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Technical Report

# A Literature Review of the Effects of Natural Light on Building Occupants

L. Edwards and P. Torcellini

**National Renewable Energy Laboratory**

**1617 Cole Boulevard**
**Golden, Colorado 80401-3393**

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## 1. Background

This paper presents summary information from a noncritical literature review on daylighting in buildings. It is by no means exhaustive, and no attempt has been made to determine the scientific nature of the studies that are cited. It was the goal of this document to compile a listing of the literature that is commonly cited for showing the impacts of daylighting in buildings. NREL does not endorse any of the findings as the citations have not been critically reviewed.

Many building owners and architects have reported energy savings received from daylighting. Looking at the energy consumption of commercial buildings in the United States demonstrates the importance of saving energy. According to the Department of Energy's Office of Building Technology, State and Community Programs (BTS) 2000 Databook, commercial buildings consumed 32% of United States electricity in 1998, of which 33% went to lighting. Not only is electrical lighting responsible for a significant amount of the electrical load on a commercial building, but it can also cause excessive cooling loads. Utility costs for a building can be decreased when daylighting is properly designed to replace electrical lighting.

Along with the importance of energy, studies have demonstrated the nonenergy related benefits of daylighting. Quantitative studies and qualitative statements are used to summarize the use of daylighting in buildings, its effects on occupants, and its potential economic benefits. Data have been compiled from books, periodicals, Internet articles, and interviews. The books, periodicals and Internet articles provided the background information necessary to identify the main subjects of the paper. Interviews provided details related to specific buildings and companies that have integrated daylighting into their building.

Daylighting data have been divided into Wavelengths of Light, The Affects of Light on the Body, and the following building sections: offices, schools, retail, health care, and industrial. The sections Wavelengths of Lights and The Affects of Light on the Body help describe the impact daylight has on building occupants. Each building section includes the effect daylight has on the building occupants psychologically and physiologically. Economic data have been cited in the categories in which information was found.

## 2. Introduction

Before the 1940s, daylight was the primary light source in buildings; artificial lights supplemented the natural light. In the short span of 20 years, electric lighting had transformed the workplace by meeting most or all of the occupants' lighting requirements. Recently, energy and environmental concerns have made daylighting a rediscovered aspect of building lighting design. The physics of daylighting has not changed since its original use, but the building design to use it has. Daylighting is often integrated into a building as an architectural statement and for energy savings. However, benefits from daylighting extend beyond architecture and energy. The psychological and physiological aspects of natural light should also be considered. The comforting space and connection to the environment provided to building occupants provide benefits as significant as the energy savings to building owners and managers.

This paper summarizes the benefits that different wavelengths of light have on building occupants. Daylighting has been associated with higher productivity, lower absenteeism, fewer errors or defects in products, positive attitudes, reduced fatigue, and reduced eyestrain.

## 3. Wavelengths of Light

Electrical light sources include cool white fluorescent, incandescent, energy-efficient fluorescent, and full-spectrum fluorescent lighting. Each type has a different level of energy consumption. However, the most important factor affecting building occupants is the different spectrums of light that each source produces (see Appendix).

Different wavelengths or spectral distributions of light have different effects on the human body. Most electrical light sources lack the spectral distribution needed for complete biological functions, although full-spectrum fluorescent lighting does come close to that of natural light (Hathaway, et al. 1992).

*Cool white fluorescent* lights are concentrated in the yellow to red end of the visible light spectrum. *Incandescent* lamps, similarly, are concentrated in the orange to red end of the spectrum. In comparison, *energy-efficient fluorescent* lighting is typically concentrated in the yellow to green portion of the spectrum. These three light sources lack the blue portion of the color spectrum (Liberman 1991), which is the most important part for humans and is best provided by natural light. *Full-spectrum fluorescent* lighting is the electrical light source that has a spectrum of light most similar to natural light because it provides light in the blue portion of the spectrum.

*Daylight* provides a better lighting environment than cool white or energy-efficient fluorescent electrical light sources because "daylight…most closely matches the visual response that, through evolution, humans have come to compare with all other light" (Franta and Anstead 1994). The majority of humans prefer a daylit environment because sunlight consists of a balanced spectrum of color, with its energy peaking slightly in the blue-green area of the visible spectrum (Liberman 1991). According to Hathaway, et al. (1992), natural light also has the highest levels of light needed for biological functions:

> The photobiologic action spectra of greatest importance to humans ranges from 290 to 770 nanometers. Skin reddening and vitamin D synthesis occurs in the range of 290 to 315 nanometers. Tanning or pigmentation of the skin and reduction of dental…[cavities] occurs in response to band light in the band from 280 to 400 nanometers. Vision is the most sensitive to light in the 500- to 650-nanometer range (yellow-green light). Billirubin degradation occurs in response to light in the 400- to 500-nanometer range (blue light) (Hathway, et al. 1992).

## 4. Effects of Light on the Body

Humans are affected both psychologically and physiologically by the different spectrums provided by the various types of light. These effects are the less quantifiable and easily overlooked benefits of daylighting. Daylighting has been associated with improved mood, enhanced morale, lower fatigue, and reduced eyestrain. One of the important psychological aspects from daylighting is meeting a need for contact with the outside living environment (Robbins 1986).

According to Dr. Ott (Ott Biolight Systems, Inc. 1997a), the body uses light as a nutrient for metabolic processes similar to water or food. Natural light stimulates essential biological functions in the brain and is divided into colors that are vital to our health. On a cloudy day or under poor lighting conditions, the inability to perceive the colors from light can affect our mood and energy level. Dr. Liberman (1994) also mentioned that light plays a role in maintaining health:

> When we speak about health, balance, and physiological regulation, we are referring to the function of the body's major health keepers; the nervous system and the endocrine system. These major control centers of the body are directly stimulated and regulated by light, to an extent far beyond what modern science…has been willing to accept.

A 1986 study by West as cited by Heerwagen (1986) evaluated the effects of light on health by evaluating prison inmates with different window views. He found that inmates with windows facing a meadow or mountains had significantly lower rates of stress-related sick calls than inmates with a view of the prison courtyard and buildings. Furthermore, inmates on the second floor had lower rates of stress-related sick calls compared with inmates on the first floor. Reasons for the differences in sick calls included a more expansive view from the second floor, which provided increased positive psychological benefits. Inmates on the first floor had added stress from lack of privacy because of visibility to passersby.

Because natural views tend to produce positive responses, they may be more effective in reducing stress, decreasing anxiety, holding attention, and improving mood. Studies in 1979, 1981, and 1986 by Ulrich (Heerwagen 1986) support the effectiveness of natural views. Ulrich found that viewing vegetation and water through slides or movies is more effective in creating psycho-physiological recovery from stress than built scenes without water or vegetation. Also, individuals recovered faster and more completely from a stressful event when exposed to films of natural settings as opposed to urban scenes. Nature group subjects also had lower muscle tension, lower skin conductance, and higher pulse transit along with possibly lower blood pressure from these health differences. Furthermore, Ulrich reported more positive emotional states and wakeful relaxation states for people exposed to natural scenes.

### *How the Eye Works*

The human eye functions at its best when it receives the full-spectrum of light provided by daylight (A Closer Look at Daylighted Schools 1998). Many fluorescent lights are concentrated in the yellow-green portion of the spectrum to obtain the most lumens per watt; this unbalanced, narrow spectrum limits the blue in the source, which leads to improper functioning of the eye. Therefore, the superior spectral content of natural light makes it the best light for the eye (Ott Biolight Systems, Inc. 1997a). Looking at what parts of the eye are affected by light helps to understand how it functions in different light sources:

> The human eye is a light-sensing system with a pupil and a photoreceptive medium called the retina. The retina contains two photoreceptors: rods and cones. Cones (which see photopic lumens or bright light) are responsible for day vision. Rods (which see scotopic lumens or dim light) are associated with night vision…Studies at UC Berkeley Laboratories by Dr. Sam Berman, senior scientist, have proven that pupil size and brightness perception at typical office levels are, in fact, strongly affected by rod activity within the retina of the eye.
>
> Light reaching the retina of the eye is converted into electrical signals that are transmitted by the optic nerve. Most of these signals end up in the visual cortex of the brain and produce our sense of vision. However, some of the nerve fibers split off from the optic nerve soon after leaving the eye and send signals to the suprachiasmatic nucleus, which is the area of the brain where the main clock for the human body resides (Light, Sight, and Photobiology 1998).

### *Affects of Light on Internal Body Systems*

Wavelengths of light help control the human body's chemistry (Ott Biolight Systems, Inc. 1997a). Many functions, including the nervous system, circadian rhythms, pituitary gland, endocrine system, and the pineal gland are affected by different wavelengths of light.

#### *Nervous and Endocrine System*

Both the central nervous system and the neuroendocrine hormonal system are influenced by the powerful stimulus of light (Ott 1982; Brody 1981; Wurtman 1975; Kotzsch 1988 ). Wurtman (A Summary of Light-Related Studies 1992) claimed that light has biological effects important to health and that some of these effects could be measured in a laboratory. The effects of light fall into two categories: those modifying individual endocrine, hormone, and metabolic state by light reaching the retina and those resulting from light on the skin. Some effects of light on the skin are vitamin D production, skin tanning, and dissociation of bilirubin. Other studies have also supported the possibility of physiological benefits from light.

> Danzig, Lazarev, and Sokolov…contend that physiological disorders may occur in the human system if the human skin does not receive some exposure to solar radiation, either direct or diffused, for long periods of time. They believe there will be a vitamin D deficiency followed by weakened body defenses and an

> aggravation of chronic diseases. Wurtman and Neer (1975) suggest that non-visual retinal responses to light mediate a number of neuroendocrine hormonal functions, which, in turn, regulate such mechanisms as pubescence, ovulation and a wide variety of daily rhythms. Faber Birren has been quoted as saying that ultraviolet radiation intensifies the enzymatic processes of metabolisms, increases hormone system activity, and improves the tone of the central nervous and muscular systems (A Summary of Light-Related Studies 1992).

*Circadian Cycles*

Light falling on the retina and being transmitted to the hypothalamus controls our circadian rhythms (Samuels 1990), which are responsible for synchronizing our internal clock to 24 hours (Light, Sight, and Photobiology 1998). The effects of light on circadian rhythms can be studied using physiological variables such as the daily patterns of core body temperature, levels of melatonin, urine production, cortex activity, and alertness (Light, Sight, and Photobiology 1998). In 1980, Bickford noted that prolonged exposure to cool white fluorescent lights might induce abnormal circadian rhythms because the hypothalamic pacemaking mechanism is thought to react to all the color frequencies. Other lighting studies have shown that the light absorbed by the eye controls the production of the hormone melatonin, which affects sleep, mood, body temperature, puberty onset, and tumor development (Salares and Russell 1996). By looking at the purpose of an internal 24-hour clock, the significance of circadian rhythms can also be seen.

> The circadian system is organized neurologically to drive bodily functions up and down every day and is a pervasive physiological regulatory mechanism. The timing of such circadian rhythms as body temperature is independent of an explicit knowledge of external clock time—and, indeed, in the absence of periodic environmental cues, the internal clock produces a "subjective" day length that differs reliably from 24 hours. Humans living under experimental isolation conditions may cycle at lengths greater than 24 hours. This kind of deviation would pose the risk of continual lack of synchrony with the external world were it not for the ability of light to force a daily correction in the internal clock and a strict match to 24.00 hours (Terman, et al. 1986).
>
> Among the hormone activities that closely follow 24-hour cycles, the secretion of melatonin from the pineal gland (which induces sleep, modifies mood and mental agility, and plays a role in the activities of the reproduction system) is the most notable. Secretion of melatonin is closely followed by cortisol secretion from the adrenal cortex (which affects the breaking down of carbohydrates, protein and fat; the development of white blood cells; the activity of the nervous system; and the regulation of blood pressure)(Bryan 1998).

