DAYLIGHTING IN OFFICE BUILDINGS

by

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Abstract

This thesis presents a conceptual framework for the introduction of daylighting considerations into the design of office buildings. Design is an intuitive process, yet the intuition must be educated by study and analysis. The framework developed in the thesis enables the systematic study of daylighting principles and techniques and is a major step towards a grasp of daylighting design.

The thesis is divided into nine chapters. The introductory chapter contains a brief history of daylighting in office buildings, examines reasons for daylighting, and explains the structure of the thesis. The following chapter analyses the performance criteria that the luminous environment in office interiors must fulfill in order to provide a satisfactory performance of visual tasks and result in user acceptance.

Each of the next five chapters examine specific techniques, under five general objectives:

i. promoting daylight access
ii. promoting daylight penetration
iii. interior space planning for daylighting advantage
iv. controlling brightness extremes
v. integrating daylight with electrical light

In each chapter, these techniques are listed in order of decreasing scale: from site planning, through building configuration and building envelope, to building interior.

The thesis shows that daylighting can be incorporated into building design at various levels of commitment, ranging from a total commitment to daylighting, in which the building is conceived as "a light fixture that can be engineered to a state of optimal performance", to a minor commitment, in which, for example, perimeter lights in an otherwise standard office building design are controlled in response to daylighting needs. Furthermore, it is shown that daylighting techniques can be introduced at various scales--some techniques may modulate the massing, while others deal with specific building components.

Following the study of techniques, there is a discussion on daylighting design tools and the integration of daylighting with other aspects of design.

The thesis concludes that daylighting offers architects the opportunity to design office buildings so that they use less energy and, at the same time, provide a better working environment than is the case with most buildings today.

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I wish to extend my appreciation to Professor Raymond J. Cole for his patient guidance and striving for excellence. Much of the merit this paper has is due to him, although its shortcomings are obviously due to my own limited vision.

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Finally, my thanks go to my wife, Catharine, and daughter, Megan, for their continued and cheerful support.

I.

INTRODUCTION

We were born of light. The seasons are felt through light. We only know the world as it is evoked by light, and from this comes the thought that material is spent light. To me natural light is the only light, because it has mood--it provides a ground of common agreement for man--it puts us in touch with the eternal. Natural light is the only light that makes architecture architecture.

Louis Kahn[1]

When it comes to design--the design of our environment, cities, buildings, houses, utensils, clothes, furniture, cars and planes--there is one overriding test: is it done with a deep sense of commitment to people, a commitment in the broadest sense to man in all his complexities--his desires, hopes, fears,and, above all, his well-being? It is a surprisingly simple test."

Moshe Safdie[2]

1. NATURAL LIGHT AND ARCHITECTURE

Light gives life to form, to pattern, to void and solid. Architecture is the shaping, in light, of vessels for human activities--made of void and solid, pattern, form.

The light of the sun--diffused through sky and clouds and reflected from the ground--has inevitably been the means of celebrating the power and majesty, the drama and play of architecture, both on the exterior and the interior of buildings.

The use of natural light for the lighting of interior spaces, with the predominant goal of facilitating the performance of visual activities, we call daylighting. Daylighting is coeval with architecture. Until as recently as sixty years ago, daylight was the pre-eminent means of lighting the interior of buildings.

The need to allow daylight into building interiors has naturally had an impact on massing, layout and detailing of buildings. The extent of this impact has been greater in building types dedicated to visually demanding activities, such as industrial buildings, hospitals and office buildings. This thesis explores the impact of daylighting requirements on the form and detailing of the modern office building. This building type was chosen, because it is the predominant type in the commercial/institutional building sector. Furthermore, energy use for office buildings is a substantial percentage of the total building sector use, and daylighting can help in reducing these costs. Lastly, the nature of visual tasks in offices is demanding enough to offer scope for testing daylighting principles and techniques.

2. HISTORY OF DAYLIGHTING IN OFFICE BUILDINGS

The history of daylighting in office buildings may be divided into four eras, as shown in figure 1 .

