Lighting Res. Technol. 35,2 (2003) pp. 111–125

A review of the development of daylighting in schools

Wei Wu BArch MSc(Building) PhD and **Edward Ng** BA(Hons) BArch(Dist) MBA(Dist) PhD(Cantab) RIBA IESNA MSLL
Department of Architecture, Chinese University of Hong Kong, Hong Kong, China

Presented at the National University of Singapore 29 January 2002

This paper reviews the progress of daylighting in school buildings. It examines the publications that discuss daylighting design for school buildings in early 1874. It also traces the developments of the open-air school movement from 1900 up to the 1930s and describes research at the present day in the context of an emphasis on environmental factors defining healthy and comfortable buildings for education. The regulations and standards of lighting in schools in the different periods in Britain are summarized. The review reveals that there is a need to examine the relationships between the responses of school occupants and the quantity of daylighting. The conclusion of the paper gives an overall summary of daylighting in schools and identifies gaps in current knowledge. In addition, it provides the authors' opinions for future lighting research in schools.

1. Introduction

The study of lighting in school buildings has been a subject of interest for many years, and rightly so. Good daylight has shown to be closely associated with improvement in student performance and promotion of better health. It also contributes significantly to the aesthetics and physical character of the learning space.[1–3]

2. The development of daylighting in schools

Throughout history daylighting has been considered as a crucial factor in the design of schools, more, perhaps, than in the design of any other building types.[4] The following sections describe in chronological order the development of daylighting together with school design from the early nineteenth century to the present day.

Address for correspondence: Dr Wu Wei, Department of Architecture, Chinese University of Hong Kong, Hong Kong, China. E-mail: wuwei@cuhk.edu.hk

2.1 Developments during the nineteenth century

The single-room house was perhaps the typical school classroom in the eighteenth century in western societies. As the influences of urbanization and industrialization spread, this led to the pursuit of educational provision for the industrial classes from the beginning of the nineteenth century. As a result, the schools often overflowed into the church or the institutional workhouse during their early development. The single classroom style had to be used for the instruction of the whole school simultaneously (Figure 1).[5] The style of these school buildings spread quickly but disappeared almost instantly since the school population in the UK rose which resulted in the provision of separate classrooms for children of different abilities and age. Moreover, the poor standard of health and safety for the children at that time attracted much concern from the welfare societies.

A book by Robson published in 1874 under the title *School architecture: being practical remarks on the planning, designing, building*

10.1191/1477153503li072oa

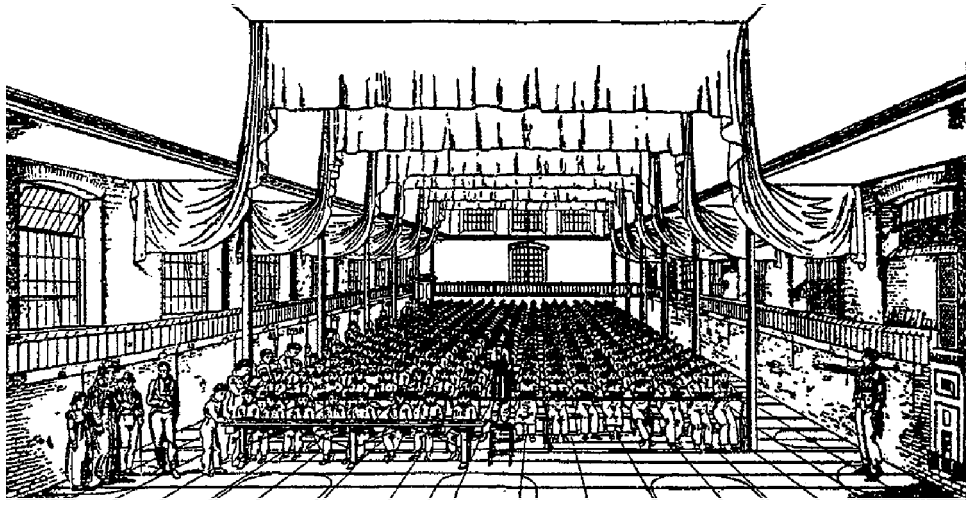

Figure 1 An interior view of a class at Southwark Central School, early nineteenth century (from the British and Foreign School Society manual of the system of primary instruction, 1831, by permission of the Society)

and furnishing of school houses, made suggestions about the layout of schools, and the planning of classrooms and the interior environment.[6] The book set out a view that the classroom design should take into consideration health, comfort, and effective teaching of children. Robson believed that the daylighting of classrooms was important. He urged that the main lighting of the schoolroom should never be from the south or south-west, though some sunny windows should always be provided. He suggested that the coolest and steadiest light from the north was the best light source for the classroom, as he found that too much sunlight produced painful glare in hot summer weather both to the teachers and the pupils. Also, Robson clearly advised the other school designers at the time in this publication: *'A classroom is only well lighted when it has 30 square inches [19300 mm^2] of glass to every square foot [92900 mm^2] of floor plan.'*[6] This is equivalent to about 20% glazing area to floor area in the classroom.

Robson's recommendations for daylighting in schools was widely implemented in the UK and in the west. During the nineteenth century and up until the turn of the century, schools were predominantly designed to take advantage of north light. Glare from south or west-facing windows was avoided.

