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Lighting Quality Contributions from Biopsychological Processes

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Abstract

Internal processes, both biological and psychological, are thought to mediate the relationships between luminous conditions and such behavioral outcomes as task performance, mood, social behavior, aesthetic judgements and satisfaction. This review paper summarizes the state of knowledge concerning mediating biopsychological processes: visibility, photobiology, and stress and arousal. Visibility is well-understood and obviously relevant to lighting practice. Photobiology, however, is a new entrant to the realm of lighting research; its findings could have important implications for recommended illuminance levels if these were based on more than visibility. Stress and arousal, interrelated concepts, are popular notions, but close examination reveals only weak support for these mechanisms as explanations of lighting effects on behavior. The improved organization of research and increased predictive power that would result from clear exposition of theoretical mechanisms in lighting research holds promise for progress in linking research and application.

Introduction

Renewed interest in lighting quality emerged in the early 1990s, in parallel with the development of energy codes and standards. Lighting practitioners remembered the energy conservation strategies of the 1970s energy crisis, in which delamping reduced overall light levels and produced uneven distributions of light. Energy was saved, but lighting quality declined. Lighting designers of the day decried this simplistic approach to conservation and feared that similar strategies would occur again.¹⁻³ Committees were struck by the major associations, and many conference sessions on lighting quality were convened.

The definition of lighting quality most widely adopted in these discussions has been an emergent one, in which lighting quality is the degree of excellence achieved, in terms of meeting human needs⁴ and integration of these outcomes with energy conservation and architecture.⁵ Veitch and Newsham presented a behaviorally-based model for the relationships between luminous conditions and human needs served by lighting (Figure 1).⁴ This review used this model as a basis for an examination of the body of knowledge about these relationships.

The procedure in conducting this review was, first, to identify empirical research relating luminous conditions to behavioral outcomes. The behavioral outcomes fell into the six categories described by Veitch and Newsham: seeing; task performance; communication and social interaction; mood; health and safety; and, aesthetic judgments⁴. The luminous conditions are those generally agreed as useful descriptors of the lit environment: luminance/illuminance; uniformity across tasks; luminance distributions within rooms; glare; spectral power distribution; flicker; indirect lighting systems; and, windows and daylighting.⁶⁻⁸ Each paper was analyzed to determine the relevant mediating processes (if none were specified), and the literature relating to each process was then synthesized to reach an overall conclusion concerning that process. This review paper concerns one subset of individual processes that mediate these relationships, the biopsychological processes (psychological processes have been considered elsewhere⁹). It summarizes the empirical literature relating to each process and relates the state of knowledge to current recommended practice documents, concluding with suggestions for new research directions and dilemmas that remain to be solved.

Other researchers have labeled some of these processes "indirect effects of lighting", in opposition to vision, which they would categorize as a direct effect.¹⁰ This model makes no such distinction. All behavioral outcomes, including perception, are the result of cognitive processing, and may therefore be considered indirect in the sense that if there is no mental processing, the luminous energy has no effect on behavior. Lighting for visibility is a minimum criterion for lighting quality, and visibility is central to the processes by which good-quality lighting will be achieved. Where this discussion of lighting quality differs from others is in explicitly considering other outcomes to be as important as making objects visible.

As has been noted elsewhere, the scholarly quality of lighting research is generally poor,^{4,11-15} but an extensive critique of each study is beyond the scope of a journal article. Instead the conclusions here are limited to those that may be reasonably drawn from each study.

Within the discussion of each process, the review is structured using the luminous conditions to group similar studies. Not all luminous conditions have been equally studied with respect to each process. The absence of one or more conditions under a process means only that no literature concerning it was identified, and is not a theoretical statement about the luminous conditions that trigger each process. In addition, relatively little detail concerning spectral power distribution is presented here because this topic has been reported extensively elsewhere.¹⁵ The heavy emphasis on office lighting applications reflects the focus (and the economic imperative) in most of the literature. In keeping with this focus, the review is limited to suprathreshold viewing at adaptation levels typical of interiors.

