Shukuya and Kimura (1994), who reported that both horizontal illuminance and vertical illuminance at the eye predicted visual comfort judgements.

Jointly, the Quality of the Visual Environment (QVE) committee of the Illuminating Engineering Society of North America and the Metrics of Quality (MOQ) committee of the International Association of Lighting Designers have conducted a series of pilot studies on preferences for various luminous conditions. These studies all share a source of bias in that lighting experts acted as participants; nonetheless, their opinions are important, for their consensus results in recommended practice documents. All three pilot experiments thus far have related room surface luminance to judgements of preference, acceptability, and overall lighting quality in offices.

Miller (1994) reported an informal experiment in which conference attendees rated their opinions of five scenes in simulated offices. The most-preferred scene had approximately equal amounts of lighting energy directed at the walls and working plane. The task illuminance of that scene was 387 lx and the ratio of maximum to minimum wall luminance was 3:1 (the range over all scenes was 2:1 to 4.5:1, and illuminance ranged from 108 to 646 lx).

This pilot study paved the way for a more detailed examination of ceiling and wall luminances in relation to acceptability judgements (Miller, McKay, & Boyce, 1995). In that study, for direct/indirect luminaires, higher desktop illuminance was preferred (range 300-700 lx) and ceiling:wall luminance ratios between 1:3 and 3:1 were preferred over the extremes of 1:5 and 5:1. For low-brightness recessed parabolic louvered luminaires, the participants preferred having some light on the walls: ceiling:wall luminance ratios of 1:3 and 1:5 were preferred over 1:1. In a re-analysis of the data combining all lighting systems, they found that the best predictor of acceptability judgements was the average of the wall and ceiling luminance, which they called volumetric brightness. The higher this value, the more acceptable the lighting.

The QVE/MOQ committee followed this with an investigation of the effects of varying lighting systems in a realistic manner in an open-plan office with VDTs. The results did not precisely replicate Miller et al. (1995), but were consistent with it. The average luminance of the partition in front of the seated viewer and of reflected luminaire images in the VDT screen predicted lighting quality judgements (Veitch, Miller, McKay, & Jones, 1996). The brighter the partition and the darker the reflected images, the higher the lighting quality judgement.

The luminance distribution between the task and its background, and horizontal illuminance ratios across a space, have become more important with the advent of task/ambient lighting designs. Rather than a single level of general illumination, the ambient level is lower and task illuminance is raised using a local luminaire or task lamp.

Bean and Hopkins (1980) found that the highest percentage of raters were satisfied with task lighting when the illuminances for the task and background lighting were equal. They recommended that task:background illuminance ratios be close to 1:1. However, McKennan and Parry (1984) found that nonuniform distributions can be acceptable. All the installations, both localised (directed from the ceiling to the desk) and local (task lamps) lighting, were rated as satisfactory, even though some of these systems produced illuminance ratios for desk surfaces and wall:task that were much lower than the recommended practice.

Nonuniform distributions from task/ambient combinations can contribute to the creation of environments that one would describe as comfortable, particularly for VDT work (Inui, Nakamura, & Lee, 1989). The degree of acceptable nonuniformity remains undetermined. The relationship appears to depend on the level of overall illuminance. Slater et al. (1993) found that illuminance ratios as low as 0.6 between desks in an open office were acceptable when room illuminance was high (730 lx), but the lower limit of acceptable illuminance uniformity between desks for lower illuminance (350 lx) was 0.7. This suggests that at low illuminance, people want more uniformity.

This result is consistent with Tabuchi, Matsushima, and Nakamura (1995), who asked for settings of participants' preferred ambient illuminance and the lower limit of acceptable ambient illuminance for a range of task illuminance levels. The preferred levels were much higher than the lower limits. For task illuminances up to 500 lux, participants preferred equal levels of task and ambient illuminance. Above 500 lx, the optimal conditions consisted of ambient illuminance slightly lower than the task illuminance. The participants' lower limits of acceptability, however, showed that conditions with ambient illuminance much lower than the task illuminance can be acceptable.

Judgements that a space appears interesting or pleasant are associated with nonuniform luminance distributions in the field of view. VDT operators preferred having a spot light to highlight a painting on the wall beyond the VDT screen, over the same wall with uniform illumination (Yearout & Konz, 1989). Yorks and Ginthner (1987) found that visitors to a mock office preferred to have a bright wall in front of the desk, and tended to move farther into the room towards the brighter wall. Tregenza et al. (1974) found that preferred wall:desk illuminance ratios were different for the front, rear, left and right walls. Their participants preferred a brighter wall behind the desk.