2.2 Open-air school movement

From 1900 up to the 1930s, an open-air school movement was the dominant idea.[7] This movement stressed aspects of health and welfare in school buildings and placed emphasis on better ventilation and increased daylight. It strove to improve upon the stuffy, often gloomy, classrooms of the typical school plan of the late-nineteenth century.

An open-air school requires a garden site and classrooms that could be opened completely on one side. To achieve cross-ventilation and increase the window area, a more open form of planning with corridors and verandas separating classrooms appeared. The bilateral lit classroom then became a standard form.[8] Since the importance of facilitating sunlight penetration into the classroom was restated, the school buildings were oriented in a southern direction and employed folding or sliding windows; therefore, teaching areas were exposed to fresh air and direct sunlight for at least some hours during the day.[9] Figure 2 illustrates the exterior view of a typical open-air school.

In 1913, PJ Waldram published a paper which

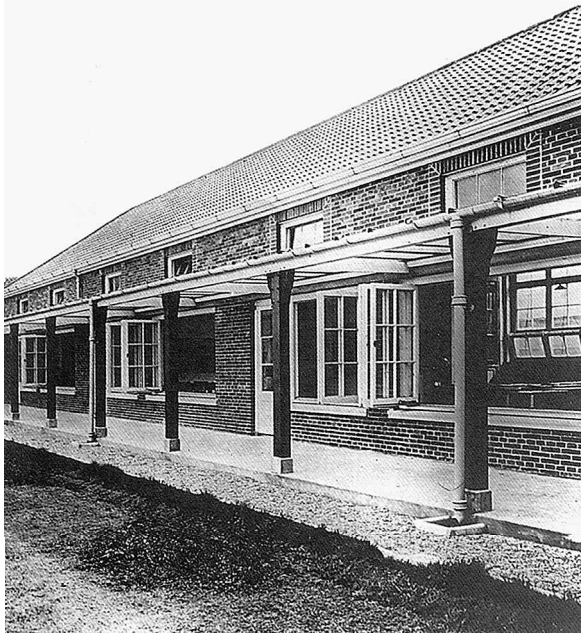

Figure 2 A 1930s open-air school with windows which fold back.[9] Reproduced with permission of Her Majesty's Stationery Office, London, UK

reviewed the history of daylighting in schools from 1866 and placed an emphasis on the effects of the open-air movement.[10] Besides listing the available rules and data for daylighting in schools at that time, Waldram discussed the main problems for designing the daylit classroom. 1) What is a suitable and practical method of measuring and predicting daylighting in the classroom? 2) What is the minimum natural illumination required in a classroom for general teaching purposes? 3) Is it desirable to recommend the minimum reflectance of the walls and ceilings in a classroom? An announcement was then resumed based on discussion of Waldram's paper in a meeting held by the Illuminating Engineering Society in the UK. At that meeting, there was general agreement that high reflectance walls and ceilings could improve daylighting and roof lighting, which was the optimum sources of illumination for reading and writing in classrooms. However, there was no recognized agreement on the other problems, for example, what is adequate natural illuminance for a schoolroom.

In addition, some doubts were expressed about using bilateral lighting in the classroom in the open-air school movement.[8,11] For example, there were a few recommendations that the direct light and the light reflected by the ceilings and walls was so diffused that shadows were scarcely noticeable. As a result, a rule-of-thumb method was used to determine the window height in a side-lit room: the window area should be one-fifth of the floor area. Because of the problems of high contrast from roof lights and undesirable overheating in summer-time, the Board of Education reluctantly requested that direct sunlight should not be allowed to penetrate into the classroom. As a result, some school buildings began to use a dormer window above the access verandas on the south side.[12]

Just before and immediately after the first world war, light and air were still seen as being very important, because of the persistent influence of the open-air school movement. In addition, innovations of construction technology such as the use of steel framing made possible the use of maximum glazing area in schools. Many schools retained the open-air feel with windows and door partitions that could be opened fully. This set the pattern for a large proportion of the new schools commissioned after the second world war. Following the publication of the post-war building study 'The lighting of buildings'[13] and the subsequent school building regulations, it was regarded that daylight was the principal source of illumination in schools. This regulation also recommended a minimum 2% daylight 'sky factor' (then called the daylight factor) in 1945, and its memorandum suggested 5% daylight factor where possible.[14]

To achieve even the lower daylight factor of 2%, windows had to be made as large as possible in most school buildings.[15] However, large windows caused many drawbacks, such as glare, and uncomfortable overheating in the summer. These drawbacks led to the reassessment of the use of daylighting in school design. After 1954, the ability to take account of the internally reflected

light into calculation of daylight factor had a considerable effect on the design of school buildings.[16] Concurrently, the concept of 'permanent supplementary artificial lighting of interiors' (PSALI) was introduced in school design.[17] Later, new attitudes in education brought radical changes in the way of using school space. In particular, it was no longer necessary for pupils to sit in rows of desks facing a blackboard, so lighting from one side no longer needed be a dominant design factor.[18] More compact plans of school buildings with smaller windows appeared.