Biopsychological processes in lighting-behavior relationships

Visibility

This process requires the least introduction. Interested readers are directed to the physiology literature for detailed presentations on visual processing.^{16,17}

Luminance and illuminance— The long history of lighting research is dominated by sound systematic investigations of the relationship between luminance and visual performance, with the result that we understand well how light levels affect visibility.¹⁸⁻²⁰ 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 suggested that a fifth variable, blur, be added to the visual performance model.²¹

Visibility measured using reaction times to a visual stimulus²²⁻²⁴ and the time required to perform a number-checking task²⁰ 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. suggested that this change relates to a shift from rod- to cone-based processing of retinal stimulation.²²

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.²⁰ *^a 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 40.²⁶

The asymptotic relationship between visual performance and luminance means that, as Boyce said, “To put it bluntly...for many visual tasks, lighting is unimportant to visual performance.”^{27,p.44} There is a broad range of acceptable light levels (illuminances) that provide adequate quantity of illumination to see.

Ambient and task lighting systems are most commonly thought of as the principal sources of adaptation, but VDT screens are also potent influences. Empirical results show predictable relationships between luminance and visual performance, for 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.²⁸ In several experiments with letter recognition, typing, or proofreading tasks, performance was better when the text to be viewed was dark, and the screen light.²⁹⁻³¹

Uniformity across tasks— The conventional wisdom has been that uniformity of illumination is optimal. Saunders 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.³² Luminance ratios of 1:1 are considered optimal in North America, with 3:1 (i.e., task brighter than surround) being acceptable.⁷ These values are nominally based on research results combining optimal visual performance and comfort,³³ although other reviewers have noted that “the research on performance and preference effects has not resulted in a comprehensive set of luminance ratio specifications to guide...better practice.”^{34,p.45}

Closer examination of the scientific 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, and very small differences in long-term visual performance over the luminance ratio range 10:1 to 1:1.³⁵ 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 rigorously studied the question.³⁴ They 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.

Similarly, illuminance uniformity across the desk has little effect on task performance. Slater and Boyce varied the minimum:maximum ratio between 0.2 and 0.8, but found no effect on a variety of paper-based clerical tasks.³⁶ They noted that this was not unexpected, because calculation based on the Rea and Ouellette relative visual performance model²⁰ showed that all the illuminance conditions were sufficient to see the tasks.

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 examined the speed of data entry for a wide range of task:screen luminance ratios and found no effect up to 20:1.³⁷ The data suggested that more extreme ratios might reduce performance. Technological advances since then have led to the development and widespread adoption of higher-resolution, color VDTs and the use of bright backgrounds with dark text, making this problem trivial.

Glare— Unwanted luminous energy can decrease visibility in two ways. Disability glare, directly from a light source or reflected from a surface, disrupts vision because of intraocular light scatter.³⁸ This also reduces the task contrast internally, at the retinal level. Currently, the IESNA handbook recommends a formula based on Fry’s work, in which the retinal 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.⁷ Conditions that increase the degree of intraocular scatter, such as cataract, worsen the effects of disability glare sources.

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. The degree of contrast

^a 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.²⁵

determines the visual performance, regardless of the source of the contrast reduction (e.g., task specularity, lighting geometry)³⁹ Thus, the effects of veiling luminances are predictable from visual performance models, provided the extent of the contrast reduction is known.²⁰

Visual display terminals present special glare control challenges.⁴⁰ 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.⁴¹ Sanders and Bernecker found that performance of a VDT letter recognition task declined with increasing veiling luminance (veiling luminance range 0-53 cd/m²),²⁹ although in a replication with veiling luminances from 0-25 cd/m², there was no effect of veiling luminance on a proofreading task.³⁰

Recognizable reflected images of luminaires are particularly troublesome glare sources in VDT workplaces. Hultgren and Knave 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.⁴² In some cases, VDT operators appear to compensate for the veiling luminance from reflected luminaire images: Bernecker et al. found that adding a reflected luminaire image to a VDT screen had no effect on proofreading task performance.³⁰ However, they speculated that such effects might be observed with a larger number of reflected images or a longer-duration task.

The superiority of light-background, dark-text VDT displays can be explained as a luminance effect (as above) or also as a function of contrast.²⁹⁻³¹ Higher screen luminances reduce the degree of contrast reduction caused by veiling luminances. Whatever the mechanism, the higher-resolution screens and use of light backgrounds that are common today may reduce the incidence of problems reported when computer technology first gained widespread use.