More systematically, the Bartlett research group found that nonuniform luminance distributions were preferred over more uniform ones. Hawkes et al. (1979) found that 8 configurations with diffuse light sources were all rated as uninteresting; 10 configurations with one or more focused source were on the interesting side of neutral. They speculated that this related to the presence of boundaries that created contours of light and dark, but noted the difficulty of isolating a single physical measure that predicted the subjective judgements. In 1994, Loe et al. determined that ratings of interest and pleasantness were related to the log of the maximum:minimum luminance ratio in a 40-degree band centred at the eye height of a seated viewer. The higher this value, the more interesting and pleasant the space appeared.

To extract the preferred luminance ratios from the literature is a difficult task. Each team has chosen a different set of photometric measurements in the absence of a common protocol for describing the luminous environment. Recalculations have been made to convert some of the published values to common ratios. These are summarised in Table 2. Several reports included illuminance values or illuminance ratios, but these could not be converted to luminances without the associated reflectance values. It is clear from the table that generalisations about preferred luminance values are difficult to make based on current knowledge. Variability and interest appear to be desired[2], but to what degree, and where in the field of view, remain poorly understood.

Glare

Glare is to light as noise is to sound. Just as noise is unwanted acoustic energy, glare is unwanted luminous energy. Lighting professionals distinguish between two types of glare: disability glare and discomfort glare (Rea, 1993). Disability glare describes the effect of scattered light, from luminaires or bright surfaces, when it reduces the contrast between a viewed object and its background. Discomfort glare refers to the experience of physical symptoms associated with viewing bright sources, either in the field of view or by reflection. Thus, one could distinguish these two types of glare in terms of

[2] Temporal variability might also be preferred over static lighting. Aldworth and Bridgers (1971) did not find systematic effects on performance of a clerical task, but did find that ratings of room appearance were better when the lighting varied during the working session than when it was unchanging.

their behavioural effects: Disability glare is a visual performance effect, and discomfort glare is a comfort and health effect. Each is associated with particular glare sources. Systematic attempts have been made to develop predictive models for these behavioural outcomes on the basis of luminous conditions.

Visual performance and veiling luminances. Veiling luminance refers to diffuse light scattered uniformly across a visual field, either directly from a luminaire or indirectly by reflection, that reduces the contrast of the viewed object. This contrast reduction reduces visual performance in a manner that is predictable from visual performance models (e.g., Rea & Ouellette, 1991). Intraocular light scatter is understood to be the mechanism for this effect (Fry, 1954). There have been several attempts to quantify the reduction in visibility based on the luminous conditions created by specific installations (e.g., visibility level [CIE, 1972]), and efforts in this line continue to elicit debate and discussion at lighting conferences (e.g., Pai & Gulati, 1995). Currently, the IESNA handbook recommends a formula based on Fry's work, in which the veiling luminance is calculated from the illuminance from the glare source at the eye and the angle between the primary object and the glare source (Rea, 1993).

Discomfort and light sources in the field of view. Very high luminances in the field of view, or very highly nonuniform luminance distributions, can cause discomfort. Evidence suggests a physiological basis for discomfort glare complaints (Berman, Bullimore, Jacobs, Bailey, & Gandhi, 1994), although the precise mechanism is unknown. Laypeople believe that glare can cause headaches (Veitch & Gifford, 1996).

The dominant model in North America for predicting discomfort glare is the Visual Comfort Probability (VCP) model (Committee on Recommendations for Quantity and Quality of Illumination, 1966). This model uses four lighting parameters to predict discomfort glare ratings, converted to a probability that a population of viewers will consider the sensation acceptable. The factors are luminance of the glare source, luminance of the field of view, solid angle of the glare source at the eye, and the position of the glare source in the field of view. A consensus has formed that a luminaire with a VCP of 70 along a selected line of sight is acceptable (Rea, 1993). Thus, it is considered acceptable to have up to 30% of the population experience discomfort; or more, if the actual viewing conditions differ from the standard line of sight used for the VCP calculation.

The data upon which the VCP model is based were ratings of uniform, flat-lensed, recessed fluorescent troffers. Many contemporary luminaires differ from these, particularly in having nonuniform distributions (e.g. parabolic louvers). This has prompted exploration of the relationship between discomfort ratings and nonuniform light sources. Waters, Mistrick, and Bernecker (1995) found an interactive effect in which discomfort ratings for nonuniform sources (dot-matrix patterns) were greatest when the viewer was fixated on the source, whereas uniform sources were most discomforting in the periphery of the field of view. If this finding holds for ratings of actual lighting installations, it suggests that existing glare models, including VCP, are too conservative in predicting discomfort for nonuniform luminaires because they assume the source is in the periphery of the field of view. (See Veitch & Newsham (1996b), for a further discussion of VCP.)