Exclusive use of daylighting

Office buildings became a separate building type, physically removed from industrial facilities, soon after the onset of the Industrial Revolution in the early 1800's[3]. Their number multiplied as the increasing complexity of organizations led to a steadily rising demand for management and clerical personnel.

By 1890, the telephone, the electric lamp and the electric elevator had all been invented, and the first steel frame high-rise building had been constructed in New York City[4]. These developments laid the groundwork for a revolution in the design of large buildings and in the appearance of cities.

In this period, the depth (i.e. the width in plan) of office buildings was limited by the daylight penetration. With the prevalent ceiling heights, satisfactory daylighting could be obtained to a depth of about 6m. Thus, with double-loaded

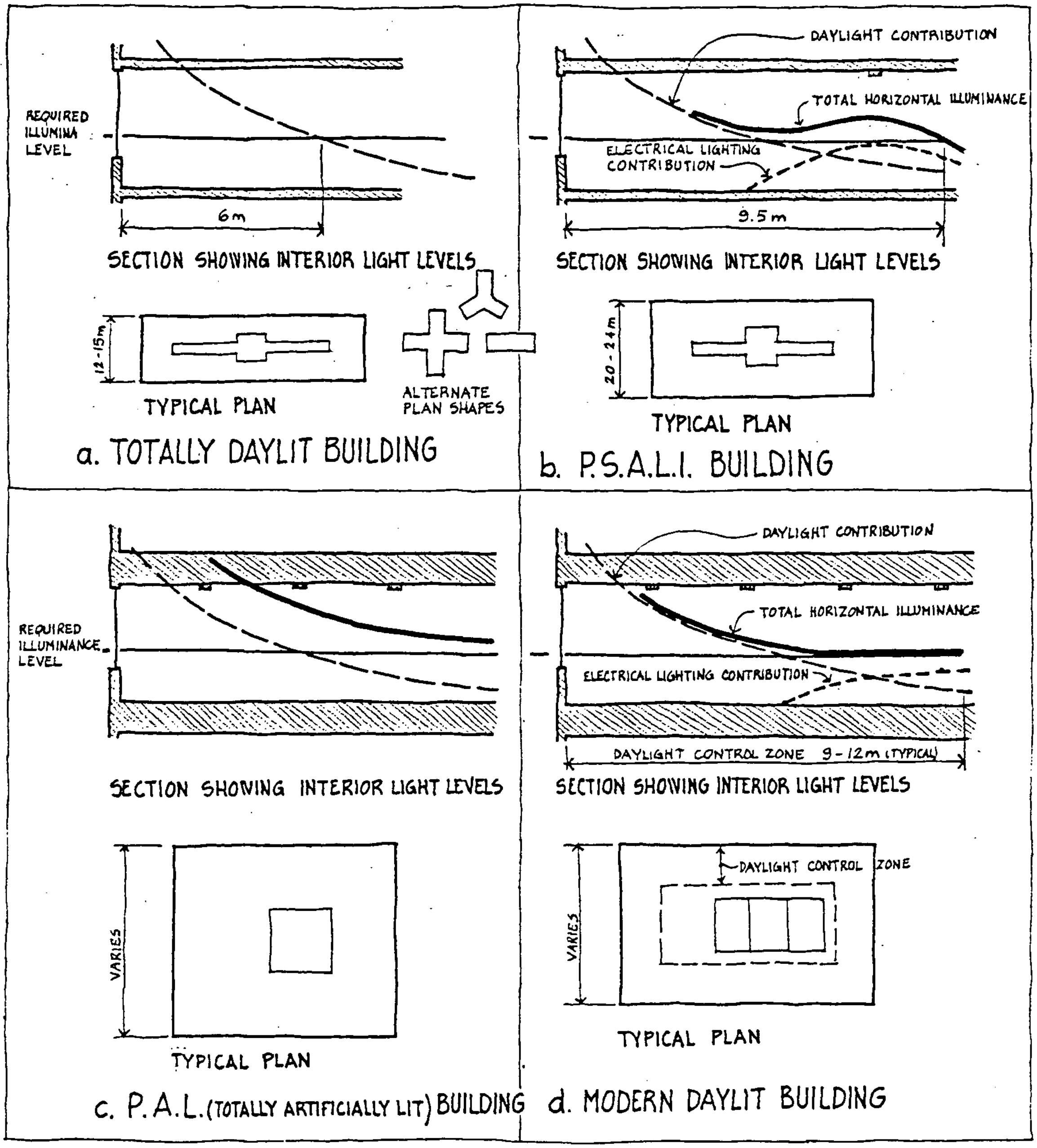


Figure 1 - Office building form and daylighting in history

corridors, the typical building depth generated was thus 12 to 15m[5].

Early office buildings were restricted in height to 3-5 floors by the limitations of construction materials and the lack of elevators. By the turn of the century, the steel frame and elevators made possible taller office buildings. However, their depth remained limited, as before, by daylight penetration. The resulting buildings were thus tall and thin, slablike; with rectangular, 'U', 'X' shaped, or similar floor plans(figure 1 a).

Transition from daylighting to exclusive electric lighting

In the two decades between the World Wars, technological improvements in electrical lighting led to its proliferation. After the Second World War, a system of lighting known as Permanent Supplementary Artificially Lit Interiors (PSALI) was proposed in Europe for institutional and commercial buildings. It endeavoured to increase the depth of office space by having the areas at a distance from windows permanently lit by electric light[6]. The added benefits were the feasibility of lower ceiling heights and a reduction in the luminous gradient from windows to the back[7]. The depth of useful space was extended to about 9.5m, resulting in an overall building width of 20 to 24m[8] (figure 1 b.). The concept of PSALI was experimented with in Europe for about a decade, but because of rapidly changing technology, complexity of the design process, or perhaps philosophical resistance, it was eventually dropped in favour of the "North-American" system of all-electric lighting[9].

Exclusive use of electric light