Spectral power distribution— Berman 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.⁴³ 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 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.⁴⁴ 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.⁴⁵ 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.⁴⁵ Moreover, other researchers have failed to find similar results.⁴⁶⁻⁴⁸

Flicker— Although the effects are small, there is a body of evidence that luminous modulation can disrupt the visual process. Luminous modulation at rates as high as 147 Hz influences neural firing, even when not perceived as flickering light.^{49,50} Rey and Rey 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).⁵¹

West and Boyce⁵² and Wilkins⁵³ 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 study was 46 Hz. Wilkins compared CRT screens with 50 Hz and 100 Hz rates, and fluorescent lamps with 100 Hz and 20 kHz rates, but in all 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).⁴⁸ Similarly, Veitch and Newsham found that office workers working under electronically-ballasted luminaires attempted more questions on a paper-based reading test, wrote more on a computer-based creative writing task, performed more accurately and faster on a computer-based reaction time task, and experienced a smaller decline in visual performance over the working day, in comparison to those who worked under magnetically-ballasted luminaires (all these effects were statistically significant).³¹

The one study that failed to find that low-frequency flicker is detrimental to task performance did not measure performance on demanding visual tasks.⁵⁴ They compared performance on a variety of tasks and subjective measures, under AC- or DC-powered fluorescent lighting (other variables in this experiment were SPD,

ambient temperature, and humidity).^b Flicker rate did not influence performance on a difficult spatial relations task, a psychomotor tracking task (neither of which requires fine visual discrimination), or a reading comprehension test (measured as the percentage of correctly-answered questions about a text). Veitch and Newsham also found no flicker effect on reading comprehension.³¹ This suggests that the effect of flicker is limited to visual processing only, and does not influence other cognitive processes.

Indirect lighting systems— Few investigations have tested for visibility changes in relation to the directionality of lighting systems, although most indirect lighting systems are designed to reduce the possibility of veiling reflections and disability glare that can, in some installations, be unavoidable using direct lighting systems. The only findings related to visibility are tangential: Participants who received lensed-indirect lighting in a lighting renovation reported fewer and less frequent problems with tired eyes and eye focusing than participants whose lighting was changed to parabolic louvered lighting.⁵⁶ In a comparison of nine lighting systems including three with an indirect component, there were no interpretable performance differences for individuals under indirect or direct/indirect systems in comparison to direct-only systems (parabolic louvered or prismatic lensed luminaires).³¹

Windows and daylighting— 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.

Other interactions— Luminous conditions that influence visibility may also affect health-related outcomes. Rea, Ouellette, and Kennedy found that participants tended to modify their posture to maintain visual performance under luminous conditions that otherwise would reduce task visibility.⁵⁷ This has important implications for offices and other workplaces and is worthy of more detailed examination. Awkward or slouching postures can lead to orthopedic 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. Empirical evidence on this point, obtained from strong multidisciplinary research, could prove important to making the economic case for carefully-designed lighting systems.

Visibility: summary— Visibility is the best-understood mediating process for lighting-behavior relationships. Visual performance varies with background luminance, the size and contrast of the target, and the age of the viewer. However, over the large range of adaptation luminances typical of most applications, visual performance is invariant. Similarly, people can tolerate nonuniformity between task and surround luminances, and across desk surfaces. Predictable decrements in visual performance occur as a result of contrast reduction from veiling luminances, reflected luminaire images and intraocular light scatter from direct glare sources. Among light source characteristics, low-frequency (120Hz or lower) flicker appears to adversely affect visual performance. The practical effect of spectral power distribution on visual performance at suprathreshold levels is arguable.

Photobiology

The photobiology literature is itself large because of the interest in the study of phototherapy for various disorders, particularly Seasonal Affective Disorder.^{58,59} The discussion here is limited to lighting for general interiors, with healthy people.

