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Indoor Pollution: Lighting, Energy, and Health

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Architecture and architectural research will be concerned with the relationship of environment and health in the next few years as a result of a growing awareness of indoor pollution. Since the end of World War II, buildings have increasingly been constructed and filled with synthetic materials, ventilated by mechanical means, and illuminated by electric light, primarily fluorescent. Since the Arab oil embargo of 1973-1974 marked the recognition of the energy crisis, substantial changes in building design and operation have aggravated a number of indoor pollution problems. While air pollution indoors has received the most attention, the problems of light, noise, chemical, and other forms of pollution have also been recognized by building occupants, designers, and researchers. This chapter examines the problem of light pollution to illustrate the interrelationships of health and the built environment.

We begin with a conceptualization of health and illness and their relationship to the broader environment. Classically, health has been considered the absence of illness. The preoccupation and concern has been with treating the ill or finding illness at an early stage to stop its progression and allow for maintenance of a healthy life. It is becoming increasingly clear that health is intimately related to an individual's normal growth and development, and as the individual grows the environment impinges upon that person both beneficially and harmfully. It both nurtures and causes stress and crisis with which the individual must cope.

Historically, concern with the broader environment emphasized the natural environment's hostility and the necessity of protection from its effects. Hence, we have the construction of buildings, the donning of clothes, the preservation of food, and the myriad other things called "civilization" in order to allow for optimal human development and activity. The natural environment ultimately has been replaced by the built environment as the most significant context in which human life takes place.

From the moment of conception, when life begins, throughout the entire growth period, the developing fetus is subjected to the external environment through noise, chemicals, food, and a host of other things that are only now beginning to be documented. Indeed, it can be said that the environment impinges upon the developmental cycle prior to conception as the DNA gets modified by environmental assaults on the genetic material forming the base of the egg-sperm relationship and the subsequent development of the fetus. From the moment of birth, which more often than not is now taking place in hospitals, the human environment is a "built" one and increasingly comprised of materials that impinge upon the total birth process. Lights, machines, noise, colors, air, chemicals, bacteria, viruses are all part of that earliest of environments. Further, a look at the living space of the modern home, the modern work space, and even the retirement home or community reveals not only less connection to the natural environment but also less control of the built environment.

One of the most important issues in health is the question of crisis and stress. At any moment in the developmental cycle stress impinges upon the human organism. The human organism must react. It can defend itself by extruding the foreign stressor, or it can adapt through chemical and other biological responses. Frequently the pattern of response to the stressor becomes repetitive, and stress builds upon stress. The organism finds itself less capable of responding to the stress itself, and over time suffers a breakdown of its system. The stressors are increasingly external and environmental and range from the physical, built environment to the humanly created social environment. The human organism, whose original development was based upon dealing with a relatively natural environment, must now struggle to cope with an externally imposed environment, which is increasingly less natural and over which there is little individual control.

Human development varies enormously. It is impossible to define a single track for the developmental process. Any human organism needs a range of different kinds of environmental stimuli to permit it to develop optimally. However, if the environment is stressful and at the same time limits the response the organism can make to stress, the environment impinges on health in a tremendous way.

In fact, we find that the very design of our environments puts limits on the possible environment-organism interaction. That is, only one environment is available to an organism that has within it infinite variations. The environment, therefore, becomes controlling and does not permit the organism to respond with all its variability. This then becomes another cause of stress leading to illness.

It was suggested earlier that the first concerns, the classic concerns, were with preventing and treating specific illnesses. It is becoming apparent that the total context (environment) of the human organism's development is more critical to health than even the ability to diagnose and to treat.

As we begin to look at the construction of buildings for birth, life, work, recreation, and death, we find that the architect is but a single player in a tremendously complex system that creates that environment. The system is "controlled" by availability of resources and materials, economic factors, and a whole host of other issues involved in the complex system. As this system unfolds it becomes not only larger and more complex, but it leaves less room for optimizing a particular individual's development. With such a process, individuals find themselves less and less capable of making even voluntary changes in the system to meet what they perceive as their own needs. There is a concept in health that suggests that the ability to command events that affect one's life is an important factor, not only in health but in the treatment of illness. If, however, one is living within a closed system in which one has minimal control of materials and processes, of lighting, of ventilation, of heat, of chemicals utilized in the structure of buildings, one becomes more susceptible to breakdown, and thus, illness.

It is not surprising that there is increasing agreement that the causes of modern diseases are primarily environmental. These environmental hazards are primarily materials and environments created by humans themselves.

Research in architecture in the past was preoccupied with specific design issues leading to the construction of the structure. If, however, the environments that are now created are complex systems interacting with important variables of health, it becomes clear that the first order of "architectural" research must be systems research. It must not be concerned with the materials and the design process alone but also with the interrelationship between architecture and human social and biological factors.

The following discussion of lighting, energy, and health illustrates some central issues and concludes with research and professional practice issues and recommendations.

MAJOR ISSUES AND PROBLEMS

The health, biological, psychological and behavioral effects of light; the energy implications of lighting design; and, the economics of different lighting schemes must all be understood to evaluate architectural lighting. The assessnent of these factors will change in relation to the purpose of the illumination, ne individual users, the goals of the owner, and myriad other considerations.