Psychological variables are not included in the existing discomfort glare models, but evidence suggests that they should be. North (1993) found that individual differences (sex and job class) can predict discomfort glare, in a re-analysis of field survey data reported elsewhere (Collins et al., 1990). Osterhaus and Bailey (1992), in studying discomfort glare for large area glare sources, such as windows, uncovered several effects that warrant further attention. For people working at a VDT screen with a bright light source behind the screen, there was a reliable step in luminance setting when the criteria changed from "too dim" to "preferred" to "too bright" source luminance. Discomfort increased with the increasing source luminance, which is consistent with existing models. Existing models, however, cannot incorporate the high degree of individual variability in preferred luminance levels, nor the finding that the preferred level depended on the initial luminance level for the glare source. Furthermore, when glare was rated immediately following a period of intense work on the VDT task, it was lower than after a period of rest.

Extension of the existing models to incorporate a broader range of light sources, tasks, and participants, might result in improved understanding of the conditions under which a high luminance or nonuniform luminance gives rise to discomfort. At present, models might overestimate discomfort in some conditions, underestimate it in others, and might not apply at all to populations and luminous conditions not included in their development.

VDT screens. Visual display terminals present special problems for lighting design (Haubner & Kokoschka, 1983). Unlike conventional clerical tasks, which are paper tasks on a horizontal surface, the VDT is a self-luminous, vertical task. General, ambient light that would be required for a paper task becomes a veiling luminance on a VDT screen. This might explain the preference for low luminances in VDT offices (Shahnavaz, 1982). Sanders and Bernecker (1990) found that performance of a VDT letter recognition task declined with increasing veiling luminance (veiling luminance range 0-53 cd/m^2), although in a replication with veiling luminances from 0-25 cd/m^2, there was no effect of veiling luminance on a proofreading task (Bernecker, Sanders, & Mistrick, 1994).

Lighter-background VDT screens are clearly superior to dark screens. Accommodative changes following a 6-hour shift were lower in night-shift VDT operators with brighter screens than darker ones (Shahnavaz & Hedman, 1984). In three experiments with letter recognition or proofreading tasks, performance was better when the text to be viewed was dark, and the screen light (Sanders & Bernecker, 1990; Bernecker, Sanders, & Mistrick, 1994, Experiments 1 and 2).

Moreover, VDTs require careful selection and placement of ceiling luminaires to avoid having luminaire images reflected in the screen. Reflected images in VDT screens both reduce visibility and cause discomfort. For example, Hultgren and Knave (1974) found ambient luminances on VDT screens that were higher than the maximum luminance of bright characters on the dark screens, which obliterated the text in that area. This contrast reduction has a predictable effect on visual performance (Rea & Ouellette, 1991).

In some cases, VDT operators appear to compensate for the veiling luminance: Bernecker, Sanders, and Mistrick (1994, Experiment 2), found that adding a reflected luminaire image to a VDT screen had no effect on proofreading task performance. However, they speculated that such effects might be observed with a larger number of reflected images or a longer-duration task.

Comfort and satisfaction also relate to VDT screen conditions. Veitch et al. (1996) found that overall ratings of lighting quality were inversely related to the brightness of reflected images in VDT screens: the brighter the reflected image, the lower the rating of lighting quality. Lighting systems that produced reflected images were rated more poorly than those that did not.

A systematic model of this effect relates disturbance ratings to the luminance modulation of the reflected image, the effect of ambient light on the display, and the degree to which the display blurs reflected images (a function of screen specularity) (Lloyd, Mizukami, & Boyce, 1995). The model predicts greater disturbance when there are brighter reflected images, when ambient light reduces contrast, and when the reflected images are sharp. This model awaits independent validation.

Spectral Power Distribution

Belief that particular spectral power distributions (SPDs) are beneficial is widespread. Members of the general public tend to believe that light that is similar to natural daylight is best for performance and health (Veitch, Hine, & Gifford, 1993; Veitch & Gifford, 1996a). Among lighting practitioners, beliefs such as "use cool colour temperatures in warm climates, and warmer ones in cooler climates" are long-standing. A variety of lamps and filters exist on the market to satisfy these beliefs.

Visual performance. Berman (1992) has found that pupil size depends on the amount of light available to the scotopic visual system of rod receptors, even at light levels typical of interiors. The more light in the spectral regions to which the rods are sensitive (peaking at 508 nm), the smaller the pupil size. The smaller the pupil, the greater the depth of field and the better the visual acuity. According to Berman, the improved acuity more than offsets the decrease in retinal illuminance that accompanies the smaller pupil size.

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. The two SPD conditions were created by using either three red and one pink lamp, or, in the other condition, one green-blue lamp (the "scotopically enriched" lamp). Pupil size was smaller, and visual 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 & Ashford, 1994). 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 (Berman et al., 1994). Moreover, other researchers' results with other tasks and more realistic conditions have failed to find similar results (e.g., Veitch & McColl, 1995).