Illuminance and luminance— The role of light in the regulation of circadian rhythms is well known.⁶⁰ 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.⁶¹ This knowledge has led to the demonstration that bright light exposure, correctly timed, can facilitate shift workers' adjustment.^{62,63}

The use of interior illumination for biological effect remains somewhat controversial. Bernecker et al. 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.⁶⁴ However, the trend to increased suppression with increased light intensity was not statistically significant (possibly because of a small sample size). Dollins et al. 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 behavior or mood measure.⁶⁵ 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 than those without bright light exposure.⁶⁶ However, there was no sign of the expected

^b Thermal comfort results from this investigation were reported by Nelson, Nilsson, & Hopkins.⁵⁵

physiological changes, so circadian phase shifting could not provide an explanation of the results.

The application of these findings to day-shift workers is still less clear. Begemann, Beld and Tenner have speculated that the changes they observed in illuminance preferences over the course of the working day relate to differences in alertness.⁶⁷ 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. However, there has been no test of this hypothesis to date. An adequate test of this hypothesis would require a multidisciplinary team of psychobiologists and lighting researchers, taking into account the issues discussed below concerning arousal theory.

Some writers advocate the availability of higher illuminance as critical to the maintenance of good health.^{68,69} It is true that in the Western world, total daily light exposure (from all sources) is low.^{70,71} Espiritu et al. 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 reports that illuminance preferences are higher than standards recommend,^{67,68} 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.⁶⁴

Spectral power distribution— Direct effects of light on health and physiology arise from light absorption through the skin; indirect effects are mediated by neural activity. 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.¹⁵ There is no evidence that points to a particular lamp type or SPD for general lighting use on the basis of its health effects.

Windows and daylighting— Beliefs in the desirability of daylight and windows are widely held. Heerwagen and Heerwagen found that office workers strongly endorsed the notion that daylight is better for physical, visual, and psychological health.⁷² Others have found similar beliefs.^{73,74} Moreover, people who endorse beliefs about the effects of lighting on health tend to prefer natural daylight over electric light.⁷³

Collins concluded that although people prefer windows, only limited evidence was available to demonstrate adverse effects of windowlessness.⁷⁵ These effects may be associated with the dynamic, changing nature of light and view afforded by windows, and appear to depend on the function of the space, its size, and the duration of time spent there.

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 at high latitudes.

Photobiology: summary— Photobiologists have established that bright light exposure suppresses melatonin secretion and entrains circadian rhythm. This knowledge has led to the development of lighting systems for shift workers, but applications to general lighting are less clear. Some researchers argue that the low daily light dose experienced by most people in developed countries contributes to malaise and unhappiness. Evidence to support this notion is preliminary, and the necessary daily dose is unknown.

Arousal and Stress

Arousal and stress are interconnected, powerful constructs in psychological science. Arousal is a general state of mental and physical activation.⁷⁶ Arousal theory holds that there is an inverted-U function between arousal levels and behaviors, with an optimal arousal level for each behavior. For task performance, the curve is believed to shift up for simple tasks (that is, the optimal arousal level is higher if the task is easier). Some researchers hold that arousal is one component of mood, with pleasure and dominance (the degree to which one feels in control of the situation);⁷⁷ other mood effects are discussed below.

Stress is the name for a set of physiological and hormonal changes that arise in response to threatening or unpleasant events, called stressors. Stressors can include environmental conditions such as direct glare, or loud noise; life events, such as bereavement; or emotional states, such as conflict. Chronic exposure to stressors can lead to unpleasant health effects, such as high blood pressure. Stress is linked to arousal because the response to such events can include a heightened state of neurological activation. Thus, in lighting, the goal is to create luminous conditions that would lead to optimal arousal, while avoiding conditions that might act as stressors.

Luminance and illuminance— Arousal theory applied to lighting holds that higher illuminance (more accurately, higher adaptation luminance) levels induce greater arousal. To the extent that the arousal level is appropriate for the task involved, this should result in improved performance. However, if the arousal level is too great, performance would be expected to decline. Two demonstrations are needed to support this theory: first, that higher illuminance increases arousal; and second, that the increased arousal leads to predictable changes in task performance following the inverted-U function.