Light pollution is the result of many variables interacting. These variables nclude light and other environmental factors, their connections or interactions vith each other and with human beings. While it is necessary and worthwhile to xamine these interactive factors in detail, it may be more valuable and nportant to describe the patterns of connections among these variables. Because it is impossible to ever completely understand the myriad specific onnections of the details, it is essential that we identify the patterns connecting hem.[1]

The harmfulness or helpfulness of light in human affairs depends on the ituation. The same environmental lighting might be prophylactic for one ndividual and health threatening to another, beneficial at certain exposures duration or intensity) and harmful at others, or altered by other environmental actors. The same wavelengths that are essential for life at one exposure level an also be variably carcinogenic or otherwise toxic, causing erythema (a edness of the skin occuring in patches of varying size and shape), cell damage, nervous system effects, behavioral changes, and so on.[2,3] Susceptibility varies mong individuals, and the same individual can be made more or less usceptible by other environmental factors, including air quality, noise, chemical exposures, diet, and so forth.[4-9] Thus, we must be cautious about generalizations, careful to consider all relevant variables when conducting or reporting experiments, nd certain not to make assumptions of safety where potential hazards have been identified. These considerations are modified even further by the value placed on the life, health, and well-being of the particular individual or ndividuals involved.

Light is not only a physical agent involved with vision, it is also important psychologically. Vision is not simply a physical or chemico-physical process, but lso a psychological one. In addition to its effects on the psychological component of vision, light also affects nonvisual aspects of human psychology.[10]

Preliminary data from the National Institute of Mental Health suggest a elationship between mood and light. Certain patients have seasonal depression triggered by subtle changes in light duration and intensity. In some cases of depression, a condition affecting 30-60 percent of Americans, the connection between light and mood seems striking. In one case, a research scientist with 20 years of persistent, severe, seasonal depression had his last cycle markedly shortened by exposure to full spectrum fluorescent lights (500 lux for 12 hours per day).[11]

The concentration of fluorescent lamp output in the yellow-green portion of the spectrum has biological and health effects that are not adequately understood. The color of light affects blood pressure, pulse, and brain waves. Research with laboratory animals shows significant differences in biological and behavioral effects under variously colored lighting sources.[12]

The biological and health effects of light are modified by other environmental factors including other pollutants and design characteristics. While research demonstrating the relationships between various health and biological effects of light and the influences of other environmental factors on these effects is sparse, there is abundant evidence from studies of interactive synergistic effects of other pollutants that such relationships might exist.[4-8,13]

> It is widely recognized that in many instances the action of a toxic agent can be modified by exposure to other agents. This modification can be additive, synergistic, or inhibitory. In a few areas, for example, chemically induced cancer, there is now an extensive body of experimental and observational data on such interactions; in other fields information and, indeed, good leads for testing such interactions are lacking. The design of protocols must always recognize the possibility of interactions with other environmental agents and realistically include appropriate tests where this is practicable.[14]

An important example of this is the case of co-carcinogens. Bingham and Falk found that a noncarcinogenic chemical in combination with a known carcinogen can increase the toxicity of the carcinogen as much as 1000 fold.[4]

There is a strong relationship between lighting design and energy consumption patterns in buildings. Since 1974 there has been increased application of modification lighting and building envelope design to conserve energy in buildings. These efforts have included the following measures which affect lighting quality and light pollution:

1. Reduction of unnecessary or wasteful lighting;
2. Reduction of heat loss (or gain) through the building envelope by reducing window area and thereby reducing natural or daylight illumination of indoor environments;
3. Increased use of daylight to reduce energy use indoors;
4. More efficient use of light sources and more efficient lighting sources;
5. Increased use of south-facing glass for direct solar heating; and
6. Sealed buildings with no operable windows for ventilation.

A substantial literature on energy conservation is now available to those who design buildings. Researchers have developed techniques for evaluating tradeoffs between conflicting goals and approaches. Many of the resulting design decisions significantly impact the effects of light on humans.

The health and biological effects of environmental lighting are not well understood and will likely remain so indefinitely. The development and introduction of new light sources and applications is proceeding more rapidly than the development of knowledge about these changes. Energy costs of lighting have accelerated interest in new sources, and several are becoming commercialized. Fluorescent lamps that screw into incandescent sockets, more efficient incandescent lamps, and various low-wattage, high-intensity discharge lamps are among these new products. The current level of funding and extent of light-health research cannot provide the necessary information to understand these changes. Even if attention is drawn to the potential hazards, the facilities, trained researchers, standardized protocols, and other elements of an effective research effort are currently absent.

Manufacturers of lighting products shape the development of new products and the research on their effects. Most lighting research has been funded or strongly influenced by manufacturers. Many of the major critics of standard fluorescent lighting have been associated with other light sources. The organization (Illuminating Engineering Society, IES) responsible for most light research in the United States is comprised of lighting engineers, designers, and researchers. The unclear distinction between these organizations and trade associations casts a shadow on their research findings.[15]

HISTORICAL BACKGROUND

A brief review of the development of lighting sources and their uses, illumination standards, design practice, and other factors affecting environmental lighting is helpful in understanding the connections between the various research and practice issues and needs.

Historically, each new lighting development has been accepted with little dispute. The progress from simple fires as a light source to explicit lighting supply (by candle, burning oil, or gas) to the use of incandescent electric light raised few questions other than how and when to change to the new source. When fluorescent lights came into widespread use after World War II, they were assessed by an emerging design-technology evaluation criteria, efficiency.[16] Since fluroescent light sources produce approximately two to five times as much light per watt of electrical energy as their predecessor source, incandescents, their use rapidly became widespread.[17]

However, with the potential to produce much more light with a given amount of energy came questions about the required or recommended lighting levels for various tasks. Research on task performance and accuracy by Blackwell and others led to new lighting standards (as published by IES), which raised recommended task illumination levels by 250 to 500 percent in the late 1950s and early 1960s.[18] Along with the increased lighting levels, fluorescent sources produce concentrated output in the yellow-green portion of the visible spectrum, that portion the eye most keenly senses as brightness.[15] The case study (Table 11.1) demonstrates the energy and other effects of this approach.