Task performance, mood, and satisfaction. A comprehensive review of this topic, covering the years 1945-1995, concluded that our knowledge of the effects of full-spectrum fluorescent lighting, in comparison to other lamp types with different SPD, on human behaviour, mood, and well-being is poor (Veitch & McColl, 1996; an earlier version is Veitch & McColl, 1994). They concluded that poor-quality research, rather than a lack of effort, underlies this state. Fluorescent lamp type does not appear to affect general appraisals of the appearance of people or spaces, activity, arousal, or cognitive task performance. Boyce (1994) and Gifford (1994) concur with this assessment. The one consistent finding is that any light source with a high CRI facilitates fine colour judgements, regardless of its colour temperature.

Health. Light can have both direct and indirect effects on human health and physiology. These pathways are poorly understood, but have been exploited to create therapies for specific disorders, such as neonatal hyperbilirubinemia (neonatal jaundice) and seasonal affective disorder (SAD). Although it is possible that specific wavelengths or SPDs are responsible for these effects, it is not clear at this point that particular lamp types or combinations are required (Veitch & McColl, 1996). There is no evidence that points to a particular lamp type or SPD for general lighting use on the basis of its health effects.

Flicker

The light output from discharge lamps oscillates at a rate dependent on the type of ballast used to control the discharge and on the rate of the alternating current. Incandescent lamps also oscillate, but this is offset by thermal inertia, in which the filament retains energy and continues to emit light during the very brief "off" portion of the cycles. Thus, flicker is only an issue for lighting installations that use discharge lamps. Most commonly in office settings, these are fluorescent lamps.

When conventional core-coil magnetic ballasts are used, the flicker rate is twice the rate of the electrical supply (thus, fluorescent lamps flicker at 120 Hz in North America and 100 Hz in Europe). This rate of luminous modulation is within the range that is detectable by the human nervous system, even if the flicker is not resolved perceptually (Berman, Greenhouse, Bailey, Clear, & Raasch, 1991; Brundrett, 1974). Energy-efficient, electronic ballasts operate at very high frequencies, in the range 20-60 kHz.

This rate of modulation is higher than can be detected; therefore, for practical purposes, electronic ballasts eliminate fluorescent lamp flicker.

Visual effects. Although the effects are small, there is a body of evidence that luminous modulation can disrupt the visual process. Rey and Rey (1963) found that working under low-frequency (50 Hz) fluorescent light caused a larger drop in perceptual critical flicker fusion (a measure of visual fatigue), a larger increase in reaction time, and poorer performance on a proofreading task, than working under high-frequency fluorescent light (100 kHz).

West and Boyce (1968) and Wilkins (1986) found that saccadic eye movements are disrupted by low-frequency flicker, but not high-frequency flicker, across a wide range of flicker rates. The highest flicker rate in any of the eight experiments in the West and Boyce (1968) study was 46 Hz. Wilkins (1986) compared CRT screens with 50 Hz and 100 Hz rates, and fluorescent lamps with 100 Hz and 20 kHz rates, but in both cases, the disruption was greater with lower-frequency flicker. This effect might explain the finding that visual performance on a Landolt ring task was poorer for low-frequency flicker (magnetic ballasts) than high-frequency flicker (electronic ballasts) (Veitch & McColl, 1995).

Two unpublished studies have found null effects of flicker on visual performance or other tasks. Start, Dass, and Wilkins (1995) attempted to replicate Veitch and McColl (1995) and found a similar trend, but not a statistically significant effect. Nelson et al. (1983) compared performance on a variety of tasks with AC- or DC-powered fluorescent lighting. The DC-powered condition did not flicker, but the AC condition with magnetic ballasts would have had a the standard 120 Hz flicker rate. There were no interpretable effects of flicker on task performance, mood, or comfort, of adult males working for half a day (the experiment also varied SPD, illuminance, temperature, and humidity).

Health and comfort. Fluorescent lamps have long been associated with complaints of visual discomfort and headache (cf. Stone, 1992). Putative causes of these effects include both flicker rate and spectral power distribution (Wilkins, 1991, 1993). Two studies have found that increasing the operating frequency of the fluorescent lighting system decreases the incidence of eyestrain, headache, and other asthenopic symptoms (Lindner & Kropf, 1993; Wilkins, Nimmo-Smith, Slater, & Bedocs, 1989). Wilkins et al. found that the installation of high-frequency ballasts led to a 50% reduction in the reported incidence of eye-strain and headaches in office workers.

The oscillations in luminous output for fluorescent lamps depend on the phosphors that coat the tube as well as on the ballast. Some of the commonly-used phosphors that emit long-wavelength light continue to do so for some time after the gas discharge, whereas phosphors with greater emission at shorter wavelengths persist for a shorter time. The longer persisting phosphors introduce a phase lag with the result that the light alternates in colour as well as intensity (Wilkins & Clark, 1990). The degree of chromatic flicker depends on the lamp type as well as the ballast type; electronic ballasts reduce chromatic as well as luminous modulation.