Evidence is weak for illuminance level effects on generalized arousal. Biner demonstrated that 1743 lx (165 fc) illuminance increases general arousal in comparison to 32 lx (3 fc),⁷⁸ but Kaye found that lower illuminance was associated with increased self-reported arousal (500 vs 1200 lx).⁷⁹ Other evidence suggests that the lighting-arousal relationship is complex, and depends on other environmental and situational conditions. Kallman and Isaac 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 (inferred from reaction time performance).⁸⁰ Delay and Richardson found that increasing illuminance (0.33 to 170 lx) decreased arousal (measured as time estimation) for women in a linear fashion, but showed a quadratic function for men in which the greatest arousal was for the highest illuminance level.⁸¹ The use of different measures of arousal in each study adds to the interpretive difficulty of this pattern of results.

The Hawthorne experiments failed to observe systematic effects of illuminance on performance of electrical assembly tasks,^{82,83} but the belief that more light leads to better work persisted throughout the 20th century and was reflected in North America by increasing illuminance recommendations until the 1980s.⁸⁴ The research evidence for illuminance effects on task performance, however, is mixed. Part of the problem is that many variables influence performance of any task, so that very sensitive experimental designs are required to detect an effect of lighting beyond simple visual performance effects.

If arousal is the intervening mechanism, then one would expect the illuminance-performance relationship to follow the inverted-U function, and that lower illuminances would be favored for more complex tasks. The literature does not support this prediction, although between-study comparisons are difficult to make because the luminous conditions were expressed as illuminances, rather than luminances, and the reflectances are unknown.

Of the studies that report illuminance-performance relationships, the results are mixed, as are the performance measures themselves. Nelson, Hopkins, and Nilsson found a puzzling U-shaped 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.⁵⁴ Hughes and McNelis 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.^{85c} However, Baron, Rea, and Daniels found that lower illuminance levels (150 lx) tended to improve performance on a complex word categorization task as compared to high levels (1500 lx).⁸⁷ Gifford compared intimate and general written communication at approximately 60 and 900 lx.⁸⁸ He reported that more communication of both kinds occurred at the higher illuminance level and concluded that this supported the arousal model; however, the outcomes do not pass the usual statistical criterion of a $p < .05$ for the multivariate test nor for the univariate test for general communication.

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 found no effect of illuminance levels on reading comprehension over a wide range (9.2 to 4540 lx).⁸⁹ Nelson, Nilsson, and Johnson found no effect of illuminance levels of 100 and 300 lx on creative writing performance.⁹⁰ Horst et al. 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.⁹¹ Kaye compared task performance under 500 and 1200 lx and found no effects on proofreading or visual search tasks.⁷⁹ Reading performance was unaffected by illuminance levels of 200-600 lx in an office simulation study.⁹²

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 applied this technique to the literature on illuminance effects on office task performance.⁹³ 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 (only 11 studies were found that provided all necessary information).

Overall, Gifford et al. found that contrasts between low (average 70 lx) and medium (average 486 lx) 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.⁹³ 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 over a broad range of illuminance levels.

Another notion about the arousal effects of illuminance is that higher light levels lead to louder conversation and more communication. The number of empirical tests of this notion is small, and each has

^c This investigation was also written up and published by Barnaby.⁸⁶

methodological weaknesses. Sanders, Gustanski, and Lawton observed this effect in naturally-occurring groups in a university corridor (over the range 10-270 lx).⁹⁴ This range of illuminances is small; moreover, it was created by delamping some luminaires, creating a luminance gradient of hot and cold spots along the corridor.

One experiment found the reverse effect. Groups of female university students conversing about fictional job candidates were louder under low illuminance (400 lx) than high illuminance (1274 lx);⁹⁵ in this case, the low illuminance was a very unusual condition for the classroom-like setting. Veitch and Kaye speculated that the reason for the difference in results between their study and Sanders et al. lies in different expectations for the settings involved. This hypothesis is consistent with Gifford's finding that intimate written communication was greater with a home-like decor than a classroom decor.⁸⁸

Overall, the lack of clarity in the results of lighting research based on arousal theory may be attributed to the weakness of the generalized arousal theory. Although arousal is popularly used as an explanatory, intervening variable, it is not a unidimensional construct.⁹⁶ Psychophysicists 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 or behavioral indices,^{97,98} as was the case in the studies cited here. Inferences about arousal require that simultaneous observations of all the elements in the system occur as predicted. Moreover, arousal research in general suffers from a logical flaw in that the optimal arousal levels for a given task are defined post hoc as whatever level led to the best performance of that task. This prevents a test of the hypothesis that the achieved arousal level is equal to the optimal arousal level.