2.3 Energy efficient schools – exclusive model

Unfortunately, reducing window size in school buildings went somewhat too far, especially in the USA when fluorescent lighting became prevalent. Starting in the late 1960s, the design of daylit classrooms was opposed for a number of reasons such as the need for reduction of excessive glare. When air-conditioning was used in schools, engineers suggested that the smaller windows could improve energy efficiency.[19,20] Moreover, educational theorists complained that windows distract students' attention.[21,22] As a result, many newly built classrooms had little daylight. Since the oil crisis in the 1970s, numerous windowless schools appeared.[22,23] In fact, at one point in Florida, USA, legislature even passed a law requiring all schools to be air-conditioned and windowless! Graves shows an example of the interior view of a windowless school built in the 1960s in the USA.[24]

The term 'exclusive' has been applied to buildings which strive to exclude the effects of the environment.[25] These buildings are distinct from 'selective' buildings, which seek to maximize the use of ambient energy in the form of solar gains and daylighting, etc. The basic characteristic of the school buildings of the 'exclusive' model is their compact shape. The windows are generally restricted in size and their orientations are relatively unimportant. It is worth mentioning here that the definition of this conceptual model is based on the research results of investigations into the responses of the occupants of five school buildings.[26–28]

The school buildings belonging to the 'exclusive' model, in particular the windowless designs, represented a departure from the conventional daylit, and naturally ventilated schools. Although the interior environment of the classrooms could be controlled automatically and be relatively constant and comfortable throughout the year, researchers considered that it might be harmful psychologically for school children to be enclosed for long hours in a predominantly artificial environment, particularly in 'windowless boxes'.[29] In early 1965, Karmel assessed the psychological effects of windowless classrooms by asking more than 1000 secondary school students aged 14–15 years old to draw a picture of their school.[30] This study revealed that students in the windowless schools drew windows significantly more frequently than those in the windowed schools. Also, some evidence of hostility and psychopathology were found in the drawings of the students from the windowless schools. In the 1970s, Tikkanen investigated the reactions of over 3000 students in eight schools in California, USA.[31] He found that 94% of the students in windowed schools preferred classrooms with windows while only 4% preferred windowless classrooms. The students of the windowless schools were evenly divided in their desire for windows. Concurrently, Tognoli examined the effect of environmental embellishment (e.g., windows) on attitudes towards the experimental setting and on short-term retention of verbal material. He found that subjects rated the presence of a window as substantially more pleasant than its absence.[32]

Other researchers also investigated students' performance and responses in the windowless classrooms. In the late1960s, Demos *et al*. examined the scholastic performance and attitudes of 10-year-old students in a windowless classroom and in a classroom with windows in a 2-year study in California, USA.[33] Although it was found that most children disliked their windowless classroom intensely after one year,

Demos *et al*. claimed that there were no significant differences in the achievements, personality tests or health records for the children who used these two classes. However, the teachers who were interviewed stated that the students in the windowless classroom were simultaneously more timid and more likely to complain. In 1975, Larson studied students in a primary school over a 3-year period.[34] In the first and third years windows were present in the school but in the second year the windows were removed. Removal of the windows did not change scholastic performance but there was a significant tendency for the younger students to be absent more frequently. In addition, Larson found that older students expressed a desire for the windows.

As an extension of the summary of NBS Building Science series publication 70 on the psychological reaction to environments with and without windows, Collins claimed that the absence of the windows neither improved nor impaired the performance of the students.[35] However, this author also suggested that windowless schools should be used with caution, particularly since the long-term effects were not known.[36] A similar conclusion was later arrived at by Boyce.[37]

The results of clinical research make it necessary to reconsider the above conclusions. In 1972, Wilson conducted a study that evaluated the physical and psychological benefits of windows to patients in a hospital.[38] This study followed the responses of 100 patients in an intensive care unit, and found a compelling link between daylighting and physiological health. As many as three times the number of cases of organic delirium occurred in patients in a ward without a window as occurred in one provided with natural light. This conclusion gained further support by Keep *et al*.[39] and Ulrich[40] in the 1980s. Although these studies were conducted on adult hospital patients, the results may be of the utmost relevance to the study of the long-term impact of the school environment.

In early 1979, Tikkanen examined 400 students averaging 16 years in age in five Swedish schools.[41] He found that in the northern classroom environment of mixed electric light and daylight, the reported incidence of eye fatigue was significantly higher in the classroom with only skylight as compared with the classroom with the regular side-view window at eye-level at the sitting position. Two years later, Stewart studied the behaviour and attitudes of the school students towards daylight and fenestration in 350 primary schools in UK.[42] Social factors, personality characters of the students and the varying visual characters of the building including photometric were studied. Stewart found that a significant proportion of the students chose to sit or work near windows, the chief determining factor being the amount of daylight. Moreover, it was found that view content and visual and thermal comfort were important in deciding the favourite window place of the children.

2.4 Energy efficient schools—selective model

With few exceptions, sunlight was not allowed to penetrate into the classroom.[43] Unlike other building types, school students spent most of their time in fixed positions and viewing directions. Therefore, thermal, and even more often, visual discomfort might be caused by direct exposure to sunlight. Ne'eman found that 52% of the school occupants considered sunshine to be a nuisance, in comparison with only 4% of the occupants of residential dwellings.[44,45]

Since the oil crisis in the 1970s, the passive-solar school design, a kind of 'selective' model of environmental buildings which permits direct sunlight penetration into the classrooms with careful controls has been used.[9,46] As previously alluded to, educational theories of the traditional whole-class teaching before 1970 moved towards individual and small group teaching methods in western countries, also made this design strategy more practicable.

