A Survey on Day Lighting Design Strategies in Schools

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Abstract: Throughout history, daylight has been a primary source of lighting in buildings, supplemented originally with burned fuels and more recently with electrical energy. Before daylight was supplemented or replaced with electric light in the late 19th-century, consideration of good daylight strategies was essential. As we entered the mid-20th-century, electric light supplanted daylight in buildings in many cases. Fortunately, during the last quarter of the 20th-century and early years of this century, architects and designers have recognized the importance and value of introducing natural light into buildings. Daylight can provide a welcome and dynamic contribution to the human experience in buildings and, as demonstrated in recent studies on schools and retail sales environments, can impact human performance. Most people appreciate daylight and also enjoy the outside view that windows provide. Good daylighting design can result in energy savings and can shift peak electrical demand during afternoon hours when daylight availability levels and utility rates are high. Le Corbusier so clearly identified the importance of light in architecture when he expressed the point that, “Architecture is the masterly, correct and magnificent play of volumes brought together in light ...” emphasizing that “...the history of architecture is the history of the struggle for light. This article summarizes the use of daylight in primary schools with focus on goals, climate and weather, sky, conditions, design criteria, and strategies for day lighting design.

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1. Introduction

The impact of daylighting on the performance of school children has been a subject of interest for many years. Before fluorescent lighting became prevalent, it was generally assumed that all school rooms would be daylit as a matter of course. The California Department of Education had a rigorous review process for the architectural design of classrooms to ensure that daylighting standards were met. As a result, California classrooms built in the 1950’s and early 1960’s remain excellent examples of daylighting practice. The “finger” plan with multiple rows of single classrooms, each with windows on two sides, became a standard for California K-12 campuses.

However, starting in the late 1960’s a number of forces came into conflict with the daylit design of classrooms. Engineers, asked to provide air conditioning in classrooms, argued against the use of large expanses of glass and high ceilings.

Construction economists argued that schools could be built more inexpensively on smaller sites if the classrooms could be built back to back or grouped together, without constraints on solar orientation. Facility managers often contended that windows and skylights were a maintenance and security risk. Educational theorists argued that a more flexible arrangement of classrooms, with open walls between them, would encourage team teaching and creative learning. Others worried that windows might just be a distraction for students. And specifically in California, educational planners, trying to meet the needs of an exploding school age population, required that at least one-third of all new classrooms be portable, so that, if the need arose, they could be moved to new areas with an overpopulation of new students. (Hathaway, 1992)

As a result of these various pressures, the finger plan school was largely abandoned in California, and a vast experimentation in school design was undertaken. Many of the classrooms built since the 1960’s have little day lighting. Windows are commonly built with “black glass” that allows a view out, but no useful daylight in. Numerous schools have been built with no windows at all. Similar trends occurred nationally, and internationally, though perhaps without such a dramatic shift in design practice as in California. Concerned about the trend towards schools, and all types of buildings, without windows, Belinda Collins of the National Bureau of Standards conducted a major literature review on the study of windows in 1974. At that time there was an ongoing debate about the desirability of windows in classrooms. In a compilation of studies on windowless classrooms in 1965, the editor, C.T. Larson, concluded that windowless classrooms should have no adverse effects upon their users. Larson stated, "The educational value of such a view [that windows are necessary for student learning] should be assessed against the cost of installing and maintaining classroom windows" (SenterNovem ,1995)

Collins also quotes from a book on the behavioral aspects of design, which also concluded that windows were not needed in classrooms. "At present the prowindow forces still lack behavioral data in support of their case and argue on the basis of metaphor and supposition, but their arguments must be weighed against statistics…from the windowless schools…reported to have percent greater efficiency in heating and cooling, constant light to prevent eye strain… decibels or more noise reduction, and reduced maintenance costs." (Heschong Mahone Group, 1999) The author went on to claim that the use of completely underground schools provided evidence that claustrophobic reactions were extremely rare. He stated further that, "Opponents [of windowless schools] now take recourse in the need for communion with nature, contact with the outside and stimulus variation, which are more difficult to measure, and whose importance is not readily apparent."