After the Second World War, rapid progress in mechanical and electrical systems made possible the creation of artificially controlled environments. Inexpensive electricity, utility company advertising, and engineering zeal, all contributed to the design of Permanently Artificially Lit (PAL) buildings[10]. Consideration of natural lighting was not considered a criterion for choosing the massing, floor plan and depth of these buildings. As a result, office spaces 40m or greater in depth became common[11] (figure 1 c).

Light came to be understood only in terms of light fixtures; windows were reduced to viewing apertures and abstract design elements on facades; the users had to adapt to the inconveniences of any heating or cooling problem these design decisions created, and/or more equipment was introduced to counter the negative effects[12]. Electric lights were used day and night, and eventually electric lighting, and the energy used to remove the heat generated by lighting, became the largest portions of the energy used in office buildings[13],[14].

Integration of daylight with electric lighting

The energy crisis of 1973-74 has brought about changes in all industrialized economies. In the office building sector, lighting has been clearly identified as the most important energy conservation item. Optimum building depths for daylighting have been rediscovered (figure 1 d.), but advanced HVAC and lighting technology now allows flexibility in this regard.

Energy responsive, daylit office buildings designed shortly after the energy crisis[15] were typically premised on the idea that "the building is a light fixture that can be engineered to a state of optimal performance"[16]. More recently, issues of both light quality and quantity are being addressed by many designers. Many recent projects have demonstrated that natural light can be a beautiful, as well as efficient, source of light[17].

3. REASONS FOR DAYLIGHTING

There are many advantages to daylighting that more than compensate for the extra time, patience and ingenuity needed to integrate daylighting concepts with other requirements. These may be addressed under the following headings:

i. Considerations of user satisfaction

ii. Economic considerations

iii. Socio-political and environmental considerations

iv. Philosophical considerations

3.1 Consideration Of User Satisfaction

Daylight influences various aspects of our being: our bodies react to the energies in light, our eyes perceive it, our minds interpret the information and our emotions react to these. While these influences are highly interactive, they can nevertheless be considered as affecting essentially either the productivity, comfort, or health of building users. The consideration of improved human satisfaction is central in the design of daylit office buildings. These issues will be discussed at some length in chapter 2.