This emphasis on brightness generated concern with glare and contrast. Uniformly bright interiors were the common solution to potential glare problems. The widespread use of fluorescent lighting coupled with the increasing use of mechanical ventilation systems made the window a superfluous item for many architects, and the windowless building became commonplace.[15]

TABLE 11.1
Illustrative Case Study

Standards	*"Old" Standards (pre-1959)*	*"New" Standards (since 1959)*
Design illumination level	30 fc (footcandles)	70 fc (footcandles)
Office size	150 sq. ft. (assumed)	150 sq. ft. (assumed)
Lamps/fixture	1	2 or 3
Source	incandescent	fluorescent
Fixtures	2 or 3	3 or 4
Total lamps	2 or 3	6-12
Watts/lamp	60-100	35-40
Total watts (range)	120-220	210-480
Total Watts (typical)	160	360
Watts/sq. ft.	1.07	2.40
Illumination at work surface	50-70 fc	40-70 fc
Color rendition	acceptable	poor
User control	good to excellent	poor to nonexistent
Maintenance	simple, inexpensive	difficult, costly
Lamp replacement	simple	complicated
Illumination at work surface vs. energy used for lighting	60 fc/160 watts .375 fc/watt	55 fc/360 watts .153 fc/watt

The high recommended lighting design levels contrast with standards in industrialized Western European countries at 30 to 70 percent of U.S. IES recommended levels. Some countries use levels as low as 10 percent of the U.S. recommended levels.[19] Dr. Case Crouch of the Illuminating Engineers Research Institute reveals the history of this dramatic rise in illumination: "Short of glare, our working group felt more light is better." "Besides, the energy cost was very low," adds Dr. Crouch.[20] However, review of IERI data shows that performance tasks are only marginally (3 to 7 percent) impaired at illumination levels only 10 percent of those recommended by IERI (Fig. 11.1).

Recent Changes in Environmental Lighting

Recently, there have been intensified efforts to reduce energy use in buildings and to improve the quality of light. Prominent among these efforts are renewed interest in daylight sources of illumination; use of task lighting as opposed to ambient lighting; and increased use of fluorescent as well as the newer mercury and sodium vapor electric light sources.[15,22,23] Designers and researchers have been concerned with illumination in relationship to visual task performance; glare, contrast, and reflections that affect visibility; energy efficiency of various sources of illumination; and manual and automatic lighting controls, to name a few.[18,19,24-27]

In the past decade there has been growing interest in possible health and psychological effects of light.[28,29] In particular, researchers have examined the effects of the differing spectral distributions of various light sources. A great deal of this work has focused on comparisons of various fluorescent sources, and the results indicate that there are significant differences in the biological, psychological, and health effects of light sources with varying spectral distributions.[2,22,29-41] There is currently a growing interest in "full-spectrum lighting" or lighting that approximates the color (or spectral qualities) of sunlight. Several new products have appeared on the market during the past few years to respond to this growing interest. Some of the recent research (cited above) has compared the effects of full-spectrum lighting with standard "cool-white" fluorescent illumination. Much of this research has been funded by manufacturers of lighting equipment, particularly those who produce the "full-spectrum" sources.

Interest in the health effects of light has been stimulated by the research of Richard Wurtman and his collaborators. Wurtman, an endocrinologist at Massachusetts Institute of Technology, has investigated the health effects of light on

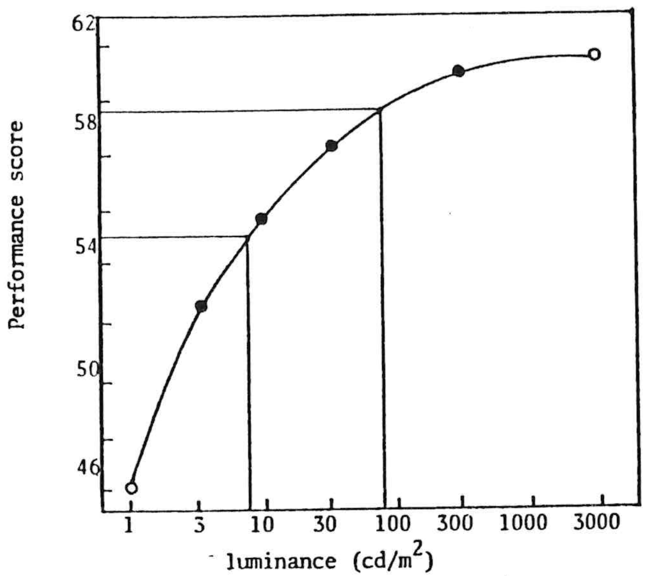

Figure 11.1
IERI 1977 numerical verification task experiment. *(After S. W. Smith, "Is There an Optimum Light Level in Office Tasks?" IES Journal* **7**(4): 255-258, July 1978.)

laboratory animals and in some human experiments. These effects include growth or developmental differences, vitamin D synthesis and its concomitant effect on calcium absorption.[34,35,36] Additionally, the mechanisms of the physiological effects of light involve the endocrine system.[40] This suggests other potential effects involving body rhythms for sleep, mood, concentration, and so forth.[28]

Other interesting findings include correlations between dental caries and light exposures, hyperactivity and lighting sources, fatigue and social interaction affected by lighting environment, and malignant melanoma associated with fluorescent light exposure.[31,32,37,42,43] European researchers have been active in the examination of the relationship between light intensity, spectral distribution, and task performance, along with subjective responses to these varying conditions.[10,21,44]

Studies of subjective and psychological effects of color are not new,[12] although work continues at a modest pace. The effect of color on other subjective experience such as perception of thermal comfort, security, general comfort or satisfaction, mood, performance, muscle strength, and others has been the subject of investigations for decades. While some designers have concerned themselves with the findings of this research, use of the research results has been limited.