*Pineal and Pituitary Glands*

Wurtman linked light entering the eye with responses of the pineal gland and secretion of the hormone melatonin in 1968; this hormone also influences the functions of other glands from direct action on specific areas of the brain (A Summary of Light-Related Studies 1992). Studies have shown how melatonin production affects human health.

> Photoelectric energy influences the functioning of the pituitary gland which controls the hormonal system (Hollwich and Dieckhues 1980) and hence our coping mechanisms, emotional and stress relations…Melatonin is normally secreted by the gland in the absence of light and where daylight and artificial lighting in the interior of buildings are inadequate the natural suppression of melatonin production during the day fails and is accompanied by feelings of depression (Wurtman 1975; Liberman 1985; Lewy 1985).
>
> Recognized scientific research inspired by full-spectrum advocates has contributed to the understanding of how the human endocrine system, triggered by light entering the eye, regulates body chemistry, and in particular, the secretion or suppression of melatonin. Melatonin levels in the body determine a person's activity and energy level. High melatonin levels cause drowsiness, while low melatonin levels correspond to an alert state of consciousness (Ott Biolight Systems 1997a).

***Medical Cures from Light***

By affecting the human body's chemistry, light can improve health and help cure medical ailments. Terman, et al. (1986) claimed that improved interior lighting could alleviate the common subclinical problems in the population at large such as oversleeping, overeating, energy loss, and work disturbance. Dr. Ott (1982) used kinesiology tests to prove that better light could increase muscle strength, but Jewett, et al. (1985) argued that light does not have this effect. Jewett, et al. concluded that the tests Dr. Ott used altered the experimental results and the true effect of lighting was so small that psychological effects would obscure any results. However, studies have shown that light can help cure rickets, osteomalacia, and Seasonal Affective Disorder (SAD).

*Rickets and Osteomalacia*

In 1919, sunlight was determined to be the key to curing rickets. Independent studies by Neer and Hollick in 1985 (A Summary of Light-Related Studies 1992) claimed that the ultraviolet radiation derived from sunlight in the region of 290–315 nanometers triggers the development of vitamin D in the skin that in turn can prevent or cure rickets (A Summary of Light-Related Studies 1992). Liberman (1991) explained the role of light in the cure for rickets.

> One of the most important phototherapeutic discoveries of the 1890s was that rickets, a disease characterized by a deformation in the developing bones of young children, could be cured by sunlight. Although the reason for sunlight's

effectiveness was not immediately understood, it was later discovered that sunlight striking the skin initiated a series of reactions in the body leading to the production of vitamin D, a necessary ingredient for the absorption of calcium and other minerals from the diet. If vitamin D is absent, the body will not absorb the amount of calcium required for normal growth and development of the bones. This deficiency leads to the condition called rickets in children and osteomalacia in adults, which is characterized by a weak, porous, and malformed skeleton. It is known that both the development and maintenance of healthy bones is dependent upon the body's ability to absorb calcium and phosphorus.

*Seasonal Affective Disorder (SAD)*

SAD has been one of the most researched areas in the illnesses that light affects. SAD is attributed to a variety of recurring events, but has been clearly attributed to the amount of light available for individuals. Without the proper amount of light available, our circadian rhythms are affected and susceptibility to SAD is increased. SAD occurrences are dependent on the availability of outdoor light in the winter and latitude.

> The farther north people live, the more likely they are to experience winter depression. For example, while SAD affects only 8.9% of the residents of Sarasota, Florida, more than 30% of those living in Nashua, New Hampshire, are affected. Although this condition is seen primarily in adults between the ages of 20 and 40, children have also been found to suffer from this affliction. For them, the irritability, fatigue, and sadness are frequently accompanied by a decline in concentration and school performance (Liberman 1991).
>
> Even under unrestricted exposure, naturally occurring seasonal variations in the availability of outdoor light may have serious consequences. With increasing distance from the equator, annual contractions in the photoperiod during fall and winter can precipitate a recurring syndrome of clinical depression, Seasonal Affective Disorder (SAD) (Terman, et al. 1986)…We all experience one or another of these problems occasionally, for varying reasons, for varying durations, and with varying severity. But in SAD they appear as a highly reliable cluster of complaints every year in late fall or early winter, and they persist unrelentingly for several months. The symptoms divide into two clinical categories: (1) melancholic, which are also common in non-seasonal depressive syndromes, and (2) atypical/vegetative, marked by sluggishness and overeating. In severe cases the winter weight gain can reach 30 pounds, and the pressure for extra sleep (sometimes until afternoon) is so great that a normal workday schedule is impossible. In springtime, SAD patients show spontaneous remissions and most often their summers are problem-free (Terman, et al. 1986).

Because the availability of outdoor light affects SAD occurrences, light can play a vital role in preventing and curing SAD. Terman, et al. (1986) explained the importance of light in curing SAD.

> Appropriate administration of light therapy clears the symptoms within a few days. This is a remarkable achievement, considering the clinical severity, and makes us think we are close to the mechanism of pathogenesis. By comparison, antidepressant medications often take several weeks to work. Upon withdrawal from light therapy, as we have observed in mid-winter experiments, the typical patient relapses in two to four days. Thus, during the dark months of the year, the SAD patient must establish a regular maintenance regimen in order to obtain consistent relief.

## 5. Daylighting in the Office

Occupants in daylit and full-spectrum office buildings reported an increase in general well being. Specific benefits in these types of office environments include better health, reduced absenteeism, increased productivity, financial savings, and preference of workers. Benefits to the office worker are so great that many countries in Europe require that workers be within 27 feet of a window (Franta and Anstead 1994).

In buildings where daylighting is not or cannot be integrated, using full-spectrum bright lights has been shown to positively affect the workers in the buildings. Full-spectrum bright lights allow day and night workers to adjust their internal clocks or circadian cycles (see section: Affects of Light on the Body) to match their work cycles. Improvements in productivity, a decrease in accidents, an increased level of mental performance, improvements in sleep quality, and an increase in morale among night shift workers have also been attributed to better lighting (Luo 1998).

### *Health in the Office*

Studies show that the proper use of daylighting decreases the occurrence of headaches, SAD, and eyestrain (Franta and Anstead 1994). Headaches and SAD are related to insufficient light levels. These ailments are reduced when the lighting level is improved by using proper spectral light. However, the number one health problem in offices is eyestrain (Ott Biolight Systems, Inc. 1997a).

Eyestrain is related to the spectrum of light present in a workspace and the ability of the eye to refocus. The proper integration and management of daylighting in an office building provides the best spectrum of light for the eye. When the eye is not allowed to refocus to different distances over long periods of time, the dilating muscles are conditioned to a limited range of perspective, promoting near or far sightedness. Eyestrain is diminished with landscape views through windows because the combination of short- and long-range views allows the eye to refocus (Franta and Anstead 1994).

Stress reduction and attentional focus can also be increased by the presence of natural vegetation in the workspace or through windows. One study found that subjects had lower blood pressure readings and felt more attentive in a windowless room that had plants as opposed to one without (Heerwagen, et al. 1998).

Another important yet simple effect from daylighting could be a more positive mood for employees. Increased job satisfaction, work involvement, motivation, organizational attachment, and lowered absenteeism could result from an improved mood (Heerwagen, et al. 1998). In 1988, Clark and Watson found that negative moods are associated with discomfort and distraction, whereas positive moods are associated with the physical setting at work and daily activities such as social interactions among employees. Owen Bailey (Bruening), research associate at the Rocky Mountain Institute, said, “If you improve the space that employees work in, then they are likely to be happier, healthier, and more productive.”

***Productivity in the Office***

Studies show that office worker productivity can increase with the quality of light. Studies of the effects of light on productivity date back to the 1920s when studies were conducted on silk weavers. No change has occurred in the workplace from then until now; a relationship between work output and the amount of daylight still exists. On tests of direct attention, Tennesen and Cimprick (Heerwagen, et al. 1998) found that people with views of natural vegetation scored higher. The view from windows is not the only important part of daylighting techniques. Natural light increases attention and alertness during the post-lunch dip and has shown to be helpful in increasing alertness for boring or monotonous work (Light, Sight, and Photobiology 1998). Lockheed Martin, VeriFone, West Bend Mutual Insurance, Pennsylvania Power and Light, and the Reno Post Office reported increased worker productivity when improved lighting conditions were implemented.

In 1983, Lockheed Martin designers successfully increased interaction among the engineers by using an open office layout with integrated daylighting in their offices in Sunnyvale, California (Romm and Browning 1994). This increase helped boost contract productivity by 15%. Lockheed officials believe that the higher productivity levels pertaining to daylighting helped them win a $1.5 billion defense contract (Pierson 1995).

Located near Los Angeles, California, VeriFone, Inc., constructed a new daylit Worldwide Distribution Center and reported increased productivity a year and a half after they started using their new building. Productivity at VeriFone increased by more than 5% and total product output increased 25%–28%, making the new building more cost effective than first predicted (Pape 1998).

Employees of West Bend Mutual Insurance moved into a new building that gave them personal control over their workstation (temperature, task lighting) in the early 1990s. This building has artificial lighting on at all times, but the building is designed so that more employees will be close to windows. From the old building to the new one, the number of employees having a perimeter workstation with a window view increased from 30% to 96% (Heerwagen, et al. 1998). West Bend has determined that they had a 16% increase in claims processing productivity in the new building compared to the old building (Romm and Browning 1994). Having employees closer to windows may have contributed to the productivity increase. The new workstations with employee control alone were determined to be responsible for a 2.8% increase in productivity over the old building (Lovins 1995). The senior vice president at the time, Ronald W. Lauret, was also convinced that he could pay his employees $1,000 less a year and they would stay at his company because his environment was superior to other places they could work (Drews 2001).

Pennsylvania Power and Light installed high-efficiency lamps and ballasts in the early 1980s to reduce glare for drafting engineers. The effects from the low-quality lights previously used were not only causing glare, but also morale problems, eye strain, headaches, and increased sick leave for employees (Lovins 1995). With improved lighting, productivity for the drafting engineers increased by 13.2% (Lovins 1995). Previously, the drafters took 6.93 hours on average to complete one drawing, which results in 0.144 drawings per hour. The upgrade decreased the time to complete one drawing to 6.15 hours, which increased productivity to 0.163 drawings per hour (Lovins 1995). The lighting retrofit also resulted in a decrease in sick leave from 72 hours to 54 hours per year, a difference of 25% (Lovins 1995).

In 1996, the Reno Post Office in Nevada was renovated to include a better quality of light in the building. Indirect light was enhanced and better quality electric lighting was installed. The quality of light helped the mail sorters become more productive. Reports from the first 20 weeks in the new building show productivity increasing more than 8% and leveling to 6% above the old numbers a year later (Romm and Browning 1994). The postal workers operating the mechanized sorting machine sorted 1,060 pieces of mail in the time it used to take to sort 1,000. The rate of sorting errors decreased to one mistake in every 1,000 letters (one-tenth of a percent). With the increased efficiency of the workers, the Reno Post Office had the most productive sorters from Colorado to Hawaii, the entire western region of the United States.

### *Absenteeism in the Office*

Some companies have seen a reduction in office worker absenteeism after moving to new office buildings that integrated daylight. Lockheed Martin, the International Netherlands Group (ING) Bank, and VeriFone, Inc. are a few of these companies.

In 1983, when Lockheed Martin moved some of its California employees into a daylit building, a 15% decrease in absenteeism from the old building was witnessed (Romm and Browning 1994).

VeriFone Worldwide Distribution Center reported a reduction in absenteeism of 6.8 hours per person per year (Sundaram and Croxton 1998), an approximate attendance increase of 47% (Ander 1998).

The International Netherlands Group (ING) Bank has no desk farther than 23 feet from a window in its building constructed in 1987. ING reported a 15% decrease in absenteeism (Romm and Browning 1994) and a dramatic growth in business (Browning 1992). Also, as a result of the new building, a "progressive, creative bank image" was created (Browning 1992).