Since the early 1980s, a number of schools with passive-solar features have been built in Europe and the United States. Practical design guidance and examples of these schools are quoted in the literature.[9,47–50] The general features of a passive-solar building are a spread out

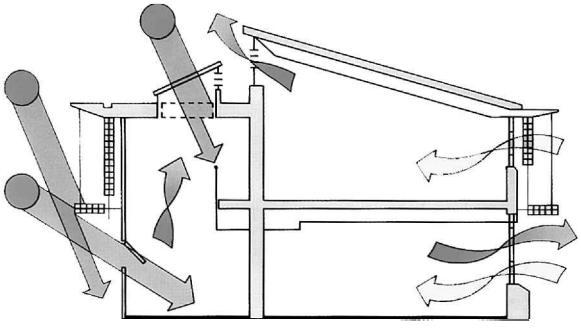

Figure 3 The concept of 'selective model' school.[9] Reproduced with permission of Her Majesty's Stationery Office, London, UK

shape with careful choices about location and orientation. Large windows were used on the southern façade for maximizing solar gain for heating. As they also provide lighting, the need and provision of additional windows, on the northern façade, is diminished. In contrast to the 'exclusive' school model, a passive-solar design would therefore make more effective the use of ambient daylight.[51] Crisp *et al.* suggested that the school buildings with passive-solar features required the designers to weigh the aesthetic and visual advantages of daylight and sunlight against the implications for both the thermal balance of windows and the other consequences such as glare. The concept of the 'selective model' school is illustrated in Figure 3.

The 'selective' model of environment was a relatively new concept for school designers in the 1980s. The first passive solar school, St Mary's (formerly St George's School) in Wallasey, UK, was built in 1961 and is still in continuous use today (Figure 4). St Mary's school is one of the brave experimental attempts at providing a thermally comfortable classroom by means of solar gain, occupancy gain and interior artificial lighting. Therefore, the research of thermal performance in St Mary's school was a major consideration and daylighting was largely ignored at the beginning.[18,52,53] Researchers then began to concentrate on the lighting and visual performance in the passive solar buildings.[54] In the 1980s, Carter and Mckennan conducted a comprehensive photometric survey and a users' attitude study in St Mary's school.[55,56] Their studies suggest that the visual aspects of glazing could not be ignored and that designers of passive-solar buildings should be at least as concerned with the interior visual consequences of glazing as with the interior thermal effects.

The studies of visual effects in the passive-solar buildings are, with few exceptions, concerned with what the occupants think and not with what they do. Consequently, there is a clear need to study the effect of the visual environment on people's behaviour. Furthermore, there is evidence that energy savings by using daylighting are little related to occupancy costs even under the most optimistic assumptions.[57] As a result, people began to consider that the most important benefits of daylighting in non-domestic buildings like schools and offices were not governed by energy conservation, but by the increase of occupants' satisfaction and performance.

Since the 1990s, a couple of studies have been conducted. They supported the premise that good daylight in the schools is positively related

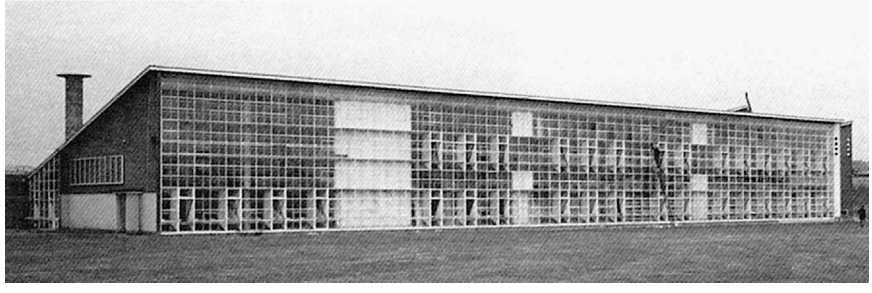

Figure 4 St Mary's School, Wallasey, UK, 1961.[9] Reproduced with permission of Her Majesty's Stationery Office, London, UK

to students' health and achievement. In 1992, a group of Swedish researchers monitored the health, behaviour, and hormone levels of 8-year-old students in four classrooms over 1 year in Sweden.[2] They found significant correlation between patterns of daylight level, hormone level, and student behaviour. The authors concluded, '*work in classrooms without daylight may upset the basic hormone pattern, and this in turn may influence the children's ability to concentrate or co-operate, and also eventually have an impact on annual body growth and sick leave.*'

In 1999 a survey, perhaps one of the largest ever done on daylighting in schools, was conducted by the Heschong Mahone Group.[3] The researchers analysed test score results for over 21 000 elementary students from three districts in the USA and looked for a correlation with the daylighting conditions of the classrooms. Their results revealed that children learned faster and did better on American standardized tests in the classrooms with good daylighting. Unfortunately, this study places an emphasis on skylight and ignores many important factors of daylighting such as the view out, etc.