There is indirect evidence that chromatic flicker can cause discomfort. Wilkins and Wilkinson (1991) developed a tint for eyeglasses that reduced the effects of the chromatic modulation of fluorescent lamps run on magnetic ballasts. Wilkins and Neary (1991) examined the visual, perceptual, and optometric effects of individualised tinted eyeglasses on people who had a history of reading difficulties and perceptual distortions. The tinted lenses reduced discomfort and perceptual anomalies when viewing grating filters, and they caused a small improvement in the speed of visual search. However, the optimal tint varies for each individual; a general lighting solution to achieve the same end is unlikely.

Although the empirical evidence is not entirely consistent, it appears that high-frequency flicker rates are preferable to low-frequency flicker in terms of visual performance, comfort, and health. This is a fortuitous finding, one of the few instances in which adopting an energy-efficient technology can benefit both the environment and people who use it.

Research on Lighting System Characteristics

Studies of the relationships between luminous conditions and behavioural outcomes are complicated by the fact that the luminous conditions are interrelated. In order to hold adaptation constant while varying luminance distribution, for example, it was necessary to prevent participants from viewing the luminaires or the ceiling (Tiller & Veitch, 1995a, 1995b). The experimental conditions for such experiments often do not resemble lighting systems as installed in buildings. Another approach to lighting research is to study the effects of lighting system characteristics on behavioural outcomes, recognizing that the change one lighting system characteristic is to change several luminous dimensions.

Direct versus Indirect Lighting Systems

The recessed, lensed troffer for fluorescent lamps has become a mass-production standard. It is a cheap, general lighting solution for commercial office space (Gabriel, 1989). However, other lighting solutions such as suspended indirect or direct/indirect systems have come into increasing favour, in response to energy conservation goals, the introduction of VDTs, and the development of a increasingly sophisticated lighting designers (Gabriel, 1993). These systems change the luminous environment in many dimensions simultaneously; therefore, the most meaningful discussion of their effects on lighting quality is as systems, rather than in terms of individual luminous characteristics such as luminance distribution, directionality, or illuminance levels.

Task performance effects. There is intense interest in the relationship between lighting and productivity because the economic case for lighting expenditures is easy to make if a purported lighting improvement leads to more work or fewer errors. For example, Kiernan (1994) reported that changing from direct to indirect lighting dramatically improved productivity in a postal station in Nevada. This study has never been published in a peer-reviewed journal or conference proceedings. Unfortunately, the systematic investigations of lighting system changes do not show such dramatic results.

Hedge, Sims, and Becker (1995) conducted a field study of suspended lensed-indirect and parabolic louvered lighting systems which were installed as part of a renovation in a building that originally was lit with recessed, lensed troffers. They gathered data on satisfaction and health (discussed below) as well as self-reported productivity. The self-reported productivity data showed that office workers whose spaces received the lensed-indirect systems believed that their productivity had increased by 2.5% after the renovation. For the parabolic-louvered group, there was no change in self-reported productivity.

Katzev (1992) compared performance on data entry, data checking, reading comprehension, and typing tasks under four lighting systems in single-occupant enclosed offices with VDTs: energy-efficient parabolic louvered luminaires with one compact fluorescent (CFL) wall washer; direct/indirect luminaires with CFL wall washing; recessed, lensed troffers; and, a recessed parabolic-louvered luminaire. The results were mixed. Reading comprehension was best in the office with the direct/indirect luminaires, but typing performance was worst in that office; there were no other statistically significant effects.

Three laboratory investigations failed to find statistically significant effects of lighting system type on office work performance, either of computer-based or paper-based tasks. Bennett (1986) compared louvered and lensed direct luminaires, and a combination of indirect luminaires with task lighting, and found no effects on VDT number-checking and form completing tasks and on a perceptual reasoning task on paper. Harvey, DiLaura, and Mistrick (1984) found no effect of lighting system (parabolic direct, lensed direct/indirect, or indirect-only) on VDT-based data checking. Similarly, typing performance did not differ for VDT operators under direct or direct + indirect lighting (Yearout & Konz, 1989).

Mood, satisfaction, and preference ratings. Many investigations consistently have found that lighting systems with an indirect component are preferred over direct-only systems. Both Yearout and Konz (1989) and Harvey et al. (1984) found that indirect systems were preferred over parabolic louvered systems for VDT work. Mean ratings on seven semantic differential ratings of the lighting system consistently favoured lensed-indirect over parabolic louvered lighting (Hedge et al., 1995), as did ratings of overall satisfaction with lighting. Ellis and Cave (1982) and Ellis (1986) reported successful case studies in which energy-efficient indirect lighting systems using high-intensity-discharge sources were installed and judged by occupants to be improvements over the previous lighting system.