Collins herself found that the research that had been done as of 1974 was suggestive of the importance of windows, but inconclusive: "Much, though not all, of the evidence from the windowless classroom studies is inconclusive, or inadequate, while that from windowless factories is circumstantial, based on hearsay, rather than research. As a result, only tentative conclusions can be drawn about the qualities of windowless spaces that make them somewhat less than desirable."

Since Collins' study, other research on the importance of windows has been done, but primarily in hospitals. The most rigorous studies have been conducted in Europe. One interesting study in Sweden in 1992 looked at the impact of daylight on the behavior of elementary school children. The Swedish researchers followed the health, behavior, and hormone levels of 88 eight year old students in four classrooms over the course of one year. The four classrooms had very different daylight and electric light conditions: two had daylight, two had none; two had warm white (3000K) fluorescent lamps, two had very cool (5500K) fluorescent lamps. The researchers found significant correlation between patterns of daylight levels, hormone levels, and student behavior, and concluded that windowless classrooms should be avoided Recent, more informal studies in the United States suggesting a relationship between day lighting and enhanced student performance have generated considerable excitement among day lighting advocates.**1** These studies, along with a rising interest in "natural" and "healthy" environments, have contributed to a resurgent interest in day lighting in schools. All three districts that we worked with in this study reported that day lighting in classrooms is currently a concern for their school boards, driven largely by parent activism. However, without credible evidence of relationship between the design of schools and the performance of students within them, classroom design issues remain subject to architectural and educational fads, just as in the past. We hope that this study provides a contribution towards more durable understanding of how the physical environment affects student performance.

2. Goals for Day lighting

In general, design professionals should try to get as much daylight as possible deep into a building while controlling the brightness of surfaces within the users' fields of vision. Review and understand lighting requirements for critical and non-critical task areas. A building's critical load must also be considered as human comfort and energy performance are crucial. (Berkeley University, 2000)

3. Climate and Weather

Building types and site conditions vary widely for different geographic locations and from one climate type to another. For design guidelines, consider four specific climate types, as discussed below.

New Orleans, LA is an example of a hot-humid climate. In locations similar to this, reduction of heat gain is important, therefore solar gain should be controlled. The designer should also control or minimize direct sunlight. Extensive roof overhangs or external shading strategies are desirable. Windows should be sized and located to admit indirect daylight. Buildings should generally be elongated on the eastwest axis to minimize east-west exposure. Hot-arid climate locations like Phoenix, AZ require design strategies that provide relief and protection from intense sunlight. Solar gain and glare, therefore, must be minimized. Strategies that admit indirect light are appropriate on south elevations while larger glass areas may face north. Solar controls should dominate on the east and west. Enclosed courtyard spaces are frequently used in hot-arid locations, especially in the Southwestern US and Northern

Mexico. The temperate climate of locations like Eugene, OR benefit from building forms elongated on the east west axis to maximize south-facing walls. Larger glass areas may be considered, however glare conditions should be carefully studied. Often, solar heat gain needs to be balanced with shading on a seasonal basis. Temperate climates allow greater flexibility in design due to modest temperature and seasonal changes. Greater connections between indoors and outdoors should be considered. Exterior horizontal louvers are effective for creating deep penetration of sunlight on south facades.

Madison, WI is often referenced as an example of a cool/cold climate. This climate type experiences tremendous seasonal changes in temperature, precipitation, and sky conditions. Sensible design combines daylight and passive solar light. Daylight openings should be on the east, south, and west while glass on the north should be minimized. Special effort may be required to control glare and contrast from direct solar gain and bounced daylight, especially in snowy winter conditions. Architects generally attempt to minimize building surface areas due to the temperature extremes. Wind protection is often essential.

4. Sky Conditions

Season of the year, weather, and time of day combine with predictable movement patterns of the sun to create highly variable and dynamic daylighting conditions. Atmospheric and pollution conditions vary depending on season, weather, and time of day. Densely populated urban cities, like Phoenix, have more pollutants than rural cities. Daylighting design is usually based on the dominant sky condition and the micro-climate for the building site. There are three common sky conditions: clear sky, overcast sky, and partly cloudy sky.