3.2 Economic Considerations

Whatever the merit of daylighting may be in terms of environmental benefits--both at the human and at the societal scale--economic benefits on a project by project basis must be demonstrated, in order for it to gain acceptance. Economic benefits fall under one of the following:

i. savings in electrical energy
ii. savings in peak demand charge
iii. failure tolerance
iv. increased building value
v. legal and taxation incentives

Savings in electrical energy

Widely published literature by researchers, architects, illuminating engineers and mechanical engineers indicates that daylighting can provide substantial savings in the electrical energy used in office buildings[18,19,20,21,22,23]. Lighting is a dominant load in office buildings. Average figures for North America indicate that electrical energy used in these buildings attributable to lighting is between 40-50% of annual energy consumption[24]. For mild climates like California, this figure can be up to 60% of total on-site energy consumption[25]. For cold climates, because of the extra heating load, the percentage figures attributable to lighting may be less per unit floor area, but the absolute figures are similar[26].

When we look at energy costs, rather than energy units, the importance of lighting becomes even more evident. Heating, the other main component of the energy load in office buildings, is generally provided by fossil fuels on site, whereas lighting and air conditioning use electricity, which is more expensive per unit of energy and incurs peak demand charges that further add to its cost. Thus, lighting clearly becomes the major target for energy conservation in office buildings.

Savings due to a reduction in peak demand

Owners of office buildings pay for their electricity not only in energy consumed but also for their peak power demand, called a demand charge. This demand charge reflects the cost incurred by the utility in having to provide electrical generating capacity sufficient to meet the peak demand; this generating equipment is inevitably idle at other than peak demand times[27]. Demand charges[28] are a significant fraction of the total electrical bill[29,30]. Most of this demand charge is money that can be saved by the building owner with appropriate microprocessor controls, off-peak thermal storage, on-site power generation and/or with daylighting[31].

Electrical consumption in office buildings typically peaks during summer months[32], when cooling loads are at a maximum. This coincides with the time of most abundant daylight: the sun is up for more hours, outdoor illumination levels are higher and clear skies are more prevalent. By substituting part of the electrical lighting component with daylight, peak power demand can be considerably reduced[33]. A secondary effect of a reduction electrical lighting is a proportionate reduction in the heat-of-light component of the cooling load: every watt reduction in electrical lighting results in 1/2 watt reduction in the cooling load[34]. However, this reduction can only be realized if appropriate steps are taken, at the same time, to minimize solar heat gain.

Bryan[35] has indicated that in many instances, the savings in peak demand charge through daylighting can be significantly greater than savings in energy costs. Selkowitz[36] and Bobenhausen and Lewis[37] have calculated that between typically 10-20% of peak power savings can be achieved by daylighting conventionally designed buildings.

Failure tolerance of daylit buildings

Our buildings, especially the larger ones, are dependent on complex, centralized energy systems to meet user needs. The electrical grid is one of these systems. Disruptions, although not common, have generated large scale disasters when they have happened in recent years. Selkowitz[38] writes concerning failure tolerance of daylit buildings:

> Daylighting, as well as passive solar heating and cooling, is a design option which, at the scale of a single building, reverses the trend toward greater reliance on remote centralized systems. As such, it has a flexibility and a degree of failure tolerance that appears to be important, but which is difficult to quantify. Activities in a building with daylighting will be less subject to disruption from a power failure or brownout than those relying entirely on electricity for illumination.

Selkowitz has made preliminary calculations on the cost of disruption due to a power loss on worker productivity[39]. With present worker's salaries and energy costs for a typical office situation, the savings resulting from even a single hour's productive work during a power loss are significant. In fact, though energy savings are not insignifiant, the savings due to even that one hour is equivalent in dollar value to energy savings for a whole year.

Savings in life cylcle costs

Daylighting schemes are potentially economical at present energy costs for a large number of office buildings, if the life cycle cost of the building is used as a criterion. These schemes are penalized by short term investment goals[40]. For some of the more elaborate daylighting strategies (eg. beamed daylighting) economic viability may have to take into account the increased value of the building due to an improved visual environment and consequent increase in worker productivity.