RELATIONSHIP BETWEEN THE DESIGN PROFESSIONS AND ENVIRONMENTAL LIGHTING

Examination of the health, physiological, psychological, and performance effects of lighting is often done under controlled experimental conditions that are not easily extrapolated to actual conditions of illumination. The difficulty in translating laboratory findings into practice may help explain why experimental research has had so little impact on the design professions. Most designers of lighting systems for buildings consider initial costs first and foremost, operating costs second, and energy costs third. Sometimes these are combined as "life-cycle" costs. Designers consider lighting in regard to its energy use (1) directly for conversions to light; (2) as a generator of heat (and the impact of waste heat on the heating or cooling loads imposed on a building's thermal control system); and (3) indirectly to reflect the preferences, experiences, and needs of a building's intended occupants. Operating costs of buildings reflect the maintenance of lighting equipment, including the cleaning of lenses and diffusers and the replacement of worn lamps.

Beyond these functional and economic considerations, lighting design solutions may also consider the architectural implications of a selected illumination scheme. Such architectural factors as the location and brightness of light sources bear upon interior spatial qualities; color rendition will affect the mood or atmosphere; and the use of windows or skylights can serve to highlight certain areas or objects or to subtly guide the occupant to or through certain portions of the building.[23]

Information from research is incorporated into practice through the revision of design standards promulgated by the illuminating engineering societies or by the development and marketing of new light sources by manufacturers of lighting equipment. The societies have been concerned with extremely detailed research on visibility, task performance, lighting levels, glare, contrast, and other aspects of vision. More recently manufacturers have become interested in energy use characteristics, luminaire design, and color rendition. Designers generally rely on manufacturer's literature for information about lighting sources; they do not normally conduct independent research.

Typically, designers of office and other nonresidential buildings engage the services of an electrical engineer who specifies the amount and location of lighting equipment necessary to obtain the designated level of illumination. When this equipment is evenly distributed in the ceiling of the occupied spaces to provide uniform illumination throughout, many people find this homogeneous illumination unpleasant or discomforting. Others may suffer physiological, psychological, or health effects from this form of lighting. This diversity of human response has stimulated new interest in the human effects of lighting. Lawrence Berkeley Laboratory recently inaugurated a comprehensive pilot research effort at the University of California San Francisco Medical Center on task performance and physiological, psychobiological, and biochemical effects of various common lighting sources.

LIGHTING AND ENERGY EFFICIENCY

As lighting levels were increased to meet the new recommended standards, it was discovered that substantial quantities of excess heat were generated by the fluorescent lights. While they were producing less waste heat per watt of electrical input, the much higher levels of illumination, the manner of installation, and the sealed-exterior, larger-volume interiors resulted in the production and retention of large quantities of waste heat. New ceiling systems were designed to use the waste heat of lighting where heating was required. Where air conditioning was required, this waste heat was problematic.

When the mid-1970s brought concern over energy conservation, new research revealed that waste heat from lighting required considerable energy use for cooling and ventilation. Efforts to conserve energy in offices and other buildings included renewed use of operable windows to reduce cooling and ventilation energy requirements. The health and comfort effects of lighting systems were not considered explicitly by lighting or energy specialists or researchers. Efficiency and energy conservation became the dominant forces.

It happened again this summer: a call from the utility company to please turn off the office lights and adjust the air conditioning. For two days the women could wear their summer dresses without sweaters and the men happily discarded their coats and ties. The halls, receiving only spill light, became quite pleasant. While the lights had to remain on in the inside offices, people on the perimeter opened the curtains, adjusted the blinds and carried on by daylight. The atmosphere was strangely more friendly and peaceful, and we had a small satisfaction in doing something "to alleviate the energy crisis." On the third day it rained; down went the temperature, on went the lights.[45]

LIGHTING STRATEGIES AND ENERGY EFFICIENCY: MYTH AND REALITY

Aggressively higher recommended illumination levels and uniform illumination throughout building spaces are commonly provided by ceiling mounted fluorescent fixtures evenly distributed without regard to the location of the task areas or work stations requiring illumination. Typically an entire office is illuminated to 70 footcandles plus a margin of safety to account for worn lamps, dirty lenses, or diffusers. This results in considerable wasteage of light, energy, and heat.[15] Efforts to conserve energy during the mid-1970s led to a reduced recommended level around 45 footcandles. More sophisticated designs use a "task-ambient" approach and an upper limit or design goal of one watt per square foot. Ambient lighting is provided at 15 to 30 footcandles, and tasks are illuminated as needed with appropriate fixtures located close to the task surface. Such an approach is gaining popularity, and some governmental authorities are mandating its use. It is interesting that it resembles the approach most commonly encountered in pre-World War II buildings, including a return to reliance on daylight sources as a major lighting strategy. Ventilation problems in modern buildings are also resulting in renewed interest in windows. Together, lighting and ventilation are having a profound effect on building form as well as building science research.

Of course, a task lighting strategy is likely to be more energy efficent, since it eliminates unnecessary lighting and moves the light source closer to the task to be illuminated. Since light energy reaching a surface is inversely proportional to the square of the distance from the source, task lighting strategies that place the light source close to the task surface will reduce energy consumption.

While fluorescent lighting was touted and sold as more energy efficient, the actual manner of its use resulted in considerable inefficiencies. Higher lighting levels, even illumination of an entire space, elimination of task lights, and mounting fixtures in the ceiling all resulted in energy wastage, which is being addressed by emerging lighting design strategies. The analysis presented above as well as the emerging lighting design strategies show that much of what was done in the interest of more efficient and improved lighting during the 1960s and early 1970s was more myth than reality in its results. Furthermore, many of the potentially adverse health, biological, psychological, and performance effects of typical, uniform, ceiling mounted, overly bright fluorescent illumination may be exacerbated in relation to the excess power used.