The clear sky includes sunshine and is intense and brighter at the horizon than at the zenith, except in the area around the sun. Daylight received within a building is directly dependent upon the sun's position and the atmospheric conditions. Easily used charts, diagrams, and software programs allow study of solar geometry for any geographic location and time of day.

The overcast sky is characterized by diffuse and variable levels of light and has dense cloud cover over 90% of the sky. It is generally three times brighter overhead (zenith) than at the horizon. Because direct sun is not present, the brightness of this type of sky depends on sun position. Generally, higher daylight illuminance occurs at higher solar altitudes.

The partly cloudy sky may have cloud cover that ranges from heavy to light and is similar to the clear sky at one moment and the partly cloudy sky the next. Most designers do not base decisions on the partly cloudy sky because it is constantly changing and therefore, too variable.

5. Design Strategies for Daylighting Systems

As outlined above, the application of daylighting systems is only one constituent of a daylighting strategy. Although a poor selection of systems can spoil the performance of a building with good daylight potential, a sound selection cannot compensate for errors and omissions in previous design stages. To select a system, the designer must understand:

• The function of the window or other opening(s),
• The function of the system, and
• The interplay of the system with other systems.

A reasonable selection of systems should reduce the negative effects of windows and enhance daylight performance without interfering with other desirable effects of windows for all design cases.

Daylighting systems can be categorized by many characteristics. When selecting a system, the designer must be aware of all of its properties. Function and performance parameters have the most pronounced effect on performance, but costs and details related to the skin of the building are also important. As for many decision within the design process there exists no definite procedure how to select a daylighting system. The ultimate criterion is the performance of the overall design solution.

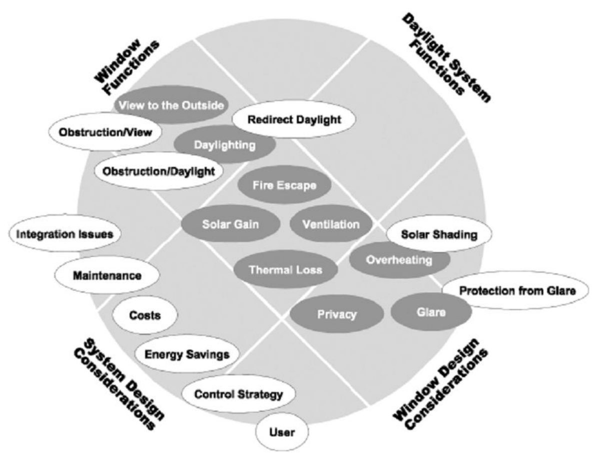

Figure 1: Functions and design considerations of windows and daylighting systems

Windows and rooflights have different roles in a daylighting strategy. The ambience of spaces receiving skylight is completely different from that of spaces receiving sidelight. For example, the design of Le Corbusier's "Le couvent de la Tourette" emphasizes the different nature of skylight and sidelight. In this design, skylight is used only in spaces that play a significant role in religious life; all secular spaces receive sidelight.

Roof lights are usually not designed for a view to the outside; therefore, obstructing elements such as deep light shafts or non-transparent daylight systems can be applied in rooflight design. The control of glare with such systems is much easier than with sidelighting designs, which must provide occupants with a view to the outside. Solar shading is a crucial issue with rooflighting. One design strategy for rooflighting in sunny hot climates is to use a very small aperture and to apply innovative daylighting systems to distribute the light homogeneously in the space. In classrooms of the Park Ridge Primary School in the sunny but temperate climate of Melbourne in southern Australia, tunnel lights are used to exclude direct sunlight and to distribute skylight to the space.

Shading systems for rooflights, such as sun-protecting mirror elements, prismatic panels and directional selective shading systems using holographic optical elements can be applied to large glazed roof areas in higher latitudes. When situated in the window pane, these systems are protected from dust and require little maintenance. These systems need to be adjusted to the individual application.