Lam, whose consulting firm has extensive daylighting experience, has stated that with appropriate integration of architecture, structure and services, it is possible to realize even first cost savings for elaborately daylit projects[41]. This is confirmed by Bryan and Bazjanac[42]. Such success undoubtedly depends largely on the skills of the consultants and their co-operation. Notwithstanding Lam's comments, many authorities in the field concede that elaborate daylighting schemes will usually carry a first cost penalty[43]. With less elaborate schemes, even without optimum integration between architecture, structure and services, net savings in initial capital cost may be realized in addition to energy savings throughout the life of the building. This is because the extra cost of dimmers and circuiting is more than offset by reduced chiller sizes and smaller HVAC distribution components[44]. As daylighting design expertise within the professions increases, as the technology matures, as the construction industry becomes more familiar with daylighting concepts, and as the cost of conventional energy sources continues to escalate, the life cycle cost of daylighting schemes will become more and more favourable.

Increased building value

An increase in building value due to improved environmental conditions--as would be in the case of a well designed daylit building--can be tangible, but not readily quantifiable. An increased building value can be demonstrated if the improved environmental conditions can translate, on the speculative market, into higher rental value; or in perceptible gain in productivity, for the owner-tenant, due to increased worker well-being.

Workers' enthusiasm for the luminous environment in some daylit buildings has been noted in the literature[45]. If this enthusiasm can be demonstrated to result in increased well-being and higher productivity, then this benefit will certainly increase the value of the building. Because more than 90% of overall costs of operating a commercial enterprise goes to salaries, with only about 8% accounting for the construction and operation of the building, an improvement of worker productivity of only 6 1/2% would be cost effective even if it quadrupled the cost of the building[46].

Daylit commercial buildings can also be shown to have an increased value because, using less electrical energy, they afford a degree of protection from inflation and escalating fuel prices[47].

Social attitudes change, sometimes rapidly. The increased frustration experienced by workers from many environmental factors in present-day offices[48,49,50], may, in a few years, radically alter the value we give to passive environmental technologies. Preference may shift strongly towards these passive environmental solutions, including daylighting.

Legal and taxation incentives

Two major legal devices may greatly increase the use of daylighting:

i. incentives in the form of subsidies or tax breaks

ii. mandatory daylighting requirements in the form of zoning by-laws and building codes

Incentives may consist of loans, grants, income tax rebates, etc. for daylighting components. Government assistance and regulation can do a great deal in overcoming the short term disadvantages of concepts--such as daylighting--that clearly provide long term benefits. These would be similar to tax credits, etc. available for passive solar heating in many states of U.S.A.

It has been suggested[51] that some utilities could profitably subsidize the cost of dimmers, ballasts and circuitry associated with daylighting schemes, as they would thus not need to add to their peak demand capacity; the payback for the utilities for this investment would be excellent--about 2-4 years[52].

Codification is another device that will inevitably increase the use of daylighting. Minimum daylighting standards for all building types, as well as for urban planning, were codified in Great Britain in the 1940s through 60s[53,54,55] and resulted in widespread use of daylight in buildings. No such standards have been adopted in Canada[56].

The California Energy Commission has recently developed

Energy Efficiency Standards for non-residential buildings. One major method prescribed for reducing energy usage is by daylighting[57]. This will have the effect of creating a greater awareness by both the design professionals and developers about the potentials of daylighting. If energy budgets for new commercial buildings become mandatory in more jurisdictions, and especially if minimum daylighting standards will be codified, daylighting will enter into the mainstream of design practice.

In 1982, daylighting considerations became mandated as part of zoning regulations of Midtown New York City. The city planning department used daylight availability inside buildings and on the street, as a major criterion for controlling building bulk[58,59]. The kind of regulations used for New York, only creates the potential for, but does not guarantee, a sensitive urban infrastructure. Nevertheless, it can be expected that through the process of mandating daylighting considerations, the multifaceted benefits of daylighting will become more widely appreciated.