2.5 Recent trends of daylighting in schools

A 'quality leap' in school design took place after late 1980s, as architects and educators responded to the changing needs and philosophies in education. Consequently, this 'quality leap' explored the needs for daylighting with the changes in school design throughout the past decade.

Some of the emerging trends that will shape the future of daylighting in school buildings are now discussed.

2.5.1 Information technology

As William[58] shows new teaching and learning technologies, such as computers, video-display terminals, and television were already changing the ways of teaching children as well as the needs of daylighting in a classroom in the recent years. These new teaching and learning technologies will continue to evolve. With the proliferation of such technologies, some interesting questions arise. Is it necessary to provide daylighting in a hi-tech classroom? How should good daylighting be provided in such classrooms? If VDT has to be used in a traditional classroom, how can the new requirements of daylighting be met through upgrading and renewal?

2.5.2 School hours

There is a worldwide move from the traditional 9:00 am to 3:00 pm school hours towards a longer school day. Schools in some countries are, and more will be, opened earlier in the day and later in the evening to serve adults as well as children. Similarly, more schools are expected to open 7 days a week and 12 months a year to serve different purposes of the neighbourhood community. The challenges generated by extending opening hours concern, solving overheating by sunlight and the integration of electrical lighting and daylighting.

2.5.3 Energy conservation and environmental consciousness

Energy conservation is one of the major concerns for school design since the oil crises and continues to influence school planning and design. Today, environmental consciousness, which includes much more than energy considerations, has imbued the designers of schools. For example, the concept of 'green schools' has appeared. School designers are placing emphasis on environmentally sound schools, which should result not only in a satisfactory level of comfort but also psychological health. The evidence for this is that attention is being paid to a burgeoning variety of daylighting techniques and methods in the USA.

The above trends show that daylighting will continually play an important role in school buildings in the future. Flexibility will be a key in influencing daylighting design in schools. Nowadays, for the benefit of people, designers are expected to consult the occupants and satisfy their perceptions and needs. From the point of view of environmental psychology, the effects

on the behaviour of the occupants in schools would be better woven into the more practical aspects of school design. In the near future, hopefully, a holistic approach, which incorporates health, comfort, satisfaction, and aesthetic pleasure within the environment as an essential part of daylighting quality, will be developed for daylighting design in schools.

3. Standards of daylighting in schools

In his 1913 paper, PJ Waldram stated, '*the minimum requirements of the London Building Act,*[59] *viz.: a glass area of one-tenth of the floor area for vertical lights and one-twelfth for skylights, are frequently adopted as maxima and the now discarded rule for schools of a glass area of one-fifth the floor space for vertical lights is equally respected.*'[10] In 1945, the British Standards Code of Practice recommended a minimal amount of sunlight over at least 10 months of the year and a minimum 2% 'sky factor' in classrooms.[14] However, JB Collins thought that these recommendations were somewhat arbitrary and were based on the conclusions of a survey reported in 1944.[13,60]

The legal requirements for schools set out in the 1954 regulations stipulated that, '*In all teaching accommodation and kitchens the level of maintained illuminance and the daylighting factor on the appropriate plane in the area of normal use, should be not less than 10 lumens per square foot (100 lux) and 2 per cent respectively*'.[61] The Code of the Illuminating Engineering Society issued in 1955 provided design guidance for the illuminance of the visual task, which was more onerous than that for normal use.[62] The regulations in 1954 also attempted to control glare in schools by limiting the brightness of 'lighting units' within the normal field of view of the building occupants to a maximum of 5000 cd/m^2. The revised 1954 regulation, however, permitted less daylight if lighting standards were adequately met by supplementing the daylighting with artificial light.

In 1977, the CIBS Lighting Code recommended that the minimum illuminance on the working plan should be 300 lux.[63] The Education (School Premises) Regulations 1981 specified that the educational buildings should be lit by daylight whenever possible.[64] Its requirement for the minimum illuminance on the working plane was 300 lux if fluorescent lamps were the lighting sources. Where lighting of a space was achieved by a combination of daylight and artificial light, the Code insisted on a minimum illuminance of 350 lux. However, the requirement for a minimum daylight factor across the appropriate working plane no longer existed in the 1981 Regulations. The Code for Environmental Design and Fuel Conservation in Educational Buildings (DES Design Note 17)[65] as well as the CIBSE Code For Interior Lighting, 1984 contain the requirements of the Education (School Premises) Regulations 1981.[66]

CIBSE Code For Interior Lighting, 1994 did not make any change to the Education (School Premises) Regulations 1981 but mentioned that DES Design Note 17[65] was currently under review.[67] In 1997, the constructional standards of Building Bulletin 87[68] recommended that a space is likely to be considered well lit if there was an average daylight factor of 4–5%. It also suggests that teaching spaces should have a view out and a minimum glazed area of 20% of the internal elevation of the exterior wall to give an adequate view out. Table 1 summarizes the regulations and standards for schools in the different periods in Britain. As can be seen, there is a trend for recommending higher illuminances with the passage of time. Also, more qualitative data are required as a result.