6. Daylighting Strategies for Rooms

The aims of room daylighting are to adequately illuminate visual tasks, to create an attractive visual environment, and to save electrical energy. Both the building design scheme and the application of systems play roles in meeting these goals. The performance of a daylighting strategy for rooms depends on:

• Daylight availability on the building envelope which determines the potential to daylight a space;

• Physical and geometrical properties of window(s), and how windows are used to exploit and respond to available daylight

• Physical and geometrical properties of the space.

7. Function of Windows

The old definition of a window as an aperture in an opaque envelope is no longer strictly applicable. Innovations such as fully glazed skeleton structures and double-skin facades defy the scope of this definition. Nevertheless, we will use the term "window" to analyse daylighting strategies. Windows have several functions, which vary depending on the individual design case. One key function of a window is to provide a view to the outside. View plays an important role in an occupant's appraisal of the interior environment even if the exterior environment is not especially attractive. The size and position of windows, window frames, and other elements of the facade need to be considered carefully in relation to the eye level of building occupants. Daylighting systems can affect the view to the outside. If an outdoor view is a priority in a daylighting design, visual contact with the exterior has to be maintained under all facade operating conditions. Advanced daylight strategies therefore often allocate different functions to different areas of the facade or to different facades. View windows then can be preserved without being compromised by other functions. (Groot, E.H. de, J.S.C. van Putten, 2000)

Daylighting is one of the main functions of windows. The window design determines the distribution of daylight to a space. Windows chosen solely for their architectural design features may perform satisfactorily in many cases. For dwellings and other buildings that have relatively minimal visual requirements, application of advanced daylighting systems is not usually appropriate. Advanced daylighting systems can be useful in cases where:

• Difficult tasks are performed, and a high degree of control over the visual environment is required;

• The building's geometry is complex, e.g., there are heavily obstructed facades or deep rooms;

• Control of thermal loads is required (adjustable solar shading can be an effective Strategy in this case).

Daylighting is inseparably linked to solar gain. In some design cases, added solar gains from daylighting may be welcome; in other cases, heat gain must be controlled. If solar gains are desirable, windows are a good way to provide them. In general, the goal of building design is to reduce cooling loads. There are a number of ways to control solar gains from windows and facades; the simplest method is the direct gain approach, where a shading system simultaneously controls the visual and thermal environments. More advanced techniques, such as collector windows and double-skin facades, allow some degree of separate control over the thermal and visual environments. In passive solar architectural concepts, solar gains are controlled by the orientation and the application of shading systems as a function of the sun's position.

The operability of windows needs to be considered when daylighting systems are selected.

Shading systems located in the window pane do not work properly when the window is open; if daylight-redirecting systems are attached to the window, the window's operation will have an impact on the systems' performance. Operable windows also often serve as fire escapes. The impact of fire balconies on daylight performance needs to be considered.

Glazed areas are an interface between exterior and interior; therefore, windows involve a number of design considerations. Aside from the abovementioned primary functions, the following issues are especially important for glazed areas:

- glare
- Privacy/screening of view
- Protection from burglary

8. Design Strategies for Windows

A window system must address the range of a building's exterior conditions to fulfill the range of interior requirements. The placement and sizing of windows are among the most powerful features of architectural design for daylight. Because the design of windows has a decisive effect on the potential daylight and thermal performance of adjacent spaces, it needs to be checked very carefully. The LT (Light-Thermal) method, which was developed for typical climates in the European Union, allows the estimation of energy consumption for heating, lighting, and cooling as a function of glazing ratio. Simple design tools allow a quick evaluation of window design and room geometry.

Windows are almost always exposed to the sky; daylighting systems can adapt windows to changing sky conditions and transmit or reflect daylight as a function of incident angle.

Daylighting systems are primarily used for solar shading, protection from glare, and redirection of daylight. Whether or not daylighting systems are required to support the performance of window systems, and which system or systems is appropriate, are key decisions in the design process. The adjustment of daylighting strategies to specific sources of skylight is an important characteristic of daylighting strategies.