Table 11.2 presents a "typical" office under "old" lighting standards—pre-1959, "new" standards that prevailed during the 1960s and early 1970s, early energy conservation standards, and emerging design strategies. Daylighting can further reduce electric illumination requirements in both the pre-1959 and the emerging strategies.

RESEARCH ON HEALTH EFFECTS OF LIGHT

There is now abundant evidence that environmental lighting exerts more important effects upon human health and productivity, far beyond its requirements for vision. (Even the visual effects of light depend upon more than brightness: the poor color rendition of most artificially lit interiors provides a major source of errors to physicians attempting to make diagnoses based upon small changes in skin color . . . .

Environmental lighting has been shown to affect humans and experimental animals *directly* or *indirectly*: directly from interactions between photons and molecules in cells or blood near the surface of the body; indirect effects, like vision, result from nervous impulses generated by light impinging on retinal photoreceptors. Light has perhaps several hundred important effects on bodily functions, but only a few dozen are currently known and even a smaller number really understood. Since these particular biological effects presumably evolved in relation to a particular lighting environment, i.e., sunlight, filtered and reflected by atmospheric constituents, architects, lighting designers and engineers might be well-advised to be conservative about introducing great deviations from "natural" lighting in designing the lighting environments in which people spend their working hours.[46]

Health Effects of Fluorescent Lights

There is a growing interest in the health effects of fluorescent light. Much of this interest has been stimulated by the research and writings of John Nash Ott, who learned about the effects of light in his time-lapse photography of growing plants for clients, including Disney Productions. Ott extended his work into observations of the effects of light on animals and human beings.[47] Ott's work has been controversial, apparently because of his lack of scientific background and rigor in much of his experimental work. However, he deserves credit for identifying a number of important problems and bringing them to the public eye.

An excellent summary of scientific research on the effects of light on life is Wurtman's article in *Scientific American* (July 1975), "The Effects of Light on the Human Body." In an earlier article, Wurtman wrote that most of the information about biological effects of light has

. . . been accumulated only during the last decade. It seems likely that much more information will become available during the next decade. Meanwhile, knowing only that we do not know enough,

TABLE 11.2
Typical Office under Various Lighting Designs

	Illuminating Engineering Society pre-1959	*IES 1963 on*	*Energy Conservation*	*Suggested Strategy*
Room illumination (fc)	15	70	45	15
Illumination level at task (fc)	30	70+	45	25-45
Office size (sq ft)	150	150	150	150
Fixtures				
Ceiling	1	8	4	0-1
Desk	1	0	1	1-2
Total lamps	2	16	9	3
Watts/lamp	100/60	40	35/60	35/60
Total watts				
Range	120-160	480-640	140-340	105-190
Average	140	540	340	155
Watts/sq ft	0.93	3.6	2.3	1.03
User control	some	none	some	most
Maintenance	good	poor	poor	good
Lamp replacement	easy	difficult	difficult	easy
Illumination at work surface/watts lighting (fc/watt)	0.20	0.13	0.13	0.29

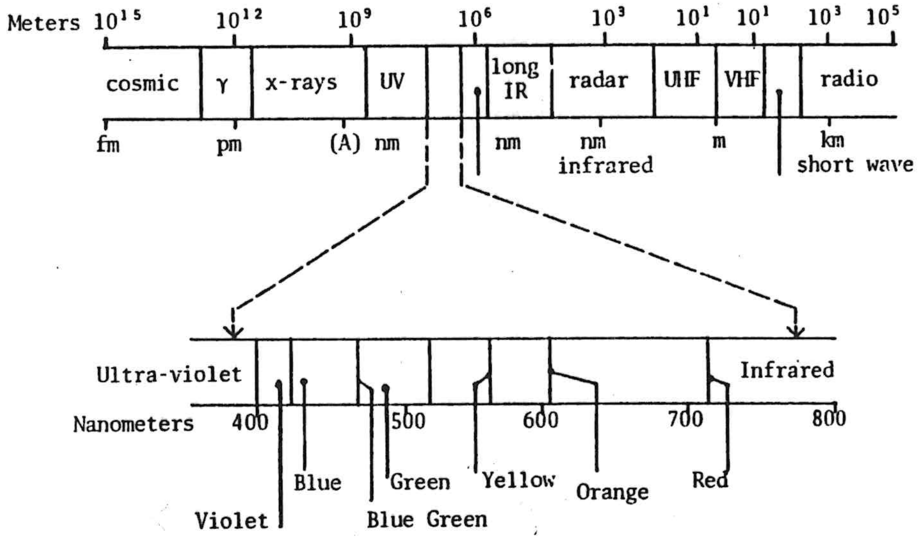

Figure 11.2
The electromagnetic spectrum. *(After S. V. Szokolay, Environmental Science Handbook for Architects and Builders, Construction Press, New York, 1980.)*

architects, lighting designers and engineers will have to continue to decide on the lighting spectra under which most people will live.[48]

It seems reasonable that the light sources to which we expose people should not deviate markedly from the lighting environment under which people evolved in nature. The fragmentary data now available suggests that working under such "natural" conditions significantly decreases visual fatigue, and may also increase productivity. I, for one, would worry somewhat about keeping my children under, let us say, pure green light, or, of more immediate concern, yellow sodium light, even if it can be shown that the brightness indices of such lights are greater than that of existing broad-spectrum light sources. I suspect that all one can do is hope that new information about biological effects of light accumulates as quickly as possible, and that such information is applied on a continuing basis in the design of light sources.[49]

Many investigations on the health effects of light suggest that fluorescent lights may present a health hazard. Most of these investigations focus on the spectral distribution and intensity of fluorescent light compared to that of sunlight and incandescent sources. Researchers like Wurtman argue that organisms that have evolved primarily under sunlight or "natural" light may be adversely affected by the altered "unnatural" wavelengths of fluorescent lights.[28] Some of the research results are summarized in the following pages.