In comparison, the lighting regulations for schools in the USA require higher illuminances in the teaching space.[69,70] The Illumination Engineering Society of North America (IESNA) recommends 50 footcandles (538 lux) for regular class work and 100 footcandles (1076 lux) for instruction at a chalkboard in the 1980s. Also, IESNA suggests that an instructional space should provide a minimum of one window for an educational environment to be of adequate quality. The new, 9th Edition, of the IESNA Lighting Handbook still suggests that daylight is

Table 1 A summary of the regulations and standards in the different periods in Britain

Code	Recommended daylighting in classrooms
The London Building Acts 1894[59]	One-fifth the floor space for vertical lights in classrooms. Recommended illuminances in classroom is 9 footcandles (91 lux)
British Standards Codes of Practice, 1945[14]	A minimum 2% daylight 'sky factor' in classrooms, and 5% sky factor where possible in the classroom
IES lighting code, 1955[62]	The level of maintained illuminance and the daylighting factor in classrooms should be not less than 10 lumens per square foot (100 lux) and 2%, respectively
CIBS lighting code, 1977[63]	The minimum illuminance on working plane should be not less than 300 lux
The Education (School Premises) Regulations 1981[64]	For the daylight illuminance to be adequate for the task, it is necessary to achieve a level of not less than 300 lux. When the lighting of a space is achieved by a combination of daylight and artificial light, the regulations insist on a minimum illuminance of 350 lux.
CIBSE code for interior lighting, 1984[66]	Same as the Education (School Premises) Regulations 1981. Recommended illuminances in classroom is 300 lux.
CIBSE code for interior lighting, 1994[67]	Same as the Education (School Premises) Regulations 1981. Recommended illuminances in classroom is 300 lux.
Guidelines for environmental design in school, 1997[68]	The school premises: recommended illuminances in classroom shall be not less than 300 lux on the working plan. Recommended constructional standards: whenever possible, a daylit space should have an average daylight factor of 4–5%.

a primary consideration in schools.[71] With the movement from quantity to quality in the lighting professionals, this edition of the handbook does not recommend light levels for special applications or visual tasks. As a substitute, the handbook only lists the important factors that might affect quality of lighting in school buildings.

4. Discussion and conclusion

It is obvious that daylight has been the favoured 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.[12]

4.1 The major factors influencing daylighting in schools

Based on the review above, three major factors that affect the development of daylighting 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. 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 emerge 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. When the twenty-first century was reached, the needs for quality education demanded a multifunctioning 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 that 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.[72]

4.2 The future of school daylighting—lighting quality

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 colour in a classroom environment under different window conditions at different seasons in five Swedish secondary schools.[73] The study found that the observed sensation of colour 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.[74] 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 judgement.

In addition to the above research work, Building Bulletin 33 discussed the issue of daylighting quality in schools.[43] 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.[71]

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 (uniformity).

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.

Acknowledgements

The authors would like to thank Peter Tregenza, Guy Newsham and David L. Loe for reviewing the earlier draft and giving their invaluable comments.

5. References

1 Dunn R, Krimsky JS, Murray JB, Quinn PJ. Light up their lives: a research on the effects of lighting on children's achievement and behaviour. *The Reading Teacher* 1985; 38: 863–69.
2 Küller R, Lindsten C. Health and behaviour of children in classroom with and without windows. *J. Env. Psychol.* 1992; 12: 305–17.
3 Heschong L, Write LR, Okura S. Daylighting impacts on human performance in school. *J. Hum. Eng. Soc.* 2002; 31: 101–17.
4 Manning P ed. *The primary school: an environment for education.* Liverpool, University of Liverpool: Pilkington Research Unit, Department of Building Science, 1967.
5 Seaborne M. *The English school: its architecture and organization 1370–1870.* Toronto: University of Toronto Press, 1971: 8.
6 Robson ER. *School architecture: being practical remarks on the planning, designing, building and furnishing of school-houses.* London: John Murray, 1877 (2nd ed.).
7 Dudek M. *Architecture of schools: the new learning environments.* Oxford; Boston: Architectural Press, 2000.
8 Clay F. *Modern school buildings 49.* London: Batsford, 1929.
9 Great Britain, Department for Education, Architectures and Building Division. *Passive solar schools: a design guide, Building bulletin 79.* London: HMSO 1994.
10 Waldram PJ. Some problems in daylight illumination with special reference to school planning. *The Illuminating Engineer* 1914; 7: 15–27.
11 Gruber M. The daylight illumination of schoolrooms. An Abstract published in *The Illuminating Engineer* 1914; 7: 30.