### *Employee Turnover*

Story County Human Services in Iowa moved into a daylit building in 1999. The three social service groups in the building have attributed many of their non-energy-related benefits to their daylighting. Brent Shipper of Wells Woodburn O'Neil (2001) stated, "…without an increase in staff, one social service group tripled the amount of people seen and served." Another group doubled the amount of people that came through their office. Also, one group experienced a 200% decrease in the turnover of their staff. Furthermore, that group also received a record number of job applicants as well as a high number of people wanting to transfer into their building from other counties.

### *Financial Savings*

In 1998, the average commercial building's construction cost was $\$150/ft^2$ (McHugh, et al. 1998). This was the largest initial cost incurred, making construction a primary concern. By cost comparison, the 1998 average annual utility cost of office buildings is about $\$1/ft^2$ (McHugh, et al. 1998). The energy and operating costs of a building are small when compared to the cost of employees and initial construction. For daylighting to pay for itself, the dollar value associated with office worker productivity must increase beyond the added cost of implementing daylighting technology. Many companies have found that the increased dollar value of productivity does indeed outweigh the increased cost of technology, as is illustrated by the following examples.

Productivity gains of $400,000 to $500,000 per annum at the Reno Post Office paid for the building renovation in less than a year (Romm and Browning 1994).

West Bend Mutual Insurance saw increased profit levels due to improved productivity in their enhanced work environment. West Bend realized that its 2.8% gain in productivity is worth approximately $364,000, with its annual salary base of $13 million (Romm and Browning 1994). This calculation demonstrates the impact of employee productivity on company profits.

Lockheed Martin reported financial savings due to increased productivity by moving some of its offices to a daylit building. Lockheed calculated that "every minute less of wasted time per hour represents a 1.67% gain in productivity… where a 2% increase in productivity equates to $3 million saved (per year)" (Thayer 1995). Construction costs of the new daylit building represented 2% of the total building cost (Thayer 1995). After that expenditure, 6% of the costs are dedicated to maintenance, and the remaining 92% goes toward employee salaries (Thayer 1995). Lockheed also reports that it has saved half a million dollars on energy bills and reduced absenteeism (Thayer 1995). Lockheed officials commented on their increased productivity and financial savings in an article by Burke Miller Thayer (1995).

> …The energy savings…are overshadowed by the rewards of improved employee productivity. To illustrate this point, we'll assume the average salary of the Lockheed engineers and staff is $50,000/year and that absenteeism (a simple measure of productivity) is down 15% (an unofficial figure attributed to company officials) from a level of 7% (14 days per year). A 15% improvement on 7% absenteeism yields a 1% improvement in productivity. Every 1% gain in productivity in Building 157 is worth $500 per employee ($50,000 salary times 1%), or $1.5 million ($500 times 3,000 employees) per year. This is three times the energy saving. And although these numbers are merely illustrative, Lockheed

officials have privately acknowledged that their gains in productivity offset the $2 million extra cost for the building in the first year of occupancy.

In the following excerpt and in Figure 1, Romm and Browning (1994) illustrated the relationship between cost per employee and average cost per square foot by estimating the savings for any commercial building lighting retrofit.

> …A three-year payback, typical in lighting retrofits, is equal to an internal rate of return in excess of 30%. This type of return is well beyond the "hurdle rate" of most financial managers. In addition, the same retrofit may cut energy use by $0.50 or more per square foot, which has significant positive effects on the Net Operating Income of a building. However, the energy and operating costs of a building are small when compared to the cost of employees.
>
> Based on a national survey of the stock of offices for 1990…electricity typically costs ~$1.53 [per square foot] (85% of the total energy bill); repairs and maintenance typically add another ~$1.37 [per square foot]; both contribute to the gross office-space rent (including all utilities and support services) of $21 per square foot. Yet paying the office workers costs ~$130 [per square foot]. Thus the office workers' salaries cost ~72 times as much as the energy costs. Or, an approximately 1% gain in productivity is equivalent to the entire annual energy cost.

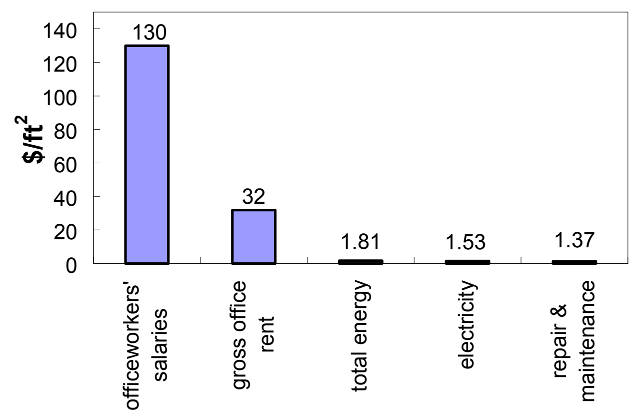


Figure 1. Approximate operating costs for an office building with 1990 data in \$/rentable ft$^2$/yr (Romm and Browning 1994)

***Employee Preferences and Perspectives***

Studies show that windows are highly valued by office workers in the workplace. A survey of office workers (Collins 1975) found that 35% of employees responded instantly that the lack of windows was their biggest difficulty with their office space. The specific reasons given for the dislike of the windowless offices were: "no daylight, poor ventilation, inability to know about the weather, inability to see out and have a view, feelings of being cooped-up, feelings of isolation and claustrophobia, and feelings of depression and tension." Another study on the affects of windowless offices supports the findings of the Collins study by stating that employees in windowless buildings had much less job satisfaction and were substantially less positive (Finnegan and Solomon 1981).

Wotton and Barkow (1983) found that employees highly value any size of window that they can have access to and value it more than privacy in their office. The tolerance of windowless areas is lowered by "the workers' knowledge that the executives have large offices upstairs with splendid views of the city… [whereas] the lower level personnel are left without windows and highly dislike their location" (Collins 1975). Wotton and Barkow (1983) also found that 74% of the surveyed employees prefer having a window close to their workspace. If offered a window, 57% of surveyed employees would like the window to be beside their workspace rather than in front or behind their workspace.

Markus (1967) used a questionnaire to determine how satisfied office workers were with their workspaces. Ten environmental factors, including sunshine and view, were presented to employees for a satisfaction analysis. The survey lacked the ability to portray how strongly each employee felt about issues, but it did provide an understanding of their overall satisfaction. From the questionnaire, approximately 96% of respondents preferred to work under natural light as opposed to electric lighting (Markus 1967). Furthermore, approximately 86% of the respondents preferred having sunshine in their office year round as opposed to only one season of the year or not at all. Also noted by the study was that employees sitting near windows were more content, whereas those sitting further away from the windows complained more. Therefore, workers with daylight and a view may suggest having a window is not important, but workers without either believe having more light and a view is very important.

In a 1983 study, Kit Cuttle examined England and New Zealand office workers on their attitudes toward their workplaces. Cuttle concluded that office workers believe large windows are important for an office environment. The workers preferred sitting close to a window, although in many office environments people of lower status are denied this privilege. Also, four out of five office workers preferred working in natural light because they believe working by electric lighting caused discomfort (Cuttle 1983). The employees believed that short-term discomfort from the electric lighting was more of a concern than the long-term deleterious effects. Furthermore, employees did not believe working by electric lighting resulted in poor work output; they believed that their work output was achieved at greater personal stress levels (Cuttle 1983).

Employees in daylit office buildings have expressed their feelings about their workspaces. The employees in the Lockheed Martin building had quite favorable responses to their workspace.

> [Ben Kimura, staff engineer, said] "My workspace is 15 feet from the literium (a central area in the building which has daylight streaming in from skylights), and the lighting is great. The office décor, arrangement, and temperature are ideal. There are many people working on this floor, but the feeling is not one of crowding, but of spaciousness. Interface with other departments is greatly facilitated because we're finally all in one building. By nature I'm very cynical, but the conditions in this building are far superior to any I've experienced in 30 years in the aerospace industry" (Romm and Browning 1994).

> [Joanne Navarini, financial controller, said] "I love my work space. I think the building itself is very functional. I am five workstations from the window and the light is fine. I use my task light and could order an additional desk lamp if I felt like I needed to. I like the daylight" (Romm and Browning 1994).

Employees in the VeriFone building have also shown greater satisfaction with their daylit workspace. One employee stated, "Working in this building is like working outdoors–the light streaming into my workstation is wonderful…"(Sundaram and Croxton 1998). Another employee also enjoyed the building and stated, "In my previous office, it felt cooped in, always artificially lit…but here, if I look up, I can see glimpses of the sky outside and that makes me feel good…"(Sundaram and Croxton 1998).

Another building that integrated daylighting was the Iowa Association of Municipal Utilities, which was occupied in February 2000. This building was designed to have an inviting feeling and set an example of energy efficiency techniques. Daylighting fit the design goals of the building. According to Patti Cale (2001), Energy Services Coordinator for the building, "When people walk into the building they say wow and comment on how the building is nice, light, and airy. The building does not divide the occupants from the outside environment; the employees can watch what is going on in the world outside the window." Cale (2001) said she would "choose to be in this building over a traditional building" because she can "see what is happening outdoors."

Even integrating a central atrium that brings in natural light can affect the attitudes of office workers. The 3M Austin Center used a daylit atrium as the central point of its building complex. Task lighting is used in workspaces, but windows close to the ceiling let natural light deep into the building. David Wilson (2001), Director of Human Relations and Head of Corporate Services for the 3M Austin Center, said, "Visitors comment on how nice it is to have natural sunlight and they find the building bright, airy, open, and spacious." Wilson had an office on the outside of the building with floor-to-ceiling windows on two walls. He said, "I couldn't have a better office. I have a stressful job and the view of hills and distant skyscrapers through my windows help me to relax. I wouldn't work anywhere else." Some employees had windows opening to the atrium as opposed to the outside.

Nick Lampe (2001), an employee of the 3M Austin Center, said, "The atrium creates a more welcoming, relaxed, and comforting environment because artificial lights are not clicking overhead." Part of his day was spent in an office one workspace away from a window and the other part was spent in an office with windows opening to the atrium on two walls. Lampe (2001) said that in the office with more window space he "does not feel as drowsy and is more alert.” He did note, however, that for part of the morning, direct sunlight entered the windowed office space and his eyes had to adjust to the direct light. Even with the direct glare, Lampe preferred working in the office setting with more windows because of the natural light. The fact that the 3M Austin Center was built more recently than his previous working environments also affected his attitude toward the center. However, Lampe (2001) noted that the natural light is the most effective part of changing his attitude toward his working environment. He found taking breaks in the daylit atrium to be “refreshing.” Overall, Lampe (2001) prefers having the more natural environment in the center and said “it is motivating, calming, and puts me in a better mood.”

However, integrating natural light into all parts of an office has the greatest impact on building occupants. In the Story County Human Services building, visitors comment that the building has a friendly environment. Employees said that they “love the windows” and “the building is wonderful” (Shipper 2001). Although more notable was the employee who stated that “you’ll never be able to put into numbers what the windows do for us” (Shipper 2001).

### *Improper Daylighting*

Studies show that daylighting can provide substantial benefits to staff and employers alike, but improper usage can lead to unpleasant conditions within the structure. The benefits of daylighting will only be realized if it is implemented correctly. Improper use of daylighting can reduce productivity and increase employee absenteeism due to the possibility of extremely high lighting levels, excessive glare, and high temperatures.

A 1992 study of energy efficient buildings investigated the tactics office workers used to reduce discomfort. All the tactics distracted employees from their work and were not effective. To improve comfort, some employees changed clothing, walked around, went for a break, complained, got something to drink, or added a heater or fan to their workspace (Heerwagen, Loveland, and Diamond 1992). With these ineffective coping methods, dissatisfaction, loss of work efficiency, reduced motivation, and fatigue were possible results. If employees tried to ignore the problem, mental energy would be absorbed that could have been focused on their work. To aid in keeping employees on task, a comfortable work environment is necessary.