9. Strategies for Skylight

Strategies for diffuse skylight can be designed for either clear or cloudy skies; however, the most significant characteristic of these strategies is how they deal with direct sunlight. Solar shading always is an issue for daylighting except on north-oriented facades (in the northern hemisphere). If solar shading is only of minor importance as a result of orientation and obstructions, a system to protect from glare can be used for solar shading as well.

Solar shading and glare protection are different functions that require individual design consideration. Solar shading is a thermal function that primarily protects from direct sunlight, and glare protection is a visual function that moderates high luminances in the visual field. Systems to protect from glare address not only direct sunlight but skylight and reflected sunlight as well.

10. Strategies for Cloudy Skies

Daylighting strategies designed for diffuse skylight in predominantly cloudy conditions aim to distribute skylight to interior spaces when the direct sun is not present. In this case, windows and roof lights are designed to bring daylight into rooms under cloudy sky conditions, so windows will be relatively large and located high on the walls. Under sunny conditions, these large openings are a weak point, causing overheating and glare. Therefore, systems that provide sun shading and glare protection are an indispensable part of this strategy. Depending on the design strategy, various shading systems that transmit either diffuse skylight or direct sunlight may be applicable in this case. To avoid decreasing daylight levels under overcast sky conditions, moveable systems are usually applied.

Some innovative daylighting systems are designed to enhance daylight penetration under cloudy sky conditions. Some of these systems, such as anidolic systems or light shelves, can control sunlight to some extent. The application of simple architectural measures, such as reflective sills, is another opportunity to enhance daylight penetration, but the design of the window itself is the main influence on the performance of this type of strategy under cloudy conditions.

11. Strategies for Clear Skies

In contrast to daylighting strategies for cloudy skies, strategies that diffuse skylight in climates where clear skies predominate must address direct sunlight at all times. Shading of direct sunlight is therefore part of the continuous operating mode of this strategy. Openings for clear sky strategies do not need to be sized for the low daylight levels of overcast skies. Shading systems that allow the window to depend primarily on diffuse skylight are applicable in this case. (TNO, 2000)

12. Direct Sunlight

Strategies for sunlight and diffuse skylight are quite different. Direct sunlight is so bright that the amount of incident sunlight falling on a small aperture is sufficient to provide adequate daylight levels in large interior spaces. Beam daylighting strategies are applicable if sunshine probability is high. Since sunlight is a parallel source, direct sunlight can be easily guided and piped. Optical systems for direct light guiding and systems for light transport are applicable in this case. Apertures designed for beam daylighting do not usually provide a view to the outside and should therefore be combined with other view openings Because beam daylighting requires only small apertures, it can be applied as an added strategy in an approach that otherwise focuses on cloudy skies.

13. Functional Division of a Window

If a designer can allocate one predominant function to a window, he or she can design it for optimum performance that will not be compromised by contradictory requirements. The designer must then make sure that all windows together fulfill the full range of requirements in a room. When a window has to satisfy several functions in any operation mode, the range of applicable daylighting systems is constrained because the system selected must take account of all of the window's functions. The design approach for this type of opening therefore usually consists of applying moveable systems that can be recessed when not needed. The designer should consider controlling systems using a building energy management system because they might not otherwise be operated appropriately. The heterogeneous design of a window allots specific functions to specific areas of a window. Different daylighting systems can be applied to different parts of the window, or similar systems may be operated separately for different areas of the window. The interaction of daylighting systems in this case needs detailed design consideration. (Groot, E. de, 2001)

14. Requirements for the luminance in schools

In order to get a good lighting concept, knowledge of the different tasks in classrooms is important. Each task needs its own light conditions. During the day there are a number of different visual tasks in a classroom. So, high requirements for the light quality are important. Students and teachers have benefit by a lighting which supports them optimally in doing their activities. Important for a good lighting design is that the needs of the human being are central, but in the same time the energy efficiency may not be neglected.