3.3 Socio-political And Environmental Considerations

Passive environmental technologies--also termed "soft energy paths"[60]--of which daylighting is a particular form, do not have the large scale negative environmental, economic and socio-political consequences that centralized coal, oil, or nuclear based energy systems--"hard energy paths"--have[61]. Daylighting is therefore a real, if humble, contribution to the resolution of these larger problems. Daylighting of commercial buildings enables:

i. reduction in additional electrical utility generation capacity

ii. reduction of dependence on imported fossil fuel

iii. reduction of dependence on centralized energy distribution networks

Schumacher[62], Bockris[63], Lovins[64] and most recently, Lovins and Lovins[65], have discussed at length the large scale implications of energy use strategies.

3.4 Philosophical Considerations

> You get an order from the schoolboard that says, 'We have a great idea. We should not put windows in the school, because the children need wall space for their paintings, and also windows can distract from the teacher.' Now, what teacher deserves that much attention? I'd like to know. Because after all, the bird outside, the person scurrying for shelter in the rain, the leaves falling from the tree, the clouds passing by, the sun penetrating: these are all great things. They are lessons in themselves.
>
> Windows are essential to the school. You are made from light, and therefore you must live with the sense that light is important... Without light there is no architecture.[66]

In the above passage, Louis Kahn talks about schools, but what he says is archetypal and holds true, in essence, about any building within which people spend their lives. Good architecture exhibits a commitment to the well-being--in the broadest sense of the word--of the people whose lives it affects.

Daylight and sunlight touch deep chords within us. The rhythm of day and night is a constant reminder of an order in the cosmos that transcends the more immediate chaos on earth. The miracle of annual rebirth of plant life is triggered by the sun's rays and sustained by its energies. No two days are alike in character--a reminder of inevitable changes in our lives, within a framework of orderly rhythm. Daylight is available to all people--it can be shared and is not, as a result, exhausted--reminding us that co-operation can transcend competition. Finally, bringing daylight indoors can help celebrate the beauty of the world we live in--a celebration that can be a powerful antidote to the global turmoil which besets our times.

4. SCOPE OF THESIS

4.1 Goal Of Thesis

With the re-emergence of daylighting as a viable method of interior illumination and energy conservation strategy in office buildings, there has been a tremendous body of information emerging on all facets of the problem. Yet, there has been to date no published work on establishing a comprehensive conceptual framework for daylighting techniques[67].

At the present stage of the collective professional experience, educating the intuition is an important part of the process of daylighting design[68]. This thesis provides a framework for daylighting principles and techniques which will assist in educating the designer's intuition, as a stepping-stone to designing with daylight.

4.2 Structure Of Thesis

The thesis examines the following:

i. principles of design for the visual environment

ii. conceptual framework for daylighting techniques

iii. integration of daylighting in design

The interior visual environment

Design with daylighting can only be accomplished if the goals of daylighting are explicit. These goals can be expressed in terms visual quality parameters. Chapter 2 therefore provides an overview of the parameters which are of primary importance in daylighting.

A conceptual framework for daylighting techniques

The essential problem of designing a daylit space arises from two facts:

i. Daylight originates outside the space being lit

ii. Daylight is variable

The science and art of daylighting consists largely of responses to these two issues in terms of design and construction techniques whose aim is bringing daylight into interiors under controlled conditions and compensating for its variability. These techniques can be classified as follows:

1. Techniques aimed at maximizing daylight potential:
   - i. providing access to available daylight through massing, layout, etc.
   - ii. providing apertures through which daylight can enter into the building interior
   - iii. planning the interior space to take advantage of interior daylight.
2. Techniques aimed at control of daylight and its integration with electrical lighting:
   - i. controlling brightness extremes
   - ii. integrating with electrical lighting

The main body of the thesis consists of a range of these techniques, organized in a matrix. One dimension of this matrix lists the objectives being aimed at, as outlined above. The other dimension of the matrix is that of the scale being considered. Scale thus encompasses progressively more specific concerns: site planning (including landscaping and building clustering); building configuration (including massing and plan); building component; and building interior. The "scale" dimension of the matrix enables any technique under a particular objective to be sorted according to its level of generality, and hence, the stage at which it will be considered in design[69]. Table I shows the complete matrix.