The Iowa Association of Municipal Utilities building also had problems with glare, even though it was designed for indirect lighting. To alleviate the problem of high glare on the east side of the building, semi-opaque fabric was hung about six feet away from the windows for two to three months of the year (Cale 2001). Venetian blinds were also installed on another portion of the east side of the building. These blinds aid in darkening a room for multimedia presentations as well as reducing glare. To prevent other glare issues, new employees to the building were trained on how to orient their computer monitors in their workspaces to minimize glare. This building was a good example of how to overcome some glare issues.

The VeriFone building had some problems with glare in the afternoon and one employee stated, “…I get direct sunlight towards my workstation and must take a break because of the glare on computer and cannot work (cannot see at all)…” (Sundaram and Croxton 1998).

The Hughes Corporate Headquarters building also demonstrates potential problems if daylighting in buildings is not properly designed and managed. The Hughes Corporate Headquarters building, occupied in 1986, was designed to use daylighting, but its implementation was not planned properly. The initial positive perceptions of the building by employees became negative when the lighting levels and glare became too much to tolerate. The employees wore sunglasses at their desks, added temporary shades around their desk, and tried to match the high level of lighting with additional desk lamps to reduce eye fatigue. While one employee considered becoming a vitamin D donor, another employee stated that, "It is a beautiful building, management needs only to put down sand, beach umbrellas, and hand out piña coladas."

Occupants of both daylit and nondaylit buildings that are improperly designed have had complaints. One problem was that "office staff seem much less ready to accept what they are given and much more prone to criticize" (Collins 1975). Lighting-level criticism could also result from the simulated or real daylight dimming systems keeping a constant workplace illumination. A study by Begemann, vad den Beld, and Tener (1996) concluded that these dimming systems are too simplistic to meet human preference and response. However, a different study found that employees in one daylit building are willing to accept the glare because of the overall building quality (Bryan 1998).

## 6. Daylighting in Schools

School children and teachers can benefit from integrating and managing daylight properly. Reported benefits include reduced utility costs for school districts, improved student attendance and academic performance, and a less stressful environment for students.

A Daystar article, "Benefits of Natural Daylighting" (1998), states that there is increased student and teacher attendance, increased achievement rates, reduced fatigue factors, improved student health, and enhancement of general development. Furthermore, natural lighting eliminates noise and flickering from electric light sources and provides the best quality of light available in classrooms, gymnasiums, and corridors. Other research has shown that students in windowless classrooms are more hostile, hesitant, and maladjusted. Also, students in windowless classrooms tend to be less interested in their work and complain more.

### *Health*

Daylight has physiological and psychological benefits for teachers and students. Thomas Benton, principal of the daylit Durant Road Middle School in Wake County, North Carolina, claims that teachers who have been at his school for more than a year mentioned that they feel better mentally and physically (Bailey 1998). Physiological benefits due to daylight on school children are less dental decay (cavities), improved eyesight, increased growth, and improved immune system.

The sun is a primary source of vitamin D, and increasing vitamin D intake stimulates calcium metabolism (see also Affects of Light on Internal Body Systems). There is a strong correlation between the amount of sunlight a child is exposed to and the level of dental decay, making daylighting a very important element for cavity prevention in children. Reports show that students' rates of dental decay have decreased in fluorescent full-spectrum and daylit schools.

Research in the 1930s (Liberman 1991) provided evidence of the effects daylighting in school buildings has on students. McBeath and Zuker (Liberman 1991) conducted a study showing children are more prone to dental cavities in the winter and spring when they spend more time inside a school and less prone during the summer months when they are outside in the sun. These results are supported by a study that compared full-spectrum lit schools in Canada to traditional schools with fluorescent lighting (Hathaway, et al. 1992). Full-spectrum fluorescent light closely resembles daylight, but it does not provide the same spectral content. The full-spectrum fluorescent schools reported that student dental decay decreased nine times [compared to schools with fluorescent lights] as a result of the increase in vitamin D.

Studies supporting full-spectrum lighting effects on dental decay include research on golden hamsters by Sharon, Feller, and Burney in 1971(Liberman 1991). Two groups of hamsters were fed the same cavity-producing diet for 15 weeks but were raised in different spectrums of light. One group of hamsters was raised under cool-white fluorescent lights; the other group was raised under full-spectrum fluorescent lights. The hamsters that were raised under cool-white lights had five-times more severe dental cavities than the hamsters raised under full-spectrum fluorescent lighting.

Quality of light is also important for students' eyes. Eyes collect and convert visible light into electrical impulses called photocurrents (Ott Biolight Systems, Inc. 1997b). These photocurrents flow through the optic nerves to the brain. Studies at University of California–Berkley Laboratories suggest that light sources with richer spectral content provide more usable light to the eye. Daylight provides the richest spectral, usable light, and it eases some of the stress to the eye. Research shows that reading is the most visually stressful task for students (Liberman 1991). Stress causes a contracted visual field in the eye that can lead to a decrease in information processing and learning ability (Liberman 1991). The direct affect of eye strain can be seen from a 1975 study showing that 88% of postgraduate students in the United States are nearsighted, although only 45% of the general population are nearsighted (Liberman 1991). Being nearsighted can be attributed to the high amounts of reading done by these students; poor lighting may also be a contributing factor.

A school with insufficient light can also reduce a student's ability to learn due to the effect lighting has on physiology. Poor spectral light can create strain on students' eyes, leading to a decrease in information processing and learning ability, causing higher stress levels (Liberman 1991). Dr. Walker (1998) found that stress impacts certain growth hormones. He determined that "persistent stress stunts bodily growth in children" because the activity of the growth-inhibiting hormones cortisol and ACTH increase under stress. Students in the Canadian full-spectrum fluorescent schools grew 2.1 cm more in two years (Hathaway, et al. 1992) compared to students who attended traditional fluorescent-lit schools. The increased activity of these hormones supports researchers' observations that children under electric lights all day have decreased mental capabilities, agitated physical behavior, and fatigue.

Daylight also produces ultraviolet radiation. Dr. Ott claims, "trace amounts of certain wavelengths of light…can have a staggering affect on your health" (Liberman 1991). Ott also said that the trace amounts of UV light, measured as parts per trillion, are important because "we need a basic amount [of UV light] to support life and maintain a healthy immune system" (Liberman 1991). Faber Birren states that this basic amount of UV light needed has been demonstrated to "intensify the enzymatic process of metabolism, increase hormone system activity, and improve the tone of the central nervous and muscular systems" (A Summary of Light-Related Studies 1992).

***Attendance***

Schools that have integrated full-spectrum fluorescent or natural light show an increase in student and teacher attendance when compared to traditionally lit schools. A study of the full-spectrum fluorescent Canadian schools reported that students had an attendance increase of 3.2 to 3.8 more days per year than the students in traditional fluorescent lighting schools (Hathaway, et al. 1992). Durant Road Middle School is a daylit school in the Wake County, North Carolina, school system. Durant reported the best health and attendance in the entire school system, an attendance rate above 98% (Bailey 1998). Teachers also have lower absenteeism rates, claiming the lowest number of faculty health absences in the area.

***Achievement***

A study on the North Carolina Johnston County schools specifically analyzed the academic benefits of daylighting (Nicklas and Bailey 1997). The Johnston County school study compared the scores of students from newly constructed daylit schools to schools that were artificially lit. Students in the daylit schools had higher reading and math achievement scores.

Four Oaks Elementary is a daylit school in Johnston County and is a unique case because fire destroyed the original school and students were temporarily placed in mobile classrooms for two school years. During this time, a new daylit building was constructed. In Figure 2, test scores are compared between the old, temporary, and new school buildings in order to gauge the academic performance affects of daylighting (see Table 1 for timeline of school building occupancy).

Before the original building was destroyed in December 1988, California Achievement Test (CAT) scores of Four Oaks students were 7% above the average. When the students moved to the mobile classrooms, scores dropped to 10% below the average. Results from the new daylit building showed substantial improvement in test scores. First year test scores increased to 9% above the county average. Between 1988 (the last year in the old building) and 1992 (the last year of the study), Four Oaks had a 15% increase in test scores. The Four Oaks increase was 3% higher than the county's 12% average for the period.

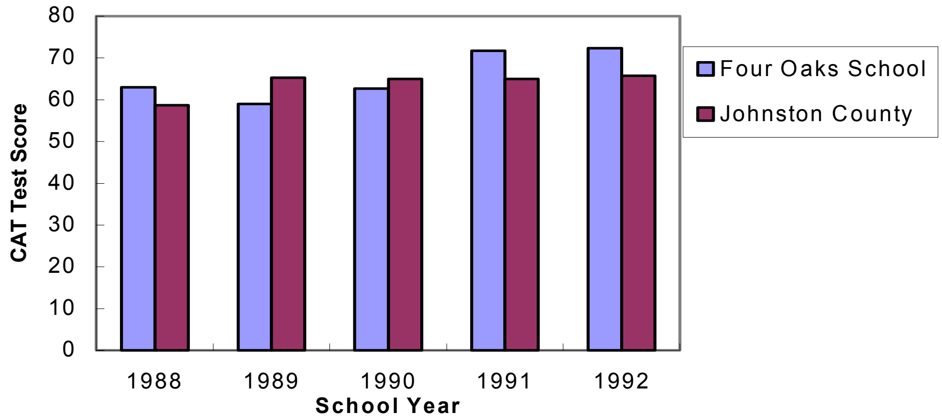


Figure 2. California Achievement Test scores for Four Oaks School vs. Johnston County (Nicklas and Bailey 1997)

**Table 1. Timeline of Events for Four Oaks School**

| Date | Event |
|---|---|
| December 1988 | School burns |
| 1989 and 1990 | Students placed in temporary classrooms |
| June 1990 | End of temporary facilities |
| August 1990 | Occupy new school |
| April 1991 | First CAT in new school |
| April 1992 | Last CAT test |

Other daylit schools that were built in Johnston County after the Four Oaks school were the Clayton Middle School and the Selma Middle School. Also, the North Johnston Middle School was built after Four Oaks, but did not incorporate daylighting. Table 2 compares the average reading and math scores for multiple grades between these schools and the county average.

Clayton's daylit school building had a 7% test score improvement that was above the county's 5% improvement. Selma Middle School also showed signs of benefiting from their daylit building with an 18% increase in test scores. The North Johnston Middle School, built without daylighting, only had a 5% increase in test scores, the same as the average for the county.

**Table 2. Average of Reading/Math for Multiple Grades (Nicklas and Bailey 1997)**

| School and Grade | 1992/93 Base Year Average Scores | 1993/95 Average Scores | % Improvement Base-Average |
|---|---|---|---|
| Clayton 6–8 | 68.4 | 73.2 | +7% |
| Selma 6–7 | 46.3 | 54.8 | +18% |
| N. Johnston 6–8 | 62.5 | 64.2 | +5% |
| County Avg. 6–8 | 62.1 | 65.4 | +5% |
| County Avg. 6–7 | 61.3 | 64.6 | +5% |

Reports of the End-Of-Grade (EOG) testing scores for the daylit schools are also much better than North Johnston Middle School (Table 2). Clayton reported an EOG scoring of 1.5% above the county average, and Selma was 5.2% above the county average. North Johnston, the non-daylit school, was 1.6% below the average. The North Johnston test scores indicate that a **new** building does not necessarily correlate to positive affects on student performance.

**Table 3. EOG Score Percentage Relative to Norm (Nicklas and Bailey 1997)**

| School | 1992/93 Base Year | Average 1993/95 | Improvement Base-Average |
|---|---|---|---|
| Clayton | +6.3 | +7.8 | +1.5 |
| Selma | -15.00 | -9.8 | +5.2 |
| N. Johnston | +.4 | -1.2 | -1.6 |

Average reading and math test score results between 1992 and 1995 are included in Table 3. The eighth graders at Clayton had a 21% increase in their scores, which was well above the 10% increase of the average. The Selma seventh graders also had improvements and reported a 32% increase, exceeding the 15% increase of the county average.