The following values for luminances and contrasts have been required: the luminances must be below 3000 cd/m² and the luminance contrasts in the (wide) visual field must be lower than 1:30. According to the tasks of teacher and student and the light requirements for the different activities the classroom has been divided in zones: A blackboard zone and a classroom zone. The classroom zone has again been divided in two zones parallel to the facade in order to create the possibility to optimize the use of daylight: a window zone and a corridor zone

First, for a better understanding of daylight quality in schools, measurements have been done in a number of existing schools. That has showed, it was difficult to compare the different schools to each other .The divisions of the classrooms were different and the same holds for plants at the window-sill, drawings on the window-glass, opposite buildings and public green, etc. And of course the most important problem, measurements in different schools could not be done at the same time under the same weather conditions. For that reason, in order to get more insight into the daylight qualities in schools, nine different classroom designs were simulated with Radiance. The Figures shows the different designs: a reference model, five basic models and three situation models. The situation models are based on designs of real schools. All the nine models satisfy the Dutch Building Regulations. (fig2)

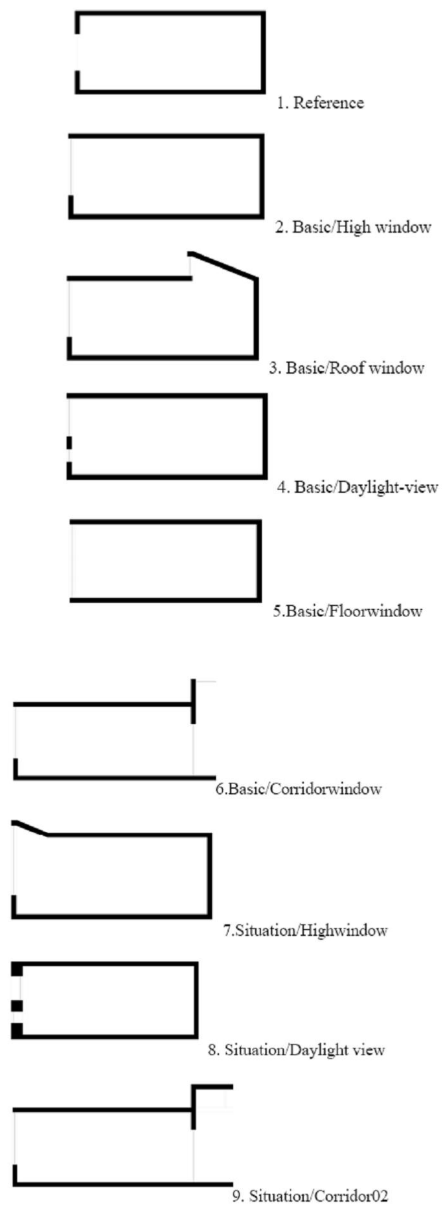

Figure2. A reference model, five basic models and three situation models.

15. Discussion and conclusion

It is obvious that daylight has been the favored light source in school buildings up to the present day. This is probably because the design of school buildings is relatively free from commercial influences in comparison with the design of the other building types. In addition, the variation of daylighting within a day, the view out giving visual relief, and contact with the constantly changing outdoor scene are all good reasons to keep daylighting in schools.

The major factors influencing daylighting in schools

Based on the review above, three major factors that affect the development of day lighting in schools are evident. First, improvement of technology acts an important role in the progress of the use of daylighting in schools. This can be seen to have followed a series of logical steps in line with development of building science. For instance, the use of steel framing, which allows the area of glazing to be maximized led to the open-air school movement in the early twentieth century. In recent years, advanced design and measuring tools for daylight has involved photometrical technology and computer simulation, etc. These technologies could improve the understanding of the interior daylit condition as well as allowing the distribution of daylight to be precisely predicted. (Groot, E. de, 2002)

The use of information and communication technology may also fundamentally change the classroom environment, building ecology and other areas of school design and building. Second, the need for daylighting often emerges with social, political and economic transformation forces. For example, unhealthy living conditions caused by industrialization and urbanization of the nineteenth and early twentieth century were responsible for the open-air school movement. The oil crisis in the 1970s made people realize the importance of energy conservation. As a result, the windowless schools and the passive solar schools appeared. Today, the radical green thinking related to school buildings places an emphasis on natural and environmental criteria.