Katzev (1992) reported somewhat confusing results. Depending on the method of evaluation, either energy-efficient parabolic luminaires or recessed direct-indirect luminaires were the preferred lighting for enclosed offices. The recessed lensed system was always the least preferred of the four (the fourth was a less-energy-efficient parabolic louvered luminaire). Acceptable illuminance settings were also highest for the recessed lensed system; people preferred lower illuminance levels for the other three systems. The encouraging thing about this finding is that people can find energy-efficient lighting not only acceptable, but preferable to conventional, lensed troffers.

The QVE/MOQ joint committee found similar results in their comparison of lighting quality ratings for suspended direct/indirect, furniture-mounted indirect + CFL task, recessed parabolic troffers, and recessed lensed troffers (Veitch et al., 1996). Overall, the two systems with an indirect component were preferred over the direct-only systems. Of the two direct-only systems, the parabolic louvered system was preferred. The furniture-mounted indirect system was preferred over the suspended direct/indirect system, but there was reason to believe that this was an artifact of the particular suspended system, and not typical of all such systems.

One exception to this pattern is Collins et al. (1990), who found that the least-preferred of all systems in their field study was the combination of furniture-mounted indirect lighting and undershelf task lighting. However, closer analysis of these data revealed that this was partly an artifact of the particular installation. It featured very high task illuminance, but low overall room luminance; the extremes of bright and dark in this case may be been too great.

Health. One study has included a measure of health, although this outcome deserves greater attention as a possible index of the effects of lighting on organisational productivity. The participants in the Hedge et al. (1995) field study who received lensed-indirect lighting in the renovation reported fewer and less frequent problems with tired eyes and eye focusing than participants whose lighting was changed to parabolic louvered lighting.

Control

The sophistication and complexity of lighting controls have increased dramatically in recent years. Devices such as daylight-linked dimming systems and occupancy sensors support energy -efficiency initiatives by ensuring that electric lighting is used only when needed. The success of these devices for lighting quality will depend on the extent to which they provide the necessary luminous conditions, as described in the section above.

Another use of lighting controls to provide individual controls to occupants, in contrast to old-style switching in which a single on-off switch controlled the lighting for large open-plan zones. Additional local control over lighting occurs when task lighting is provided. Some lighting designers believe that providing control to individual occupants will have beneficial effects by permitting lighting to be tailored to individual needs and desires (e.g., Simpson, 1990; Wotton, 1989). Aldworth and Bridgers (1971) went further, suggesting that individual controls would allow greater variety in lighting, which would decrease monotony. Empirical evidence to support these beliefs is scant.

Preferences and satisfaction. Field surveys are consistent in reporting that a sizeable percentage of office employees prefer to have some degree of control over their office lighting. Fifty-four per cent reported this in a large North American survey ("Office lighting", 1980), and 67% in one Midwestern U.S. building (Ne'eman, Sweitzer, & Vine, 1984).

Health. Another possible benefit of individual control over lighting could be to reduce or ameliorate the harmful effects of other stressors (Wineman, 1982). Barnes (1981) argued that choices about physical environmental conditions can prevent detrimental effects such as feelings of powerlessness and hopelessness. Becker (1986) considered that providing individual control over workplace conditions is one component of a quality work environment, in which workers feel competent and satisfied, and in which they perform well, with lower absenteeism and turnover. However, Wineman (1982) also noted that individual control can also add to job demands, thereby increasing the number and intensity of stressors that can affect performance and health.

Task performance. Little systematic evidence exists concerning the effects of personal control over lighting. Only one experiment has varied the degree of control available for workplace lighting and examined its effects on task performance. Veitch and Gifford (1996b) reported that participants who had control over the lighting under which they worked performed more poorly and more slowly on a creativity task than participants who had no control. Both having had control and having worked under lighting that one preferred led to the perception of having controlled the workplace lighting. Thus, the perception of control did not influence performance; however, the exercise of control led to a small performance decrement. This is consistent with Wineman's (1982) observation that in some circumstances, control may contribute to unwanted effects by presenting an unwanted choice.

Becker (1991) noted that providing individual control over workplace conditions to employees can be costly, and will be justified only if it provides an economic benefit to the employer or building owner. Advanced lighting controls are, as yet, relatively expensive; choices that lead to productivity losses are doubly costly. Further research will be needed to determine under which conditions, and in what form, individual control over lighting is desirable.

Daylighting and Windows

The lighting energy-efficiency potential of daylighting is obvious; daylight is free light. The overall energy-efficiency of windows depends also on thermal effects (heat loss in winter months, gain in summer) and their balance against the heat production of electric luminaires. Thus, the overall effect of windows and daylighting on building energy-efficiency is a complex calculation that depends on climate, latitude, and building orientation. The effects of windows and daylight on behavioural outcomes are no less complex.