**Table 4. Average of Reading/Math for Specific Grades (Nicklas and Bailey 1997)**

| | 1992/93 | 1993/94 | 1994/95 | % Improvement Base to 1994/95 |
|---|---|---|---|---|
| Average Score | | | | |
| Clayton 8$^{th}$ | 69.2 | 67.8 | 83.8 | +21% |
| County Avg. 8$^{th}$ | 63.8 | 64.3 | 70.2 | +10% |
| Selma 7$^{th}$ | 45.6 | 51.8 | 60.3 | +32% |
| County Avg. 7$^{th}$ | 61.4 | 59.7 | 70.4 | +15% |

Other studies on schools report the effects of full-spectrum fluorescent lighting on academic achievement. One study reported that learning-disabled children with extreme hyperactivity problems are calmer and overcome some of their learning problems in classrooms that use full-spectrum fluorescent lighting (Walker 1998). The benefits are not limited to learning disabled children. Students have shown better behavior in properly lit libraries than traditional fluorescent-lit schools (Nicklas and Bailey 1997).

The Heschong Mahone Group also showed improvements in student academic rates in a 1999 study for Pacific Gas and Electric in California. For this study, test scores for students in grades two through five were evaluated in Orange County, California; Seattle, Washington; and Fort Collins, Colorado. For the California schools, data were collected during the school year to produce a learning rate. This analysis provided information with the highest confidence of the three school districts because only a few variables influencing the students were involved in the data. For the Washington and Colorado schools, end-of-year data were evaluated. Variables were added in these studies due to the nature of the data collection.

The Capistrano Unified School District in Orange County, California, had different building plans to bring in natural light. Results for these schools were divided into groups but were also evaluated collectively. Overall, the classrooms with the most amount of daylighting had a 20% faster learning rate in math and a 26% faster learning rate in reading during one school year when compared to classrooms with the least amount of daylighting (Heschong Mahone Group 1999a). These results can also be evaluated by looking at the learning rate of an average child in the Capistrano district. Students in classrooms with the most daylighting are progressing on the order of one to two points above the average rate in reading and math over the time span between fall and spring testing. By advancing more quickly, the Heschong Mahone Group stated that schools "could be saving up to one month of instructional time for the reading and math curriculum that could be used for other areas of learning." Also determined from the study on Capistrano schools was that the variable of daylighting had larger effects than the window variable. Therefore, the presence of natural light was responsible for the positive results of student performance, not the view from the windows.

As previously mentioned, the studies on the Seattle and Fort Collins schools used the absolute value of students' final scores on EOG tests. From this data, more variables were introduced, creating less confidence in the study results. The Seattle Public School district, in Seattle, Washington, had 9% higher math scores and 13% higher reading scores for students in classrooms with the most daylight compared to students in the least daylit rooms. In Fort Collins, Colorado, the Poudre School district had 7% higher test scores in reading and in math for students in daylit rooms compared to those with the least daylighting. The difference in scores from each district could be due to the difference in daylight exposure in the different locations. Children in Seattle and Fort Collins might show greater effects from daylighting because they see less sun in their geographical location compared to California, which makes them more sensitive to the light.

The Heschong Mahone Group summarized its study by stating that it "found the positive effect of daylighting was distinct from all other attributes of windows." Also, a positive correlation was found between daylighting and better test scores for all three school districts. The Heschong Mahone Group also noted that daylighting is complex and its study cannot prove why daylighting causes the positive affects on students. Reasons that were cited as possible causes for the good performance from students was the better distribution of light, improved visibility from improved light, better color rendering, and the absence of flickering from electrical lighting.

***Perspectives***

Researchers may give physiological and psychological evidence associated with the benefits of daylighting, but the most convincing evidence comes from the students, teachers, and administrators. The following are excerpts from student essays comparing natural light to fluorescent light from the tenth grade English class at Florin High School in Sacramento, California (A Closer Look at Daylighted Schools, 1997).

> Fluorescent lights try to reproduce that which the sun provides for us. At night we are able to read and see just as if it were day, because of this technology. The unnatural lights, however, give life a different perspective. Color does not appear normal. Things become more dull…the skylights allow the sun to penetrate and illuminate the room. There is less strain upon the eyes and no energy is required. Things look natural and the sleepy feeling fluorescent lights give is not felt.
>
> The advantages of the natural skylights are the quietness, the softness, and the calmness I get when I am in the classroom. I can work better and think better because it is more natural and I feel comfortable. The lights are more soft to your eyes and you can see better…The disadvantages of fluorescent lights are they can make me nervous and block my ability to learn…It hurts my eyes and it makes me want to get out of class early.
>
> Electric or fluorescent lighting is a much brighter light than a skylight…Skylights produce a dimmer light. Its light is softer and more natural. Its light seems to inspire peace, nature and creativity. It's much easier to think with this light.

Teachers also have ideas about what daylighting techniques can do for them. A teacher from the Capistrano School district in Orange County, California, stated the following:

> When I've had it with the kids and I can't answer another question, I just take a minute, look out the window at the view, and then I'm OK. I'm calm and ready to go back into the fray (Heschong Mahone Group 1999).

David Peterson (2001), the Director of Operations at Mesa Public Schools in Arizona, said that fewer problems are associated with the naturally lit classrooms in the district. Some schools in the district had skylights, some had windows, and others had windows covered due to vandalism. When in the windowless rooms, Peterson says the students are more edgy in their seats, don't hold attention well, and are not at ease. When other districts and parent groups come to see the daylit rooms, they cannot believe the light is natural. After seeing the buildings, they want to have daylight in their buildings. Daylighting was included in some schools because Peterson had seen studies discussing the benefits of natural light for students. "Even though it costs more initially," he says, "the daylighting was worth the money after a few years."

The Superintendent of the Pendergast School District in Arizona, Ron Richards (2001), says his district works hard to integrate daylighting into its buildings. Daylighting is desired for this district because it is better for the students' health and is easier on their eyes. Students with

Attention Deficit Disorder (ADD) are calmer because they are not distracted with the humming of the fluorescent lights. Overall, classrooms are calmer and cooler with the skylights. Anyone who goes into the daylit rooms is impressed with the natural light, and in fact, people are so impressed that they want to know how to get daylighting in their own buildings.

Universities, such as the Center for Energy and Environmental Education at the University of Northern Iowa, have also begun to integrate more daylighting into their buildings. Bill Stigliani (2001), the center director, said, "Along with the energy savings that have been noted in their building, students and visitors come into the building and want to stay." He finds the building to be "very refreshing and comfortable" and enjoys "the beautiful rainbow colors produced from reflectors in the atrium"; his preference is "to be in this building as opposed to other traditional campus buildings." To achieve the energy efficiency in the building, comfort is not sacrificed.

Another daylit university building is the Adam Joseph Lewis Environmental Studies Center at Oberlin College in Ohio. According to David Orr (1999), the chair of Oberlin's environmental studies program, the building design affects what students learn in "subtle but profound ways." Orr stated, "The extravagant use of energy in buildings…teaches students that energy is cheap and can be wasted…. Windowless rooms…teach that nature is to [be] kept at arm's length." By integrating daylighting, students are able to learn in a whole new way.

***Financial Benefits: Costs of Absence/Student/Day Breakdown***

The designers and the principal of Durant Middle School are convinced about the validity of daylighting because they have seen it pays dividends through lower energy costs and an enhanced learning environment (Bailey 1998). These are not the only people deciding that daylighting is worth the money. Connecticut passed bill number 6825 in January 2001 requiring that construction or renovations of school buildings must maximize the natural light or use full-spectrum fluorescent lighting. The purpose of this bill was to improve student performance (Bill No. 6825 2001).

Based on research from 1981 to 1985 (Hathaway, et al. 1992), it was concluded that there could be significant benefits for education in several areas.

> On the basis of the daily per pupil educational expenditure in 1984-85 ($21.42 per pupil space per day) and with a difference of 9.49 days of absence per year for students under different lighting systems, the cost of having these spaces vacant because of these absences amounts to $203.28 per pupil per year (i.e., an average expenditure of $203.28 is made to provide a pupil space which is not used). On the basis of reduced dental cavities, a further saving was calculated at $115.75 per pupil per year. These benefits total $320.03 per pupil per year.
>
> Although the cost of providing trace amounts of ultraviolet in classrooms amounts to no more than $30 per student per year, there is a net social benefit of $290.03 per pupil per year. It was further concluded that if these benefits could be generalized to all students in Alberta (approximately 430,000), the net social benefit would approach $125,000,000 per year. Moreover, these findings may be generalizable to other regions of Canada, the northern United States, areas

frequently shrouded in fog, and other geographical locations where the daily availability of natural ultraviolet light is minimal for extended periods of time.

***Windowless Classrooms***

Old beliefs and views of windowless classrooms still exist. It is important to address these findings and to realize that considerable changes to technologies, teaching techniques, and the knowledge of the effect daylight has on students has changed since these studies were completed. Some benefits of windowless classrooms reported in the old studies include more space for bulletin boards and bookcases, more even lighting levels, less noise, reduced maintenance costs, greater heating and cooling efficiency, and freedom from outside noise and distraction.

According to Demos and Associates (Collins 1975), even though some of the students surveyed disliked the windowless environment, no physical health problems were associated with it. Therefore, the study concluded that students should have no problem in the windowless environment. According to other studies, many students have no comments on the lack of windows in their classrooms. In addition to finding no attitude preferences, some studies found that windows or the lack of windows did not alter the performance of the occupants of the school buildings much.

Regarding the older studies, Tikkanen commented (Collins 1975) that most student reasons for windows in classrooms are psychological. Considering economic and security issues that exist for school developers, windowless classrooms will still be planned because no evidence was uncovered about possible harm from these classrooms. However, there was some evidence that small window areas are better than none and would fulfill the desire to see outdoors.

Some of the older studies did find a conflict in attitudes toward the windowless classrooms. Demos, et al. (Collins 1975) surveyed students in a windowless classroom and found that in their first year the students preferred the windowless classroom, but in their second year, the students strongly disliked the situation. Sommer (Collins 1975) found that a group of college students actually petitioned against having their class moved to a windowless room. The feeling of added spaciousness from a window in a classroom (Collins 1975) seemed to have considerable influence on the students.

Something interesting to note about windowless classrooms is that schools built in the 1950s and 1960s were designed to use daylighting. After that time, courtyards and skylights were covered in some of the buildings. According to David Drews of the Zimmerman Design Group (2001), it is difficult to remember teachers ever asking to be put into a windowless classroom. However, people who did not spend time in the classrooms, like principals, did not mind adding windowless classrooms for a potential energy savings. Also interesting is that some teachers feel that younger students do not settle down as quickly in a room that uses daylighting because they still feel like they are outdoors (Grocoff 2001).

When looking at the older studies, it is important to remember that the combination of new technology, new research, and new implementation techniques in the field of designing daylighting for buildings may offset the possible old benefits of a traditional or windowless facility. Recent studies suggest that there are advantages to a daylit school that outweigh the advantages of a traditional or windowless school.

### *Testimonials from Windowless Classrooms*

To look further into a windowless classroom environment, students at the University of Minnesota were asked how they felt about attending class in the multistory underground Civil Engineering building classrooms. These students revealed that the possible attention difference from windowless rooms might not outweigh the other effects. One student also noted that a more important time to have natural light would be in the winter, when many students and teachers alike are more prone to SAD (see also Affects of Light on Internal Body Systems).