Third, a parallel can be drawn between the development of daylighting in schools and the progression of educational theories in the twentieth century. For example, during the 1940s and 1950s the notion of progressive education seemed to fit in well with the modern movement of architecture with its emphasis on prefabrication and flexibility which allows the area of glazing in classrooms to be as large as possible. (Putten, J.S.C., E.H. de Groot, 2003)

When the twenty-first century was reached, the needs for quality education demanded a multi functioning school environment of the highest quality.

The development of daylighting in schools can be visualized as a pendulum swinging back and forth—from small windows to a demand that window area be as big as possible, from windowless classrooms to passive-solar schools.

This review shows that the above three factors have shaped the progress of daylighting in schools and it is believed that they will affect the future of daylighting in schools. Equally, the authors would like to believe that architects have learned from previous mistakes and those certain changes in philosophy and advances in technology represent a permanent improvement in daylighting development, and not just cyclical adjustment to the current condition. In addition, it can be noted that more daylight research has moved from performing specific visual tasks to understanding qualitative aspects of lighting in recent years, though previous studies on the qualitative and psychological effects of lighting have been sporadic and lack a shared agenda to guide investigators. (Groot, E., 2002b),

The future of school daylighting

A few studies have been made on daylighting quality in schools. In early 1976, Tikkanen conducted field research to study emotional reactions to light and color in a classroom environment under different window conditions at different seasons in five Swedish secondary schools. The study found that the observed sensation of color changed with quality and quantity of light, and a relationship was found between the quality of light and the pleasantness of the observed environment. In the 1990s, Iwata et al. conducted a pilot experiment to examine the relationship between daylighting and visual comfort in a daylit classroom. (NEN-EN, 2003) The researchers reported that one of the key factors to designing a comfortable lighting environment in a room was to eliminate the darkness or the excess brightness that occupants found on the desk, and both horizontal illuminance and vertical illuminance at the eye predicted comfort judgment. In addition to the above research work, Building Bulletin discussed the issue of daylighting quality in schools. It states that good design for daylighting not only provided a sufficient quantity of illumination but also gave the interior a character appropriate to its use. Moreover, three main recommendations of good quality for daylighting were listed:

1) A satisfactory balance of brightness throughout the room
2) The right proportion of direct and indirect light
3) The absence of glare from the sky or sun.

Unfortunately, there is little research evidence to support these recommendations. The ninth edition of the IESNA Lighting Handbook gives formalized recommendations of lighting quality in schools instead of recommended quantity of light for specific applications or visual tasks as in previous editions.
This Handbook describes lighting quality as the integration of human needs, architecture, and economics and the environment. In the section on educational buildings, it suggests that the most important factors contributing to lighting quality in schools should include: daylighting integration and control, direct and reflected glare, flicker (and strobe), light distribution on surfaces, light distribution on task plane.
On the whole, there is a scarcity of research on lighting quality in schools, especially in the daylighting area, although renewed interest in lighting quality has emerged since the 1990s. In addition, the absence of a common definition of daylighting quality is still a problem for lighting research as well as in practice. As it is well known, the study of lighting quality is a subjective topic that focuses on the human reaction to lighting. Therefore, it is questionable whether the finding regarding natural illumination, window size, view quality and need for privacy apply to students in different countries, of differing cultures and in climates, which may be temperate or tropical, because most daylight research has taken place in Europe and North America. It can be expected that a sounder basis for the provision of good daylighting quality may be made.
Lastly, by recalling the progress of daylighting in schools in the nineteenth and the twentieth centuries, the recent trends of daylighting development are anticipated. The literature study reveals that the development of technology, shifting educational theories, and transformation force of social, political and economic contribute significantly to the development of daylighting in schools; and it is believed that they will continue to produce similar changes in the future. The changing in the regulations and standards in recent years illustrates the movements from quantity to quality of lighting both in research and practice. In general, we have a poor understanding of daylighting quality in schools, and a poor understanding of the relationships between the quantity and quality of daylighting. These are the two areas that require further research.

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