Research on cellular level effects has included both plant and animal studies, and there has been some investigation using human cells. A few experiments have been able to isolate the effects of specific wavelengths, while others have compared the effects of different wavelengths or light sources emitting broader spectra.

Of all the suspected effects of fluorescent lights, the potential to cause skin cancer is probably the most serious. It is also extremely poorly understood, partly because of the absence of efforts to study it, partly because of the difficulty of conducting conclusive investigations. Most of our information comes from studies of the effects of fluorescent lights or their spectral components on human cells or animal cells and from studies conducted by epidemiologists. Two recent epidemiological studies are reported below.

Fluorescent Lights and Skin Cancer: Two Case Studies

Recently a study of 274 women in New South Wales, Australia, showed that chronic exposure to fluorescent lights at work was associated with more than a twofold increase in malignant melanoma risk. The risk grew in proportion to the length of exposure and was higher in offices than in other indoor work places. Neither history of sunlight exposure, nor skin or hair color, nor any other factor could explain the findings. Among the melanoma victims exposed to fluorescent lights at work there was an excess of lesions on the trunk rather than on the face, neck, hands, or forearms. In a smaller group of male malignant melanoma victims, the study showed that exposure to fluorescent lights for more than ten years resulted in a 4.4 times higher risk of melanoma than in those exposed for

less than ten years. While this is the first report of an association between melanoma and fluorescent light exposure, the association is regarded by the researchers as a plausible explanation and one that reconciles many paradoxical features of the epidemiology of melanoma.[42] The researchers suggest that while there is only a small amount of energy in the ultraviolet emissions of fluorescent lights, this UV does occur in distinct peaks (see Fig. 11.3 and 11.4).

The occurrence of these melanomas on the trunk suggests a possible synergistic effect between the ultraviolet radiation and some chemical present either in laundry soaps, undergarments, or personal hygiene products. A strong connection has been found between ultraviolet light and fluorescent whiteners (chemicals used to brighten clothing) in the production of skin cancer in laboratory animals.[5] Such a synergistic or interactive effect is plausible and represents an example of the complexity and interconnectedness of environmental contaminants and other factors.[4,6] PCBs (polychlorinated biphenyls) used in lamp ballasts could be involved.

Another recent study of malignant melanoma has shown a tenfold higher disease rate than expected in male office workers in a state office building in Sacramento, California. While fluorescent lights have not been suggested as the cause, many individuals involved have raised the possibility of an association, and the investigator has not ruled it out.[43] In light of this sort of evidence, it is important that more work be done to determine the potential carcinogenicity of fluorescent lights.

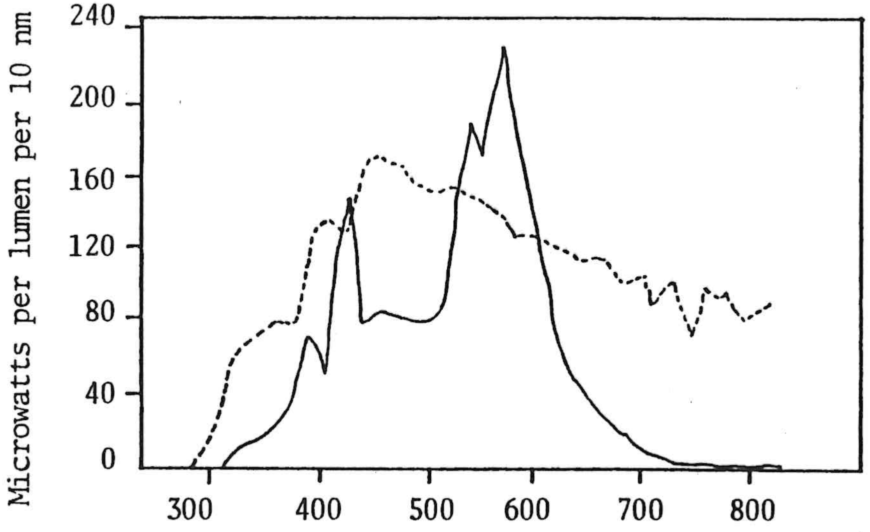

Figure 11.3
Relative spectral distribution. The solid line indicates cool white fluorescent and the broken line, typical daylight sun plus sky radiation.

Spectral Characteristics of Fluorescent Lights and Ultraviolet Radiation

Fluorescent light sources are usually weaker in the ultraviolet and blue-green regions of the visible spectrum compared with standard sunlight emission (color temperature equal to 5500°K). (See Fig. 11.4.) While ultraviolet radiation (UVR) is required for fluorescent light emission, the actual amount of UVR emitted through the glass varies according to the glass wall thickness, phosphors used, and luminaire design. UVR can have both harmful and beneficial health effects; these effects are modified depending on the characteristics of other wavelengths present. There is some disagreement regarding measurements of ultraviolet emissions from lamps; this problem has become one of the most controversial in understanding the health effects of general illuminants.