> [A professor stated that] I prefer that all offices have windows for faculty, staff, and students. However, for classrooms, windows are less important, and having windowless classrooms may help minimize distractions. It is also helpful to be able to darken a room quickly for presentation of slides, similar to typical architecture for an auditorium (Hajjar 2001).
>
> [One student stated that] I don't think having or not having windows affects me at all. I do get drowsy without windows, but I would do the same in a classroom with windows too! On a day that you wouldn't want to be in class, having windows would be a little more distracting than not having them at all (Moeller 2001).
>
> [An additional student comment about] I can focus better [in windowless classrooms], but I find that sometimes I feel I've been cheated out of seeing a nice storm, or a pretty day, or just nice blue sky. Regarding classes, windowless is good. I think I would prefer windowless for the reason of less distractions (Hines 2001).
>
> [Another student mentioned] …I do not enjoy spending my whole school day in a building without windows. I feel more energized and work better in a room where I am able to see the natural sunlight. Windows in a classroom can be distracting for some people, but I think people are more productive when they do not feel that they are trapped in a "hole" during the day. When I attend class in a windowless room, I tend to become more antsy, and the atmosphere is uncomfortable to me (Johnson 2001).
>
> [A PhD student on the $7^{th}$ floor underground stated that] …for five years I have been working in a windowless office and my classes were in mostly windowless rooms too. I feel more drowsy not having a window. I agree that you have less distraction not having a window, but I am not sure it makes you more efficient. I personally like to work at home at least one day per week because I cannot stand being in my office every day; this is due to not having a window and also to the small size of the office that I have to share with another student. I personally think that the reinvigorating effect of looking at the sky and trees (if any) overcome the effect of having more distraction and I would vote for having an office with a

> window. Also I think being able to breathe the air from outside would be good (Nathalie 2001).
>
> [A civil engineering department senior stated]…I would say that 90 percent of the rooms that I have had college lectures in have been windowless, even in other departments. I do believe that a windowless classroom contributes to an environment that is more conducive to learning…. The main problem with having classes in a given day are in the building, is that there is no sense of the weather outside. I have found winter to be the most stressful, because between studying, going to class, and working in the building it was possible to go for entire weeks, arriving and leaving in the dark. It is true that there are no distractions from windows, but I feel the productivity gained by the missing windows was lost due to the stress of working under artificial light all day and potentially not seeing any natural light for several days at a time (Erpestad 2001).

## 7. Daylighting in Retail

Some retailers have discovered the benefit or the affects that daylight can have on the retail environment. Retailers are starting to use daylighting in their stores specifically to enhance their store environment, increase sales, create a more pleasant shopping environment, attract customers, and improve color rendering. Using daylighting also has aesthetic benefits that encourage customers to enter the store. Nancy Clanton, a lighting consultant with Clanton Engineering Inc., said that daylighting is “a whole different way of looking at box retail. Daylighting brightens the ceiling and brings people into the store” (Hennesy 1996).

Substantiating the claim of increased sales, the chief architect of Southern California Edison, Gregg D. Ander, applied daylighting to stores for the largest retailer in the country and possibly the world. Ander said this retail chain has had successful sales for the daylit stores when compared to the nondaylit stores in the district. When comparing about 11 stores in one district, the daylit stores sold 28% more product than the other stores (Ander 2001).

A 1999 study by the Heschong Mahone Group for Pacific Gas and Electric in California evaluated 108 stores of a retail chain in which two-thirds of the stores have skylights. All stores were designed and operated very uniformly. In the informal interviews that were conducted with the study in 10 skylit stores, only three shoppers out of the 42 interviewed were aware that the store they were shopping in used skylights. Also from the Heschong Mahone Group interviews came the various responses of the store feeling cleaner (80% of respondents), the store felt more spacious and open (65%), and the store was brighter (33%). Although they were unaware of the skylights, three elderly respondents said the brightness and light quality were important to them. Some respondents chose to shop at the daylit stores because they liked the feeling of the store. After talking to the customers, employees, and managers, not one had a negative comment about the skylights or objected to them.

Although the Heschong Mahone Group attributed the increased sales to skylights, they also noted that a different store characteristic could be creating the difference between store sales.

However, no specific characteristic beside skylights was determined to be the difference. After evaluating the sales data, adding skylights to a nondaylit store would improve store performance by 31%–49%. Therefore, if an average sale of $\$2/ft^2$ was present in a nondaylit store, the sales could increase to $2.61 to $2.98 with a skylight addition. If this particular retail chain were to include skylights in all of its stores, the sales would be expected to increase by 40% chain-wide.

The Heschong Mahone Group study demonstrated that the benefits from daylighting could be extended to customer loyalty, more relaxed customers, better product visibility, and improved employee morale. Along with these benefits also came the possibility of increased sales for an entire retail chain.

Unfortunately, comparison of retail daylit stores to nondaylit stores is difficult because most retail sales numbers are held in confidentiality. More retailers than the ones mentioned below have integrated daylighting into their buildings, but information for these stores was unavailable. However, data have been summarized for the following retailers:

- Wal-Mart
- Target
- Recreational Equipment Incorporated (REI) in Seattle, Washington
- Lamb's Thriftway Store in Portland, Oregon
- BigHorn Home Improvement Center in Silverthorne, Colorado
- Asheville Wine Market in Asheville, North Carolina (non-daylit)
- Washington Square Shopping Center in Tigard, Oregon
- King Sooper's in Aurora and Colorado Springs, Colorado.

*Wal-Mart:* In 1993, Wal-Mart Stores Inc. built their first Eco-Mart store in Lawrence, Kansas, to show that Wal-Mart can be profitable and environmentally responsible at the same time. The store was designed to be energy efficient and incorporate daylighting. Only half of the store was built with skylights to test the effects that daylighting would have on the store. Increases in sales, employee perspective, and shopping habits have occurred in the section of the store with skylights compared to the section without skylights. The affects of the skylights on retail sales, the employees, and shopper reactions were unexpected.

Retail sales in the daylit area of the store are higher than the area without skylights, and other Wal-Mart stores in the area. "…The sales pressure [sales per square foot] was significantly higher for those departments located in the daylit half of the store" (Romm and Browning 1994).

Employees and shoppers verbalized their preferences for the daylit half of the store. Employees from departments in the nondaylit half of the store asked for their department to be moved into the daylit areas (Romm and Browning 1994). A department manager in the daylit section said that he felt better psychologically, according to Patty Brenton, the Green Coordinator at the Lawrence store (1998a). The lighting levels from the skylights helped him feel more like he was outside when he came to and left work in the dark during the winter. Brenton has received comments about the skylights from customers in the store. In 1998 she said, "I've had customers come up to me and mention how much they prefer to shop in the areas with skylights."

The current Green Coordinator of the Lawrence store says that the store no longer stands out for its environmental innovation. She believes that "society has absorbed the idea" and now takes the natural lighting for granted. Kids who come through the education center at the store still think the skylights are "neat and interesting," but the associates are not as aware of the lighting anymore (Ruth 2001). She says that most stores are now converting to the energy efficient design, but Wal-Mart is not sure of the next step in environmental innovation.

After the success of the Lawrence store, Wal-Mart built an entirely daylit store in City of Industry, California. This store was designed to create a more pleasant environment. By 1996, the building was completed, and the store was evaluated for differences in purchasing. The data for this store, however, are unavailable.

*Target:* Similar to Wal-Mart, Target also investigated the effects of daylighting by starting with a partially daylit store. The Target store in Fullerton, California, had approximately one-third of the store under skylights after a 1992 renovation. According to a manager of the Fullerton Target in 2001, there are no disadvantages to the natural light in his store and no safety issues have resulted from it. He also said that he receives positive comments about his store. With the California energy crisis in mind, the manager said that the store could still mostly operate even during a blackout because the registers are on battery backup and the store has some natural light. Bruce Bilbrey of the Natural Lighting Company (2001) said, "…the results from this store were positive and encouraged other Target stores to incorporate daylighting into store design."

Another Target store was built in Phoenix, Arizona, around 1998. This store was entirely daylit and the mixed weather (more cloudy days) allowed for a better analysis of daylighting performance (Bilbrey 2001). To evaluate the sales in Target stores, skylights were covered for six months, and the store was operated entirely by electric lighting. Then the skylights were uncovered for six months and sales differences were measured. Although Target does not publish the results, Bilbrey estimated a "15%–20% increase in sales of a daylit store over a nondaylit store." Even without knowing the actual data, the Phoenix store worked well enough that another entirely daylit store was built in Turlock, California. It opened in October 2000.

The Turlock Target store had an advantage over other stores during the rolling blackouts of the California energy crisis because it could operate fully with the natural light and battery-backup cash registers. When the blackouts began, the skylights were uncovered after four months instead of operating for an entire six months with the skylights covered. According to Pam Zensen of the Turlock store (2001), the store had another advantage over other stores because even with the energy crisis the store is "very bright and everything looks good." When the store staff first uncovered the skylights, it almost seemed too bright because the natural light provided more light than she was used to. However, the brighter lighting has come to be appreciated and useful for the store. Guests in the store do not notice the natural lighting but will ask if the Turlock Target is conserving energy. The guests are surprised when the frosted daylight panels are pointed out because they think the store is still using fluorescent lights. The store is "awesome because it looks so bright but can still conserve energy" said Zensen. In guest service surveys, this Target receives the highest level of appreciation because it is bright and clean. Zensen said these results are due in part to the natural light.

The employees of the store love the natural light and find the Turlock store much better than other Target stores they have been in. Inside the store, the employees and customers can tell the difference between a navy blue item and a black item (Zensen 2001), which is difficult under traditional fluorescent lighting. The storeroom for the Turlock Target also incorporated daylighting strategies. Zensen says employees can find items in the storeroom faster in the better light and they can also see the colors of the items better. In addition to seeing colors better, the signs designed to be bright in the store appear brighter than in other Target stores. The improved color of the signs is important to Target because money was invested in making them more eye-catching. Overall, Zensen said that in the seven years she has been at Target, this store is the most bright and open store she has been in.

*Recreational Equipment Incorporated (REI):* While planning a new store in Seattle, Washington, REI sent a letter to 30,000 of its members asking what they valued in a store. "Responses indicated that members valued natural lighting," according to Michael Collins, public affairs manager for REI (1998). Employees also indicated that they valued natural light and did not want to work in a boxed-in structure. Because the members and employees desired natural light, it became a major part of the design in the new Seattle store.

Windows in the Seattle flagship store not only provide light and a connection to the outdoors, but they also warm the building throughout the morning. Natural light is also used to light the ground floor and the clerestory that acts as a billboard to the nearby interstate. Collins said the new building couldn't be compared to the old one because of various other differences, including larger volumes of people and sales.

The visual access to the outdoors enhances the building, and occupants have indicated a preference for this atmosphere. For example, according to Collins, the first thing people do is walk over to the window and look outside when entering the meeting room in the building. The positive effects of the natural light were enough to convince REI to begin incorporating natural light into future stores.

*Lamb's Thriftway Store:* Lamb's Thriftway store, a family-owned grocery store in southwest Portland, Oregon, was redesigned in 1997. A city ordinance required that windows face the street side of the store. Lamb's Thriftway took the idea of natural light one step further and installed skylights over the produce and floral departments of the store.

Colin Lamb (1998), owner of Lamb's Thriftway, says the portion of his store with skylights has worked great, and the employees and customers love the spacious and bright feeling in the store. They also like knowing what the weather is outside. Because of the spatial enjoyment of the area, customers prefer shopping in the store and tend to stay longer. The benefit to Lamb's store can be seen by the fact that most of the profits come from peripheral items, like the produce department.

The produce department also has very low employee turnaround, the employees seem happier, and sales have increased. After the renovation, the produce department accounted for 15% of the entire store sales for Lamb's Thriftway (Lamb 1998). In the redesigned building, the produce department's sales more than doubled while the rest of the store did not quite double.

Unfortunately, the effects that the skylights have on the floral department cannot be measured because that was a new department in the store when it was rebuilt. More employee complaints come from the windowless portion of the store, making it the part of the store with the biggest problems. Overall, Lamb said his "sales are excellent and higher than other stores like it."

Lamb is "very happy with the store results" and sees "no downside to the use of daylighting." If he had the chance to redesign his store further, he would use more skylights. Lamb "would make the skylights huge and overwhelm the store with natural light."