12 Bell JAM. Development and practice in the daylighting of buildings. *Lighting Res. Technol.* 1973; 5: 173–85.
13 Post War Building Studies. *The light of building No. 12.* London: HMSO, 1945.
14 London British Standards Institution. *Code of functional requirements for buildings; sunlight; houses, flats and schools only.* British Standard Code of Practice, CP3, Chap. 1 (B),1945.
15 Stillman CG, Castle Cleary R. *The modern school, 75.* London: The Architectural Press, 1949.
16 Hopkinson RG, Longmore J, Murray Graham A. Simplified daylight table. *Nat. Building Studies, special Report, No. 26.* London: HMSO, 1958.
17 Hopkinson. RG, Longmore J. The permanent supplementary artificial lighting of interiors. *Trans. Illuminating Eng. Soc. London* 1959; 24: 121–48.
18 Manning P. An evaluation of a solar heated building. *Architect's Journal*, 1969; June.
19 Kay JD. Daylighting for schools. *Light Ltg* 1963; 56: 252–57.
20 Brown SW, Hult EE. New York's first windowless air-conditioned school. *ASHRAE J.* 1967; 1: 47–51.
21 Chambers JA. A study of attitudes and feeling towards windowless classrooms. Ed.D. Dissertation, Tennessee: University of Tennessee, USA, 1963.
22 McDonald EG. Opinions difference on windowless classrooms. *Natl Ed. Assoc. J.* 1961; 50: 12–14.
23 Lynes JA. *Principles of natural lighting*, Amsterdam, New York: Elsevier Pub. Co., 1968.
24 Graves BE. Pearson CA ed. *School ways: the planning and design of America's schools*, New York: McGraw-Hill, 1993.
25 Dudek M. The theoretical basis of comfort in the 'selective' control of environments, *Energy and Buildings* 1982; 5: 127–34.
26 Dudek M, Willey H. User response in environmental control system. *Transactions of the Martin Center for Architectural and Urban Studies,* Vol. 2. Cambridge: Wookhead-Faulkner, 1977.
27 Willey H. *The environmental control system of occupied buildings.* Transactions of the Martin Center for Architectural and Urban studies, Vol. 2. Cambridge: Wookhead-Faulkner, 1977.
28 Hawks D, Owers J ed. *The architecture of energy—user response in environmental control.* Harlow: Construction Press, 1982.
29 Burts E. Windowless classrooms: window help to promote better classroom learning. *J. Natl Ed. Assoc.* 1966; 50:13–14.
30 Karmel LJ. Effects of windowless classroom environment on high school students. *Perceptual and Motor Skills* 1965; 20: 227–78.
31 Tikkanen KT. Significance of windows in classrooms. MA Thesis, University of California at Berkeley, USA, 1970.
32 Tognoli J. The effect of windowless rooms and unembellished surroundings on attitudes and retention. *Environment and Behavior* 1973; 5: 191–201.
33 Demos GD, Davis S, Zuwaylif FF. Controlled physical classroom environment. *Building Res* 1967; 4: 60–62.
34 Larson CT. *The effect of windowless classroom on elementary schoolchildren.* Architectural Research Laboratory, Department of Architecture, University of Michigan, USA, 1975.
35 Collins BL. *Windows and people: a literature survey: psychological reaction to environments with and without windows.* Washington, DC: National Bureau of Standards, Building Science Series 70, 1975.
36 Collins BL. Review of the psychological reaction to windows. *Lighting Res. Technol.* 1976; 8: 80–8.
37 Boyce PR. *Human factors in lighting.* London: Applied Science Publisher, 1981: 355–77.
38 Wilson K. Intensive care delirium: the effect of outside deprivation in a windowless unit. *Archives of Internal Medicine* 1972; 130: 225–26.
39 Keep P, James J, Inman M. Windows in the intensive therapy unit. *Anaesthesia* 1980; 35:257–62.
40 Ulrich RS. View through a window may influence recovery from surgery. *Science* 1984; 224: 420–21.
41 Tikkanen KT. Spectral eye fatigue in a school environment. *Lighting Res. Technol.* 1979; 11: 185–88.
42 Stewart DM. Attitudes of school children to