In the chapters that describe the techniques, the format used is that of grouping them by objective, and under each

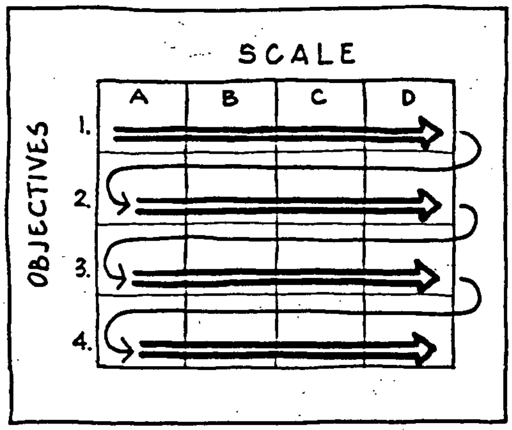
OBJECTIVES	SCALE: SITE PLANNING	BUILDING CONFIGURATION	BUILDING COMPONENT	BUILDING INTERIOR
DAYLIGHT ACCESS	• BUILDING CLUSTERING • EXTERIOR SURFACES	• BUILDING MASSING • BUILDING LAYOUT • ATRIA • NORTH AND SOUTH ORIENTATION • INTERIOR SUNLIGHT • DAYLIGHTING SEPARATE FROM VIEW • DAYLIGHTING FROM THE TOP	• OBSTRUCTIONS	
DAYLIGHT PENETRATION			• CONFIGURATION AND LOCATION OF DAYL. APERTURE • GLAZING MATERIAL SELECTION • MAINTENANCE FACTOR • NET GLAZING AREA • DEPTH & DETAIL'G OF WALL AROUND DAYL. APERT.	• ROOM GEOMETRY • INTERIOR REFLECTANCES
			• DEEP DAYLIGHT'G THROUGH VIEW WINDOWS • DEEP DAYLIGHT'G THR. WALL APERT. ABOVE EYE LEVEL • DEEP DAYLIGHT'G THROUGH ROOF APERTURES	
SPACE PLANNING				• LOCATION OF ACTIVITIES • OPEN PLAN INTERIOR • LOCATION OF CELLULAR OFFICES • DETAILING OF CELLULAR OFFICES • DAYLIGHTING AND ACOUSTICS
CONTROL OF BRIGHTNESS	• LANDSCAP'G FOR GLARE CONTROL	• DAYLIGHTING FROM MORE THAN ONE DIRECTION	• GLARE/SOLAR HEAT CONTROL – EAST & WEST • GLARE/SOLAR HEAT CONTROL – SOUTH • GLARE CONTROL – NORTH • GLAZING TILT	• INTERIOR LIGHTSHELVES • CONTRAST GRADING • LIGHT-COLOURED SURFACES
INTEGRATION WITH ELECTRIC LIGHT				• LIGHTING PHILOSOPHY • FIXTURE CIRCUITING • AUTOMATIC CONTROLS

Table I - Matrix of daylighting techniques objective, examining techniques in turn, in order of decreasing scale. This organization is shown schematically in figure 2 a. According to Ubbelohde et al.[70], this type of format is appropriate for lectures and study: it facilitates the understanding of, and developing relationships for, several principles in turn.