Visual performance. Although no studies have directly measured visibility in relation to daylight presence, the principles discussed above apply to daylight as to any light source. Spaces lit with natural light must provide adequate luminance for visual performance; this will require that electric light be available to supplement natural daylight when necessary. Daylight, like any light source, can act as a glare source, and can cause veiling luminances, reduced contrast, and lower task visibility. The presence of windows also has the potential for causing adaptation problems (and reduced visibility) if the window luminance is significantly higher than the room or task luminance. Therefore, glare control (e.g., window shading, blinds, curtains) is required for successful daylighting.

Task performance. No empirical evidence exists concerning the effects of daylight on task performance. However, laypeople believe that it is conducive to improved work (Veitch et al., 1993; Veitch & Gifford, 1996a). Heerwagen and Heerwagen (1986) reported that this belief was weaker than beliefs in health and psychological comfort associated with daylight.

Daylight is characterised by variability over time. Aldworth and Bridgers (1971) simulated this in a windowless room in a comparison of static versus varying luminance distributions on clerical work performance. They found no effects of variability on task performance.

Health. Heerwagen and Heerwagen (1986) found that office workers strongly endorsed the notion that daylight is better for physical, visual, and psychological health. Veitch et al. (1993) and Veitch and Gifford (1996a) found similar evidence. People who endorsed beliefs about the effects of lighting on health tend to prefer natural daylight over electric light (Veitch et al., 1993).

Biological effects of light require high illuminance. If there is a minimum light dose required for health, as discussed above, then daylight may be the most efficient means to deliver that dose in most settings, except possibly in the winter months in some locales.

Preferences and satisfaction. Although people believe that daylight is beneficial, the importance of having access to windows is variable. Butler and Biner (1989) found that the nature of the setting determined window preference for university students; no windows was the most common preference stated for lecture halls, public washrooms, and computer workrooms, whereas large windows were preferred for family rooms, dormitory bedrooms, and libraries. Field surveys of office workers generally report that people prefer to have a window (Wineman, 1987).

Window preferences are complex, which may account for the contradictions in various recommendations for window size and placement (cf., Wineman, 1987). Office occupants who have access to a window report that having access is less important than people who lack access to a window (Boubekri & Haghighat, 1993; Heerwagen & Heerwagen, 1986); perhaps people who have a window take it for granted. Access to a window is important to provide a view outdoors for temporal information, which appears to be more important than for providing natural daylight (Butler & Biner, 1989). Preferences for window size depend both on the nature of the view (larger windows are preferred for more beautiful views), on the requirement for a minimum acceptable lighting level, and on the size and shape of the room (Butler & Steuerwald, 1991). The achievement of lighting quality in windowed offices will require a balance of these factors against other luminous characteristics of the space, considering daylight as a light source and incorporating its complexity and variable nature.

Conclusions

Table 3 summarises the literature review in a schematic fashion, describing the degree of effort that has been undertaken in the study of lighting effects on behavioural outcomes. Empty cells in the table reveal areas in which there is too little evidence, or none at all, to reach any conclusion. A considerable effort of behavioural research will be necessary in order to identify the best luminous conditions for the broad range of important behavioural outcomes. As yet, only general statements about lighting quality are possible, and there is more disagreement than agreement about many dimensions, within the scientific community and between recommended practice and the scientific literature.

Consider illuminance. Although illuminance recommendations (which are largely based on the visual performance literature) have perhaps the best scientific foundation (Boyce, 1996), biological and health evidence suggests that current illuminance recommendations are too low. Illuminance requirements to support social interaction and communication are unknown, for there is no agreement between the various research reports.

Similarly, uniformity recommendations advocate near-unity luminance or illuminance ratios. The literature suggests that nonuniformity is tolerable across the work surface, provided that the task is lit sufficiently. Nonuniformity across a room appears to be preferable to uniformity because it creates interest and can highlight important information. Predictive models of discomfort from glare might overestimate problems when the light source is nonuniform. Common belief is that spectral power distribution is important to performance, mood, and health; the literature does not support this notion. Lighting control for individuals has been suggested as an improvement over general switching; however, the scientific literature reveals that individual control is not always desirable.

Recommended practice documents make little mention of certain luminous dimensions that appear to be important for some aspects of lighting quality. Only NUTEK (1994) advocates high-frequency ballasts to reduce health complaints associated with low-frequency flicker. Indirect or direct/indirect lighting is consistently preferred over direct-only systems, but not specifically mentioned as a recommended practice.

Criticism of lighting research is long-standing, recognising its weaknesses in scientific procedure and statistical analysis (Boyce, 1981; Gifford, 1994; Kaye, 1992; Tiller, 1990; Veitch & McColl, 1996). Boyce (1981) argued that more, better lighting research was needed because "past practice was excessive and we can't afford the energy for that any more" (p. 413). This remains true today, but its achievement will require more involvement from psychologists and other behavioural scientists than has typically been the case. We argued in a separate paper (Veitch & Newsham, 1996b) that lighting quality is a special case of a general model of the effects of the physical environment on behaviour and well-being, with implications for organisational and group, as well as individual, outcomes. Psychologists are the logical professionals to contribute strongly to the study of lighting quality.