Glare— Laypeople believe that glare can cause headaches.⁷⁴ Very high luminances in the field of view, or very highly nonuniform luminance distributions, can cause discomfort. Veiling luminances can also be unacceptable even if the degree of contrast reduction does not reduce visual performance.⁹⁹ Evidence suggests a physiological basis for discomfort glare complaints.¹⁰⁰ Although the precise mechanism is unknown, this suggests that glare sources can constitute stressors.

It appears that no research team has explicitly considered stress models for understanding the effects of glare on people. Most research effort has been expended on efforts to predict discomfort ratings from luminous conditions. Although other models are debated internationally,¹⁰¹ the dominant model in North America for predicting discomfort glare is the Visual Comfort Probability (VCP) model,¹⁰² which was critiqued elsewhere.⁴

Psychological variables are not included in the existing discomfort glare models, but evidence suggests that they should be. North found that individual differences (sex and job class) can predict discomfort glare,¹⁰³ in a re-analysis of field survey data reported elsewhere.¹⁰⁴ Osterhaus and Bailey, in studying discomfort glare for large area glare sources, such as windows, uncovered several effects that warrant further attention.¹⁰⁵ 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 the degree of glare was rated immediately following a period of intense work on the VDT task, it was lower than after a period of rest.

Flicker— Fluorescent lamps have long been associated with complaints of visual discomfort and headache.¹⁰⁶ Putative causes of these effects, which some consider stress-related, include both flicker rate and spectral power distribution.^{107,108} Two studies have found that increasing the operating frequency of the fluorescent lighting system decreases the incidence of eyestrain, headache, and other asthenopic symptoms.^{109,110} In particular, 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 as well as 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 color as well as intensity.¹¹¹ 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, but a powerful, direct test of the hypothesis has yet to be made. Wilkins and Wilkinson developed a tint for eyeglasses that reduced the effects of the chromatic modulation of fluorescent lamps run on magnetic ballasts.¹¹² Wilkins and Neary examined the visual, perceptual, and optometric effects of individualized tinted eyeglasses on people who had a history of reading difficulties and perceptual distortions.¹¹³ 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.

Arousal and stress: summary— Despite the popularity of arousal as an explanatory mechanism for lighting effects on behavior, the literature provides only weak support. Increasing illuminance might increase generalized arousal, or it might not. Moreover, task performance does not show the inverted-U relationship to illuminance that one would expect if arousal were the mediating mechanism. Certain luminous conditions can, however, act as stressors. These unpleasant conditions cause reactions associated with neurological responses. Chief among these conditions is glare, whether from a direct source or a reflected luminaire. Low-frequency flicker can also serve as a stressor.

Conclusions

Lighting quality judgments, as they relate to biopsychological processes, show varying degrees of confidence. We know much about visibility, particularly as it relates to quantity of illumination and contrast, and can confidently state whether or not a given set of luminous conditions are likely to produce adequate visual performance. Photobiological processes are in an early stage of understanding. For some applications, such as shift work, we can use this knowledge to select luminous conditions to produce desired results, but the consequences for general lighting practice are unclear as yet. Arousal, despite its long history in lighting and in psychology research, has advanced us little because it is in general defined imprecisely and poorly measured. In general, we are far from being able to predict the best-quality luminous conditions, based on our understanding of these biopsychological processes.

These three processes all relate to the quest for recommended practice guidelines. Present-day recommendations, formed principally from visual performance criteria, vary somewhat from one jurisdiction to another (Table 1). These recommendations are based on consensus among committee members, and are notorious for their weak link to published research.¹¹⁴ Some of these documents emphasise lighting for well-being, incorporating restrictions on, for example, electromagnetic fields; others do not as yet recognise these issues.

The need for increased research effort is evident from the suggestion, based on available evidence, that current lighting practice results in inadequate illuminance levels for health and well being.^{68,69} If our criteria for lighting changed from the current emphasis on visual performance to photobiological criteria, illuminance levels would have to rise in order to achieve biological effect. Similarly, if carefully designed experiments successfully demonstrated that higher illuminance can increase arousal sufficiently to beneficially affect complex task performance, there would be pressure to increase illuminance levels in some settings accordingly.