daylight and fenestration. *Building and Environment* 1981; 16: 267–77.
43 Great Britain, Dept. of Education and Science. *Lighting in Schools, Building Bulletin 33*, London: HMSO, 1967: 3–12.
44 Ne'eman E. Visual aspect of sunlight in building. *Lighting Res. Technol.* 1974; 6: 159–64.
45 Ne'eman E, Longmore J. The integration of daylight with artificial light. *Proc. Commission International de L'Eclairage, TC-4.2 conference, Istanbul, Turkey*, 1973: K-1 to K-16.
46 Great Britain, Dept of Education and Science. *Energy Conservation in Educational Building, Building bulletin 55*. London: HMSO, 1977.
47 United States, Department of Energy. *Passive solar design handbook*. Sacramento: Solar Energy Information Service, 1981.
48 Crisp VHC. The light switch in buildings. *Lighting Res. Technol.* 1979; 10: P69–82.
49 Hildon A, Howrie AJ. A case study in energy efficiency: Sutton Coldfield Deanery First and Middle schools. *Energy and Buildings* 1982; 5: 117–25.
50 Baker N. The influence of thermal comfort and user control on design of a passive solar school building—Locksheath Primary school. *Energy and Buildings* 1982; 5: 135–45.
51 Crisp VHC, Littlefair PJ, Cooper I, Mckennan G. *Daylighting as a passive solar energy option: an assessment of its potential in non-domestic buildings*. Garston, Watford: Dept. of the Environment, Building Research Establishment, Building Research Station, 1988.
52 Davies MG. The solar technology of St. George's school, Wallasey, England. *Archit. Science Rev.* 1979; 22: 83–93.
53 Davies ADM, Davies MG. User reaction to the thermal environment—the attitude of teachers and children to St. George's School, Wallasey. *Building Science* 1971, 6:68.
54 Barrie E. Energy lessons from school. *Architect's J.* April 1995: 42.
55 Carter DJ. The lighting of St. Mary's School, Wallasey. *Building and Environment* 1984; 19: 209–15.
56 Mckennan GT. St. George's School Wallasey, the Visual Environment. *Building and Environment* 1985; 20: 61–71.
57 Daryanani S. Design consideration for the daylighting of new commercial buildings. *Energy and Building* 1984; 6: 109–18.
58 William BC. *Planning and designing schools*. New York: McGraw-Hill, 1998:148.
59 The London Building Acts 1894.
60 Collins JB The development of daylighting—a British view. *Lighting Res. Technol.* 1984; 16: 155–170.
61 Great Britain, Department of Education and Science. *Standards for Schools Premises Regulations*. London: HMSO, 1954.
62 Illuminating Engineering Society. *IES Code for Interior Lighting*. London: IES, 1955.
63 Chartered Institution of Building Services. *Code for Interior Lighting*. London: Chartered Institution of Building Services Engineers, 1977.
64 *Education (School Premises) Regulations 1981*. London: HMSO, 1981.
65 *Code for Environmental Design and Fuel Conservation in Educational Buildings, Design Note No. 17*. London: Department of Education and Science, 1981.
66 *Code for Interior Lighting, 1984*. London: Chartered Institution of Building Services Engineers, 1984: 52.
67 *Code for Interior Lighting, 1994*. London: Chartered Institution of Building Services Engineers, 1997: 77–78.
68 Great Britain, Dept. of Education and Science, Architects and Building Branch. *Guidelines for environmental design in schools 1997*. London: Stationery Office.
69 Kaufman JE ed. *IES lighting handbook*. New York: Illuminating Engineering Society of North America, 1984.
70 Kaufman JK ed. *IES lighting handbook, 1987 application volume*. New York: Illuminating Engineering Society of North America, 1987.
71 Rea MS ed. *The IESNA lighting handbook: reference &* application, (9th ed). New York: Illuminating Engineering Society of North America, 2000.
72 NEMA/LRI. *Lighting and human performance: A review,* Washington, DC: National Electrical Manufactures Association, 1989.
73 Tikkanen KT. A study of emotional reaction to light and colour in a school environment. *Lighting Res. Technol.* 1976; 8: 27–30.
74 Iwata T, Hatao A, Shukuya M, Kimura K. Visual comfort in the daylight luminous

environment: Structural model for evaluation. *Lighting Res. Technol.* 1994; 26: 91–97.
75 Seaborne M, Lowe R. *The English school: its architectural and organization 1870–1970.* London: Routledge & Kegan Paul, 1977 (2nd ed.).

Discussion

Comment on 'A review of the development of daylighting in schools' by W Wu and E Ng

PR Boyce (Lighting Research Center, Rensselaer Polytechnic Institute, Troy, New York, USA)

A review paper is always interesting because it provides the authors with an opportunity to consider where an area of study has been, where it is going, and where it should go. This paper takes two of these opportunities. It provides an extensive review of daylighting practice in schools and, in so doing, demonstrates that, as in so many other aspects of education, practice has been influenced by different theories at different times. The only weakness of this part of the review is that it takes examples of daylighting practice from various parts of the world and ignores the differences in climate, differences that can have a major impact on attitudes to daylight exposure. As for where daylighting in school is currently headed, the paper reveals that it is towards 'green' schools. It will be interesting to see what excesses are perpetrated on the occupants of schools by the zealots of this cause.

Where this review fails is in suggesting where the study of daylighting in schools ought to go. The direction suggested by the authors is to try to achieve a better understanding of daylighting quality. This parallels the movement towards a better understanding of lighting quality for electric lighting. A cynic might argue that, having made it easy to provide all the light necessary for visibility, without visual discomfort, the concept of lighting quality has been invented to provide lighting researchers and designers with something to do. The cynic would continue by arguing that, given this situation, further study of daylighting in schools is unnecessary. It is well established that people in general, both adults and children, like spaces to be illuminated by daylight when available, with a nice view out, provided that good visibility can be maintained and visual and thermal discomfort are avoided. Any competent architect or lighting designer should be able to achieve these conditions, given an understanding of the climate, and a willingness to consider all the requirements of the people using the space.

An alternative belief would be that there is something about daylight that makes it more effective than electric lighting in schools for both scholastic performance and children's well-being. The authors refer to a number of papers relevant to this belief, but there is no consistency in the conclusions reached, some showing no impact and others a positive impact of daylighting. Nonetheless, the validity of this belief is a critical question and one worth pursuing until a conclusive answer is achieved. The future of daylighting in schools should be based on the demonstrated effects of daylighting on scholastic achievement and children's well-being, and a clear understanding of why those effects occur, not on the pursuit of the will-o'-the wisp called daylighting quality.

Authors' response to PR Boyce

W Wu and E Ng

We greatly appreciate the valuable comments made by Dr Boyce. The review merely states our current state of knowledge. It relates some of the previous research efforts to changes in teaching philosophy and it points out the need for further research, especially for more contextually based data.

We agree with Dr Boyce that differences in climate have a major impact on attitude to daylight exposure in school. The review actually highlights a lack of knowledge in this respect. Since most previous research work has taken place in Europe and in North America, the