Psychologists and other behavioural scientists have a second important role to play in the development of recommended practice, codes, and standards documents. International standards organisations (e.g., International Organisation for Standardization, ISO) have established procedures for the development of standards and codes: panels made up of experts and interested parties develop a draft document by consensus. The draft is sent for public comment and finally to a vote of the organisation's decision-makers. A similar process has resulted in the recommended practices of the IESNA and CIBSE (which do not as yet have the imprimatur of ISO). Consensus panels for such documents should include professionals familiar with the literature and trained in explaining and translating the empirical conclusions for incorporation into practice documents.

Lighting quality has been debated among lighting professionals for two decades or more, with little advancement. Only if recommended practice for lighting is clearly based on empirical evidence will it be possible to argue successfully that a given lighting installation is not only energy-efficient but of good quality in terms of meeting human needs. Psychologists, who interest themselves in these same behavioural outcomes in other domains, should see another opportunity here to "give psychology away" (cf., Miller, 1969).

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Table 1

Summary of Recommended Practice for Office Lighting

Source	Illuminance (E) (lux) (desk)	E ratio (room) (min: max)	E ratio (desk) (min: max)	Max. Luminance (I) (ceiling) (cd/m^2)	I ratio task: surround	I ratio task: wall	I ratio task: ceiling	I ratio ceiling max/min	Contrast reduction (max)	Other considerations
IESNA	• 300-500 • (200-300 general; 300-450 task)			• preferred: 850 @ 55-deg angle • acceptable: 850 @ 65 deg	3:1	• 10:1 or 1:10 • 40:1 max outside field of view		• pref. 4:1 • accept 10:1		• Reflectances & finishes • Maintenance
CIBSE	•	0.7	0.7	•		•	•	•		• Glare Index < 15
NUTEK	• 300-500			• 500 to 50-deg • 1000 above 50-deg	3:1	• 10:1 • 20:1 outside normal field of view	• 10:1 • 20:1 outside normal field of view		15%	• CRI min 80. • CCT > 2700 and < 4000 • Reflectances & finishes • High-frequency ballasts • EMF field limits • Energy-efficiency • Maintenance

Note. IESNA: Illuminating Engineering Society of North America Lighting Handbook (Rea, 1993). CIBSE: Chartered Institute of Building Services Engineers Code for Interior Lighting (CIBSE, 1994) **Original source on order; entries are from secondary sources**. NUTEK: Swedish National Board for Industrial and Technical Development Lighting design requirements: Office lighting (NUTEK, 1994). E: illuminance. I: luminance. Assumes high-contrast paper-based tasks on desk (Category D in Rea, 1993).

Table 2

Preferred Luminance Ratios and Luminances

Investigation	Luminance (cd/m^2)	Task:wall luminance ratio	Ceiling:wall luminance ratio	Wall maximum: minimum
Tregenza et al. (1974)		2 to 1	1.6 to 1	
Ooyen et al. (1986/1987)		3.3 to 1		
VDT work (wall)	20-45			
Other tasks (wall)	30-60			
Miller (1994)	75			3 to 1
Miller et al. (1995)				
Direct/indirect systems			1:3 through 3:1	
Parabolic direct systems			1:5 and 1:3	
Loe et al. (1994)	5		1:1	161 to 1
Berrutto et al. (1994)				
Free choice	117-179			
Restricted power use	60-109			

Note. For Loe et al. (1994), the values are those of the configuration rated as most interesting, and the luminance value is the average wall luminance in the field of view. For Berrutto et al. the luminance values are mean values for walls on the right or the left of the desk in a room with VDTs.

Table 3

Areas of Knowledge about Luminous Conditions and Behavioural Outcomes

	VISUAL PERFORMANCE	TASK PERFORMANCE ETC. NOT VISION	SOCIAL INTERACTION AND COMMUNICATION	MOOD, PREFERENCES, & SATISFACTION	HEALTH AND SAFETY	AESTHETIC JUDGEMENTS
LUMINANCE						
ILLUMINANCE						
ILLUM. / LUMIN. UNIFORMITY (TASK)						
ILLUM. / LUMIN. UNIFORMITY (ROOM)						
GLARE						
COLOUR						
FLICKER						
LIGHTING SYSTEMS						
CONTROL						
DAYLIGHTING & WINDOWS						

Note. Independent variables are rows. Dependent variables are columns. Shaded areas indicate that a body of scientific knowledge exists relating the independent and dependent variables at that row and column intersection. The darker the shading, the better the understanding of that topic. Scholarly debate continues in all areas.

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