Much of the research on ultraviolet radiation and its effects has been summarized by the World Health Organization.[3] Some of the salient findings follow:

Effects of Ultraviolet Radiation

While UV-C can damage cells, artificial lighting sources normally do not emit in this range. More interesting, cell damage by UV-C can be repaired by exposure to longwave UVR or visible radiation (320-550 nanometers), a process known as photo-reactivation. This repair mechanism has been demonstrated in all types of living organism, including mammals. However, repair is not necessarily complete and remaining damage may cause later health effects.[3]

An example of synergy among environmental constituents is the effect of concomitant caffeine on UV-exposed cells or tissues. Repair system activity is inhibited by the ingestion of caffeine, and at otherwise nontoxic doses, caffeine increases the harmful effects of UVR. Thus, those who drink caffeine-containing beverages during or immediately prior to sunlight exposure or exposure to UV-emitting lights may experience more severe health effects than those who do not consume caffeine.[3]

The same ultraviolet region (UV-B) that causes tanning and sunburn can cause skin cancer, depending on skin type, occupational exposures, latitude, seasonal exposure, and other factors, such as nutrition, which affect reaction to UV exposure.[3]

Ultraviolet radiation makes possible the production of vitamin D necessary for proper calcium and phosphorous metabolism, prevention of rickets, and retarding development of dental caries. This activity is maximal at 280 nanometers, which is UV-B.[28,29,41]

TABLE 11.3
Types of Ultraviolet (UV) Radiation

UV-A	320-420 nanometers	near UV, longwave, and black light
UV-B	280-320 nanometers	mid UV, and sunburn UV
UV-C	200-280 nanometers	far UV, shortwave UV, and germicidal UV

Note: A nanometer = 1×10^{-9} meters or approximately 4 billionths inches.

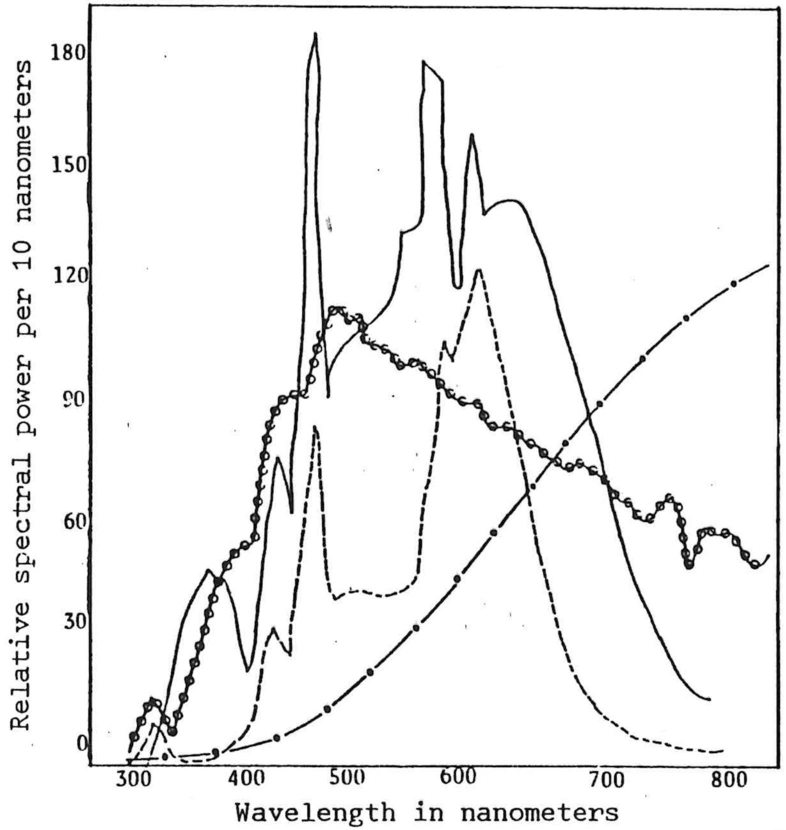

Figure 11.4
Characteristic spectra of common light sources. Ultraviolet-enriched (full-spectrum) is shown by the solid line; cool white fluorescent by the broken line; sunlight (680°K) by open circles; and incandescent by solid circles.

Ultraviolet radiation has been used to treat skin diseases such as psoriasis, acne, atopic dermatitis, and recurrent boils and has also been used in the treatment of chronic pneumonia and rheumatic diseases. This effect is due to its stimulating effect on white blood cells. Thus UV can be beneficial or harmful depending upon the conditions of the subject and the dose distributions.[3,28,41,42]

Research on Specific Wavelengths of Visible Light

R. M. Gerard, in a 1958 doctoral thesis, described differential effects of colored lights on psychophysical functions.[12] Gerard tested human subjects with red, blue, and white light. He found effects on blood pressure, pulse, and brain waves, the red having stimulating effects, blue relaxing effects, and white intermediate effects. Wurtman et al., measuring pineal hydroxindole-o-methyl transferases (HIOMT) in rats, found that green, blue, or yellow light caused decreased HIOMT activity, green being the most effective.[40] The pineal is a small gland located in the brain, known to affect growth, particularly of the sex organs, and believed to affect biological rhythms. HIOMT is the enzyme used for the synthesis of melatonin.) Red light produced no change. Retinal HIOMT was also measured, with green producing a decrease, blue producing an initial decrease followed by an increase, and no change produced by red light.[12]

Significant differences in activity responses of mice to various environmental lighting conditions—blue, green, yellow, red, daylight, and dark—were found by Spaulding, Holland, and Tietjen.[38]

Other researchers have investigated the effects of broader spectrum sources in general use. Many studies have compared the effects of the standard "cool white" fluorescent, and the "Vita-Light" fluorescent, a "full-spectrum source, having a spectral distribution very close to that of sunlight." (See Fig. 11.4.) Following are some of the effects reported in these and related studies.