*BigHorn Home Improvement Center:* The BigHorn Home Improvement Center opened in April 2000 and integrated daylighting and other energy-efficiency techniques. Not all the benefits of the new BigHorn center can be attributed to daylighting because of the various energy efficient techniques and different products, but Don Sather, owner of the BigHorn Center, stated that customers have commented on the "nice feel" of his building (Sather 2001). His employees say that this building is "much more comfortable than the old building," and new employees say the building is "more comfortable than other places they have worked." Sather also mentioned that he has captured some of his competitor's business. His added business can be partly attributed to the comfort level in his building, which includes the daylighting. Sather says he would include daylighting on another building because of the benefits he has seen from using it.

*Asheville Wine Market:* The Asheville Wine Market was constructed with skylights that divide the store into thirds to allow natural light into different areas of the store. However, the store relies on electric lighting throughout the day because the skylights and windows were not designed to light the store by themselves. An employee of the Asheville Wine Market said that he enjoys the natural light and finds it "very inviting." He also finds the light to be a nice part of the store's environment, especially after comparing it to some of his previous working conditions. The employee also commented that customers like the atmosphere of the Asheville Wine Market, which could be partly because of the different lighting. The employee compared one competitor's store to a cave because it has fewer windows and no skylights. The natural light that was used in the Asheville Wine Market has added to the appealing atmosphere.

*Washington Square Shopping Center:* The developer of the Washington Square Shopping Center wanted to update the mall to lower maintenance expenses (Janicek 1995). The concourse sections were redesigned to balance the natural light from the skylights with the electric lights used in between. To accent the light coming through the skylights, chandeliers were added to bounce light and create a nice atmosphere. According to Walt Niehoff, a partner of Loschky Marquardt & Nesholm architects, sales in the mall increased even though the stores did not use natural light. The mall has done very well and received "rave reviews" even years after the renovation (Niehoff 2001). By emphasizing the few skylights that were already in the mall, the atmosphere of the mall improved over previous conditions.

### *Problems for Retail Daylighting*

A daylighting analysis should be completed before natural light is integrated into a store. The quality and quantity of light must be carefully considered in the design process. Building orientation, daylight management, and lighting effects (coloring) on merchandise should be considered in the design. King Soopers is an example of poor daylighting design.

King Soopers grocery stores in Aurora and Colorado Springs, Colorado, incorporated active daylighting into their stores to improve their environmental image. Active daylighting uses mirrors that adjust throughout the day to track the sun and redirect sunlight into the building. A group from the University of Colorado analyzed the cost effectiveness of the stores by comparing implementation costs and maintenance to construction costs and energy savings. The analysis showed that the active daylighting was not cost effective for the stores. According to Leonard Micek (1998) of the King Soopers design center, daylighting will not be continued based on the cost analysis of the stores.

Impact on sales, employee and customer preferences, and color renderings were not a part of the analysis stage. The King Soopers daylight report only looks at the cost effectiveness of the active daylighting system. Active daylighting requires the mechanical function of tracking the sun. This mechanical function adds both initial first cost and maintenance costs to the daylighting methods.

Target also had some problems with the daylighting in its Vadnais Heights, Minnesota, store. According to a manager of the Minnesota location in 2001, the employees and guests like the store when the sun is out and he receives good comments about it. When the sky becomes cloudy, however, customers will comment on the dim lighting in the store. "Just the fact that the customers notice the lighting is bad for the store," said the manager. Along with the dim lighting, the maintenance costs for this store location are high due to leaking skylights and blown ballasts. He said that the lighting in his store also makes it seem older than a store that was opened in 1997. Even with the lighting problems, he believed the lighting itself did not affect the store sales. The manager did not recommend using natural lights in stores, but he did say that his store is trying different skylights and working to fix the problems.

Negative affects from daylighting also appeared in a Mexico City mega-market that was designed to create an open market feel. Perry Kotick of Retail Planning Associates (2001) stated that mostly direct lighting was used in this building. As a result of the lighting, processed meats in the market turned green. Even with this type of problem, however, Kotick still believes daylighting is effective when designed correctly. He stated that "you can get a very pleasing, natural environment: you can take supermarkets to another level using daylighting" (Hennesy 1996).

## 8. Daylighting in Health Care Facilities

Reported benefits of natural light in hospitals and assisted-living communities are reduced lighting and heating costs as well as improved physiological and psychological states for both patients and staff. Studies show that daylighting can reduce the mental and physical strain of patients, doctors, and nurses. Daylighting has been so successful that hospital environments, as a part of the patient care program, now utilize it. Assisted-living communities are also integrating daylighting because it provides better light. "Daylighting offers a sense of spirituality, openness, and freedom from the prison-like confinements and intensity that characterize windowless spaces" (Verderber 1983).

The effect of light in hospitals is why German hospitals and medical facilities banned the use of cool-white fluorescent lights (Walker 1998). The benefits of daylighting and the feeling of openness extend to the staff, visitors, and patients. Studies also indicate that daylighting can lower a facility's operating costs because patients recover faster in daylit recovery centers. The spatial quality from windows has also been cited as having a psychotherapeutic quality by providing pastoral views and natural light; therefore, an environment becomes more therapeutic with more spatial quality (Vischer 1986; Verderber 1983).

Regulations on windows in hospitals have also been made in the United States. These regulations specify that a window should be included in rooms where patients stay for more than 23 hours. Different policies have also been created to specify the window area to be included in patient rooms with a bed. Although there are few recent studies on the effects of natural light in hospitals, these regulations demonstrate the importance of windows in the hospital healing process.

***Benefits for Patients and Workers***

Exposure to bright light affects the natural clock of patients and employees in hospitals. In certain illnesses, the biological regulatory system (circadian rhythms) plays an important role in maintaining the well-being of the individual. Alzheimer's is one such disease. Alzheimer's patients who are exposed to bright lights during the day have improved circadian rhythms and are less prone to depression (Light, Sight, and Photobiology 1998). These improved circadian rhythms reduce the time demands of the caregivers in Alzheimer's units. Windows provide patients with a view of light and weather changes that provide familiarity and help establish a time of year (Perron 1998).

In assisted-living facilities, lighting is very important for residents. To obtain the proper visual sharpness, the average 60-year-old person needs two to three times the light of a 20-year-old, and an 86-year-old person may require five times the lighting levels (Jones 1996). These lighting-level differences are due to age clouding the lens, creating a decline in retinal illuminance, which makes the effective adaptation luminance lower for older adults (Veitch 2001). Therefore, older adults generally require better contrast and higher task luminance to obtain the same visibility level as a younger person. For someone with failing vision, lighting is important for raising confidence in many simple activities, like walking down a hallway.

Falls are one of the most common and dangerous health problems for the elderly (Jones 1996) and can be attributed to improper or inadequate lighting. The vitamin D received from natural light is also a factor in the ability to recover from a fall because vitamin D is necessary for the absorption of calcium into bones and other body tissue. Better lighting can also alleviate the duty for caregivers. Studies show that some light-deprived nursing home residents wake up and fall asleep as many as 37 times a night (Jones 1996). Proper lighting can allow the elderly to function more independently by improving social contact, appetite, mood, self-confidence, and anxiety levels.

Medical facility staff can also benefit from better lighting. Studies have been completed on the performance of night shift nurses under bright lights. By shifting the circadian rhythms of the nurses with the use of brighter lights, nurses were able to improve the number of correct answers given in a standardized exam and decrease the time to take the test (Dilouie 1997). The night shift nurses demonstrate the effects that brighter lights have on medical facility workers and show the positive affects of better lighting conditions in medical buildings.

The Way Station, a mental health facility located in Frederick, Maryland, created a pleasing and healing environment that promotes the well-being of people with serious mental illnesses (Franta and Anstead 1994). The Way Station was designed to allow daylight into different sections of the facility. Daylight has enhanced the lives of the people in the building; the "members" and staff say the building "makes them feel great and they love having daylight in almost every room." The Way Station staff has commented on the affects daylight has had on its "members." Tena Meadows O'Rear, Chief Operating Officer at the Way Station said, "Our members deal with a lot of restriction, depression, and mental walls in their lives. It makes a tremendous difference being in a building that embraces the natural world and feels expansive and sunny" (Thayer 1994).

A 2001 study by Benedetti, et al. on the effects of bright artificial light on nonseasonal depression substantiates benefits for patients with psychological disorders. Length of hospitalization for 415 unipolar and 187 bipolar depressed inpatients was recorded for those assigned to rooms with an eastern or western window. Bipolar inpatients in eastern rooms (exposed to direct sunlight in the morning) had a mean 3.67-day shorter hospital stay than patients in western rooms. However, no effect was seen for unipolar patients. Benedetti, et al. (2001) concluded, "natural light can be an underestimated and uncontrolled light therapy for bipolar depression."

***Post-Surgical Results***

Improving the mental well-being of patients improves their recovery rates. Recent studies show that daylit post-surgical facilities improve this mental well-being. Intensive Care Unit (ICU) areas in hospitals can be very stressful for patients and workers (Collins 1975). Some patients can develop "post-operative delirium" in a stressful environment, which affects the intellectual ability of the patient. Many factors affect the development of the delirium: age, alcoholism, drug abuse, sex, preoperative anxiety, sleep deprivation, and perceptual distortion (Collins 1975). Daylight helps reduce the stress associated with this environment.

D. Wilson (Collins 1975) conducted a study to see whether windows had an affect on the post-operative delirium rates in hospital units. He found that the windowless ICU had twice as many patients developing post-operative delirium and depression. Windows provided a psychological escape that decreased the stress level for patients. This environment provides a necessary mental balance for patients and reduces the tendency toward brief psychotic episodes. Windows are important in the medical field because they can reduce the stress and depression in patient units (Collins 1975).

Studies show that gall-bladder surgery patients with landscaped views had fewer negative evaluations from nurses, took fewer pain relievers, and had fewer minor post-surgical complications (Pierson 1995). A study conducted by Ulrich found that patients with a tree view had a better post-surgical recovery, while patients in the same hospital with a view of a brick wall stayed longer, took more narcotic analgesics, and had more post-surgical complications (Heerwagen, et al.1986).

### *Healing Environment*

The goal of the healing environment is to provide non-institutional surroundings and a sense of calmness for patients, staff, and visitors. Natural light is one of many ideas used to create these environments. With many different ideas for creating a healing environment, identifying natural light as having specific impacts on patients is difficult to accomplish.

Creating a healing environment was a focus of the North Hawaii Community Hospital design. The small, rural hospital was built in the mid-1990s and includes many features that a traditional hospital does not. Hallways use skylights and large windows to provide an open feeling and natural light. Patient rooms have sliding glass doors that open up to an award-winning courtyard garden or the perimeter of the hospital. Full-spectrum fluorescent lighting is also used throughout the hospital to improve the environment. John McNeil (2001), Chief Executive Officer of North Hawaii Community Hospital, said the light in his hospital "also eliminate headaches (and seizures in extreme cases) from the flickering of artificial lighting." Because the hospital includes many features that differ from a traditional hospital, specific information on the lighting is not common.

McNeil stated that visitors comment on "how nice the hospital is," but the lighting is not solely responsible for these comments, although the natural light in the hospital is "very important" and contributes to the overall environment (McNeil 2001). A skylight is located at the intersection of the two main hospital hallways, and a large picture window is used to highlight the Buddha statue symbolizing spirituality and healing. McNeil noted that "people are drawn to the sunlight" in both of these locations. Windows are also included for the benefit of surgeons and the synchronization of their circadian rhythms. "Happy employees lead to happy patients," commented McNeil. With all the innovative features in the hospital, it was rated among 15 national hospitals as a "Hospital with a Heart" for its philosophy of patient-based care. In patient satisfaction surveys of 1,000 hospitals nationwide, McNeil was proud to note that his hospital "had the highest satisfaction in the nation."

## 9. Daylighting Industrial Environments

Historically, factories eliminate windows to provide a cleaner, dust-free environment. Studies show that daylight in factories can affect the physiological and psychological health of factory workers. Sweden built the first underground, windowless factory in 1946 and found that the employees in their factories developed many health problems. The workers in the factory complained of headaches, fatigue, and strongly voiced their negative attitudes (Robbins 1986).