At present, this potential conflict is quiet, while data are gathered. Resolution of this potential problem would be speeded by specific tests of the hypothesis that high illuminances are necessary for good health; these should be the focus of multidisciplinary teams including biologists, psychologists, and lighting specialists. Specific tests of arousal theory will require careful attention to the *a priori* theoretical predictions based on systemic action, and to the development of measurement tools. Integration of these findings with recommended practice should proceed slowly and cautiously, applying high standards of scientific practice and thorough analysis of the risks and benefits of proposed changes.

The lighting community might fear that this research effort will have dire consequences for energy efficiency and for overall lighting quality. However, it is not necessarily so. Electronic ballasts, with their high operating frequency, appear to have better consequences for visual performance, task performance, and health than do magnetic ballasts; they also use less energy than magnetic ballasts. Energy-efficiency can be good for us. Similarly, renewed attention to lighting design issues such as glare reduction and daylighting control would be required to achieve luminous conditions based on a balance of theories. Visibility theory, for example, predicts reduced visual performance when veiling reflections decrease task contrast. These reflections are more likely for lighting designs giving higher illuminance, as would be required for biological effect. Controlling unwanted light (whether its source is daylight or electric light) while increasing illuminance to achieve biological goals will require the skills of the lighting specialist -- and all the more so to balance these requirements with other human needs and with architectural and budgetary considerations.

The renewed attention to lighting quality issues in recent years holds great promise for all in the lighting community. Researchers benefit from new alliances with related disciplines and new attention paid to the understanding they generate. Lighting designers receive new incentive, recognizing the potential implications of their work for the occupants of spaces they light. New markets for lighting open, where new products are needed to conserve energy while delivering high-quality light. The prospects for lighting quality, based on collaborative, cooperative effort by all interested parties, have perhaps never been brighter.

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Table 1***Summary of Recommended Practice for VDT 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	<ul style="list-style-type: none"> • 300-500 • (200-300 general; 300-450 task) 			<ul style="list-style-type: none"> • preferred: 850 @ 55-deg angle • acceptable: 850 @ 65 deg 	3:1	<ul style="list-style-type: none"> • 10:1 or 1:10 • 40:1 max outside field of view 		<ul style="list-style-type: none"> • pref. 4:1 • accept 10:1 		<ul style="list-style-type: none"> • Reflectances & finishes • Glare control (VCP) • Maintenance
CIBSE	<ul style="list-style-type: none"> • 300-500 	<ul style="list-style-type: none"> • 0.5-0.8 	<ul style="list-style-type: none"> • 0.8 • core area: max:min, 5:1 	<ul style="list-style-type: none"> • never > 200 above limiting angle (55, 65, or 75-deg) 	3:1	<ul style="list-style-type: none"> • 10:1 	<ul style="list-style-type: none"> • (ceiling:task E ratio 0.3-0.9) 			<ul style="list-style-type: none"> • Glare Index < 15
NUTEK	<ul style="list-style-type: none"> • 300-500 			<ul style="list-style-type: none"> • 500 to 50-deg 	3:1	<ul style="list-style-type: none"> • 10:1 • 20:1 outside normal field of view 	<ul style="list-style-type: none"> • 10:1 • 20:1 outside normal field of view 		15%	<ul style="list-style-type: none"> • CRI min 80. • CCT > 2700 and < 4000 • Reflectances & finishes • High-frequency ballasts • EMF field limits • Energy-efficiency • Maintenance

Note. IESNA: *American National Standard Practice for Office Lighting*¹¹⁵. CIBSE: Chartered Institution of Building Services Engineers *Lighting for Offices*¹¹⁶. NUTEK: Swedish National Board for Industrial and Technical Development *Lighting design requirements: Office lighting*.⁸ E: illuminance. I: luminance. Assumes high-contrast paper-based tasks on desk (Category D in Ref. 7).

Figure Captions

Figure 1. Conceptual model showing relationships between lighting conditions, individual processes, and individual outcomes.