Both male and female rats had smaller genitalia and larger spleens when raised under cool-white light compared to Vita-Light. Male golden hamsters raised under Vita-Light had greater total body weight and greater gonad and sub-mandibular gland weights than those raised under cool-white light.[37]

Rats exposed to cool white light showed decreased HIOMT compared with rats under Vita-Light.[30]

Elderly male subjects showed increased calcium absorption with Vita-Light exposure and decreased calcium absorption under cool-white light. Calcium absorption is important in the elderly as its absence is related to bone matrix loss (osteoporosis), a painful, commonly encountered condition among the elderly who receive little daylight exposure.[34,35,36]

Male golden hamsters raised under Vita-Light had one-fifth the incidence of dental caries compared to those raised under cool-white lamps. J. M. Dunning found that the incidence of human dental caries is inversely proportional to sunlight exposure.[49]

A small sample of college students studying under Vita-Light showed less visual and central nervous system fatigue than students who studied under cool-white light. These changes were measured by the critical fusion frequency (CFF).[31]

College students studying under Vita-Light showed improved visual acuity compared with students studying under cool-white lamps. Measurements were made using the Snellan eye chart.[31]

There was a significant decrease observed in the hyperactive behavior of school children after sixty days exposure to Vita-Light compared with children exposed to cool-white light.[32]

Individual sensitivity to flicker varies, and to that extent it may produce effects ranging from visual irritation to epileptic seizures. As lamps age and flicker increases, epileptics may be at particular risk in spaces illuminated by flickering lamps; even those who are not epileptic can become more prone to epilepsy by exposure to flickering lamps. Flicker can be controlled by luminaire design, but maintenance practices and lamp replacement are the most important factors in determining the occurrence of flicker in our buildings. The inconvenience of relamping fluorescent fixtures results in the widespread occurrence of flickering tubes (where active maintenance programs are not a matter of course).

Hum is frequently a result of ballast operation, and proper design can reduce audible hum. However, quieter ballasts are more expensive and efforts to save money in construction costs or fixture replacement costs often result in the choice of an inadequate fixture. Hum is an irritant and the noise, depending on its frequency, may act synergistically with other noises or with other environmental stressors to produce undesirable stress-related health effects.[52]

Psychological Effects

Most light research has been concerned with questions of visual comfort and task performance. In recent years there has been increased concern with more subtle effects of light. Research has shown that light has biochemical effects on the single cell level in plants and animals. It is becoming increasingly clear that light has effects on the central and autonomic nervous system. Other experimental work has shown the effects of light also influence such processes as heart rate, blood pressure regulation, electrical brain wave patterns, hormonal secretion, and circadian rhythms. These basic physiological responses to light also appear to have counterparts on the psychological level in terms of light's influence on emotions and feelings.[10]

Most lighting research experiments are conducted in the laboratory. Clearly this approach has the advantage of providing better control on the experimental conditions. On the other hand, the laboratory setting contains the potentially confounding variable of the subjects' awareness that they are participating in a scientific laboratory vision experiment. This fact alone may obscure the importance of the actual conditions of vision for which the experiment is conducted. Furthermore, the awareness in itself may skew the results.

Küller has identified several factors that raise questions about the validity of light research, particularly that which has focused on visual comfort and performance for application to lighting design. He argues that there is a general failure to incorporate the findings of health and physiological effects research into a more general model of man-environment interaction. The first of these is the failure to acknowledge and utilize the understanding that light is not only radiation but also perception. Küller suggests that scientists use two different languages for dealing with light, one physical and one perceptual, which confuses "almost evey single piece of scientific work on the subject."[53]

DISCUSSION

Lighting, like all indoor pollution sources, must be addressed in the complex context of the built environment. Designers, researchers, regulators, manufacturers, and users must consider the systemic nature of lighting. It is important to appreciate that, while we know far less than we would like, we are beginning to act on some of the information already in hand, although most decisions are still made out of habit and desire for convenience. When we consider the potential significance of the health, physiology, comfort, satisfaction, and productivity implications of the choices we make about lighting, we are impelled to carefully consider information currently available.

Ultimately we must exercise informed judgment and apply our values, intuitions, and the knowledge available to design healthy, productive, satisfying environments. Where information is not yet available, careful research may bear valuable fruit in terms of public health, energy, cost, and economic productivity. The information already available strongly supports a number of changes in current practice to minimize potential health hazards, energy waste, economic loss, and indoor environmental degradation.

Implications for Research and Practice

1. State and federal governments as well as the lighting industry should support a significantly expanded program of environmental lighting research in the following areas: health effects, biological effects, energy conservation, and lighting economics.
2. Designers (architects, engineers, space and interior planners) should maximize the use of daylight in buildings, with electrical lighting only as a supplement.

3. Electrical illumination should be accomplished with user-controlled task lighting whereever practical.
4. Lighting controls in buildings should be localized, permit variable light levels, and be accessible to users wherever practical.
5. A variety of lighting conditions through diverse illumination sources should be provided to allow maximum user choice in control and regulation of interior lighting.
6. Design of lighting and performance standards for lighting should be based on light delivered to actual task stations in buildings, not on illumination of general spaces. Standards should discourage delivery of over-illumination to nontask areas.
7. Public health authorities and building operators and occupants should consider the possible connection between occupant discomfort or illness and environmental lighting, including spectral characteristics, illumination levels, electromagnetic and chemical emissions from fixtures, and user access to effective lighting control.
8. The use of newer light sources should be restricted until sufficient research into the health effects indicates that the impacts are within acceptable limits.
9. Light sources should be selected for the best possible match between spectral characteristics and the needs of the users.

CONCLUSION

While there is clearly much to be learned, sufficient information exists to enlighten our research efforts as well as our lighting designs. Since every unique architectural design is a sort of ad hoc research project as well, architects can participate in an important way in our efforts to better understand and improve the use of light in buildings. Design itself is a research activity, and good research depends on the quality of the research design. Only where explicit lighting research and the practical application of research results are integrated in the development of light sources and their use, will architects and architectural research benefit building users.

Natural light has provided a perceptual dynamic to architectural design since its inception. The creation of the artificial has been enhanced in relation to the natural and gained vitality in response to solar rhythms. Masters of architecture may frequently be cited as masters of light.[54]

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