### *Physiological Effects*

Russian and Czechoslovakian studies show that workers in windowless factories have more headaches, faintness, and sickness compared to workers in factories with windows (Plant 1970). The cost of the products being produced will increase because of lost time from employee health. A study from Thuringia, Germany, concluded that windowless factories should only be used when necessary (Collins 1975).

Volkova (Hathaway, et al.1992) studied the blood of workers in an underground, windowless factory to find out whether there was a relation between health problems and lack of ultraviolet radiation from the sun. The study concluded that the windowless factory workers experienced increased permeability of skin capillaries, decreased white cell activity, and increased catarrhal infections and colds [compared to workers in factories with windows]. Studies by Trysin in Swedish underground factories found that lighting levels, ventilation, and inappropriate color schemes affected the employees negatively (Collins 1975). The study advised that workers should take longer rest periods in daylit rooms or outside.

### *Psychological Health*

In his study on windowless environments in 1964, Pritchard reviewed personnel managers' reports on workers' claims about their health. The workers complained of claustrophobia and unhappiness from the windowless environment, but they didn't have excessive complaints or mass resignations. N. Ruck noted that workers in windowless factories complained of headaches and general depression. Also indicated were absenteeism problems and increased vandalism in the windowless factories (Abdou 1997).

A study of blood tests for 100 underground workers over eight years indicated no alteration in the normal blood condition but determined that the psychological health of these workers was sensitive (Collins 1975). In other findings on the psychological well-being of windowless workers, F.D. Hollister found that underground conditions were so detrimental to the psychology of the factory workers that they crafted their own solution for their need to have contact with the outside world. Hollister said, "…employees broke so many wall panels that it became necessary to provide some visual contact with the outside world." After looking at the effect of windowless factories on employees' health and the attitude toward them, these factory types should only be used if necessary for a cleaner environment.

### *Productivity and Safety*

By enhancing the light in industrial environments, the time required to perform a specific task may decrease. Changes in performance are due to improved color rendering as well as better safety for workers from better light. Some of the earliest studies concerning the effects of light on building occupants were done in an industrial environment by looking at the relationship between illumination and silk weaving, linen weaving, and type setting by hand (NEMA 1989). These studies gave evidence for a clear relationship between work output and the amount of daylight available. The next studies evaluating the effect of lighting on task performance were a series of studies known as the Hawthorne experiments that took place from 1924 to 1933 (Abdou 1997; NEMA 1989). The Hawthorne experiments measured the accuracy of workers' inspection and assembly of electromechanical components under different lighting conditions for test and control groups. The control group worked under existing lighting while the test group worked under a wide range of lighting conditions, some better and some worse than the control group. The study revealed a steady increase in the test group's output as well as an unexpected increase in the control group output. The researchers concluded that the unmeasured quality of worker-management relations was responsible for most of the increase, whereas physical variables had little effect on worker output (Abdou 1997). After the Hawthorne experiments, studies again showed a relationship between worker ability and available light.

In a study by Bennett, Chitlangia, and Pangrekar (Abdou 1997), people took less time to carry out various tasks of probing needles, map reading, and measuring the diameter of bolts, among other things, when luminance was increased. Boyce and Simmons (Abdou 1997) studied the effect of light on color judgment. To do this, a series of colored discs, differing in hue, had to be arranged in a consistent order. The study results showed full-spectrum fluorescent lights producing the lowest error score, whereas the high-pressure sodium discharge lamp produced the highest error score (Abdou 1997). In three European industrial studies by Sucov in 1973 (Abdou 1997), accident rates dropped by approximately 50% when lighting was increased from 15 to 100 footcandles.

In warehouses, such as the Turlock Target store (see also Daylighting in Retail), benefits from natural light mostly result from improved color rendering. Product colors can be identified and natural light can fill the warehouse more evenly than electric lighting.

Boeing's participation in the "Green Lights" program led it to retrofit its assembly-area space lighting. The new, efficient lighting provides the employees with less glare, more control, and a nicer looking interior. The results from the retrofit were unexpected: for the first time in 12 years, one woman could see inside the 30-foot wing supports instead of relying on touch to put rivets into them. Another riveter said the environment is safer because the new lighting does not shatter when objects, such as broken rivet heads, hit the fixtures. Also noted by employees was that they could read their measurement tools easier. The new lighting also allowed for easier detection of imperfections in the interior side wall panel shop by 20% (Lovins 1995).

The Prince Street Technologies factory in Cartersville, Georgia, uses daylight as supplemental lighting. The carpet-manufacturing factory includes skylights and a picture window that provides a view of natural landscaping. Frank P. Boardman, manager of creative services for Prince Street, said that the "workers love it…. They love the light, and they love to see what's going on outside. It's made an immense difference in attitude." Before the company moved to the new facility, an average of 20 workers' compensation cases were reported per year. In three years at the new facility, only two cases have been reported (McQuillen 1998). Boardman thinks the decreased number of worker's compensation cases was due to the presence of daylight. Other benefits from the natural light have been the comfortable working conditions of the mill workers and product quality insurance. "When you work in the [Prince Street] manufacturing plant, you do see what the conditions are outside. So you're not in this shell of a warehouse, which is a typical work environment, where you never know if it's raining outside or what," says Gene

Montezinos (Bertman 2001), associate principal at Thompson, Ventulett, Stainback and Associates (who designed the Prince Street factory). Also, the mill workers have improved color rendering. Montezinos noted that, “these guys are manufacturing carpets, and they need to see the real colors of fibers that they’re weaving into their carpets.”

## 10. Conclusion

When designing buildings, emphasis is placed on construction and maintenance costs. However, real people will be working in these buildings, so consideration should be given to their psychological and physiological well-being. The improved health of building occupants benefits employers and building owners because of improved performance.

With properly installed and maintained daylighting systems, natural light has proved to be beneficial for the health, productivity, and safety of building occupants. Natural light helps maintain good health and can cure some medical ailments. The pleasant environment created by natural light decreases stress levels for office workers. Productivity increases with the improved health of workers, and with better productivity comes financial benefits for employers. Students also perform better with natural light. Across the nation, studies have shown students in daylit rooms achieve higher test scores than students in windowless or poorly lit classrooms. Along with better test scores, student health also improves from the increase in vitamin D intake. Students have fewer dental cavities and grow more under full-spectrum lighting. Daylighting also benefits retail stores because of more even light that provides better color rendering. Customers stay in stores longer and employees can identify items faster with better lighting. In health care facilities, natural light improves patient recovery rates and allows for proper vision for the elderly in assisted living facilities. Hospital staff also benefit from the natural light because of the amiable environment. Patients will be more at ease when staff is in a better mood, and the staff will be calmer when patients have improved recovery. Productivity increases in industrial environments because of improved color rendering and the better quality of light provided by natural light. Also, safety is increased with better lighting conditions.

The use of daylighting decreases utility costs and improves the well-being of building occupants. The effects of natural light on building occupants should be an important consideration for building design because studies have shown the strong influence light has on people in many different environments. Daylighting can provide satisfaction for both building occupants and owners.

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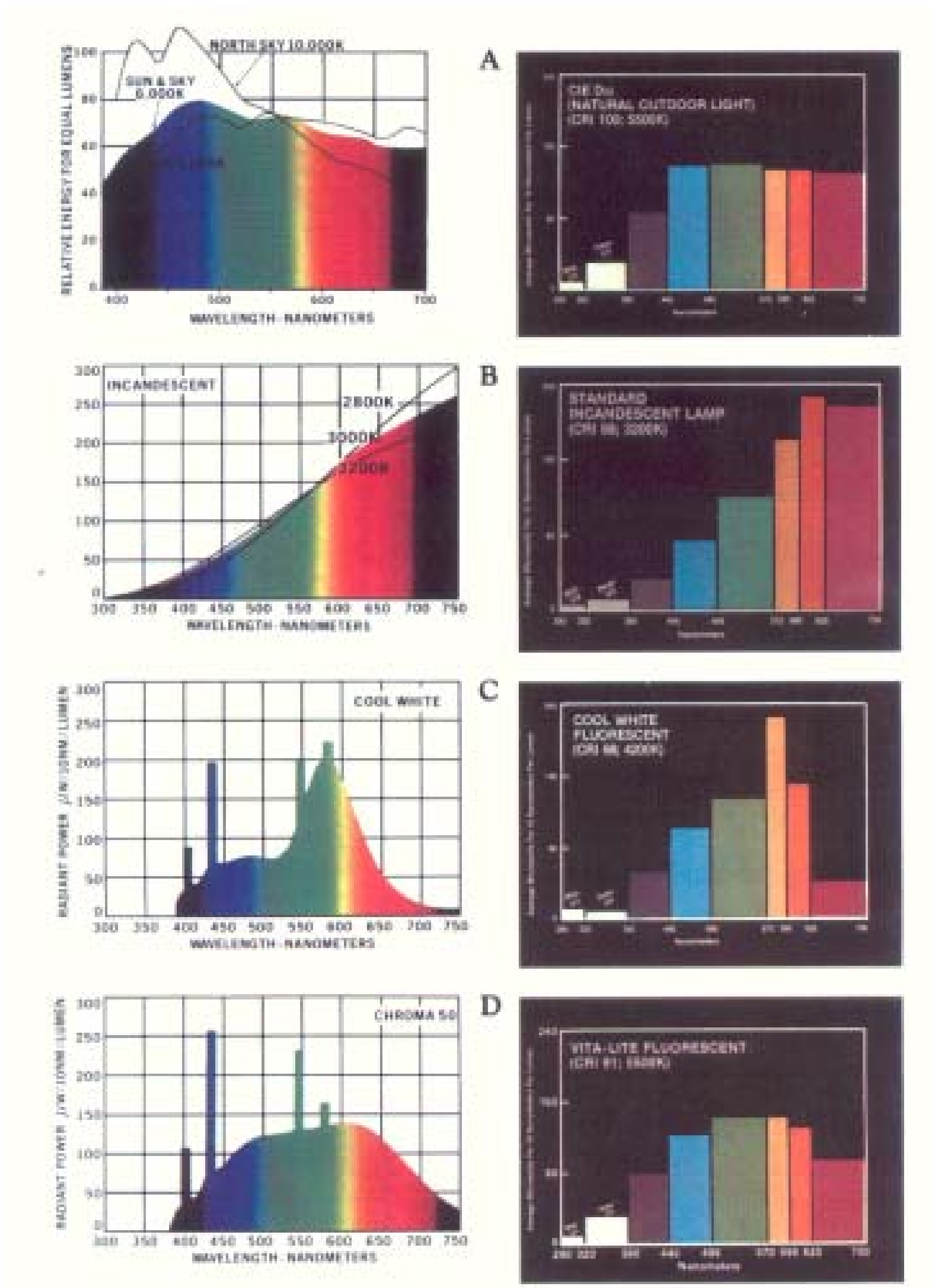
## APPENDIX

Source: Liberman, J. *Light Medicine of the Future;* 1991.

The following figure shows the wavelengths of light and spectrums of light provided by various types of electrical lighting and daylight. On the right-hand charts showing the spectrum of light emitted by light sources, the x-axis is wavelength in nanometers and the y-axis is average microwatts per 10 nanometers per lumen.



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13. ABSTRACT *(Maximum 200 words)*

This paper presents summary findings from a literature search of the term “daylighting”—using natural light in a building to offset or replace electric lighting. According to the Department of Energy’s Office of Building Technology, State and Community Programs *2000 BTS Core Databook*, in 1998, commercial buildings consumed 32% of the total electricity in the United States, of which more than one-third went to lighting. Using daylighting systems and turning off the lights will help reduce this energy load. Electrical lighting adds to both the electrical and cooling loads in a commercial building. Utility costs can be decreased when daylighting is properly designed to replace electrical lighting.

Along with the importance of energy savings, studies have demonstrated the non-energy-related benefits of daylighting. We compiled the data from books, periodicals, Internet articles, and interviews. The books, periodicals, and Internet articles provided the background information used to identify the main subjects of the paper. The interviews provided us with details related to specific buildings and companies that have integrated daylighting into their buildings.

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