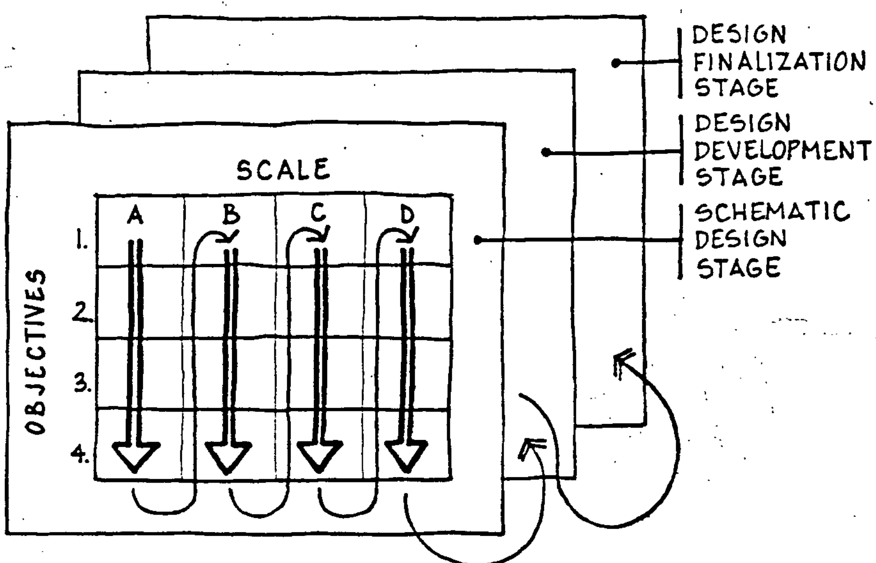
Chapters 3, 4 and 5 examine a range of techniques that aim at maximizing daylight potential. Techniques for promoting daylight access, for promoting daylight penetration, and for improving interior space organization are treated in turn, in an order of decreasing scale. Chapters 6 consists of techniques for controlling daylight: methods of avoiding brightness extremes in general, and glare in particular, are examined. Chapter 7 examines the co-ordination and integration of daylight with electric lighting: the salient features of successfully integrated daylighting/electrical lighting designs are overviewed.

Daylighting and the process of design

By contradistinction to the study situation, the design process unfolds from the general to the specific, and from larger to smaller scale, with all objectives being given some consideration at each step[71,72]. Furthermore, the design process is iterative, and a third dimension emerges in the matrix: it consists of the various stages of design--conceptual, schematic, design development[73]. For design purposes, therefore, the matrix would be arranged as shown in figure 2 b.



SEQUENCE OF TECHNIQUES DURING <u>LEARNING STAGE</u> (SEQUENCE FOLLOWED IN THE THESIS)



SEQUENCE OF TECHNIQUES DURING <u>DESIGN STAGE</u>

Figure 2 - Matrix arranged according to (a.) study or (b.) design format

Chapter 8 outlines how daylighting concepts may be assimilated into the design process. An assessment of daylighting design tools is first given. This is followed by observations on the integration of daylighting into the overall design process.

Chapter 9 summarizes the findings and places them into the larger perspective of future office building design.

5. NOTES

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5. Leu, p.56.
6. R. G. Hopkinson, Architectural Physics: Lighting (London: Her Majesty's Stationery Office, 1963), pp. 298-300.
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13. Fred S. Dubin and Chalmers G. Long, Energy Conservation Standards (New York: McGraw-Hill, 1978), p. 8.

14. Leu, p. 61.

15. For example, the TVA building, in Chattanouga, Tenn.

16. Lakin and Millet, p. 498.

17. Ibid.

18. Selkowitz mentions savings of 10-75% of total lighting energy, depending on the level of commitment to daylighting, and on the building program. Stephen Selkowitz, "Daylighting and Passive Solar Buildings," Proceedings of the 3rd National Passive Solar Conference, January 11-13, 1979 in San Jose, Calif., Newark, Delaware: American Section of the International Solar Energy Society, 1979, pp. 277-78.

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21. Lighting Design and Applications, "TVA Office Complex - A Teamwork Approach to Energy Efficiency," Lighting Design and Applications, November 1980, p. 33.

22. Sanchez and Rudoy mention reductions in electrical lighting consumtion of up to 90%, with proper daylighting design. Nestor E. Sanchez and William Rudoy, "Energy Impact of the Use of Daylighting in Offices," ASHRAE

Transactions, 1981, pt.2, pp. 145-60.

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26. Dubin and Long, p. 5.

27. In fact, the absolute utility peak time is the most important for the utilities. This may occur in summer or winter, depending on the climate and mix of building types in the region. Relative daily or monthly peaks are important to customers, as these determine the demand portion of the electric bill.

28. Many utilities have also implemented "time-of-day" pricing as an extension of peak demand charges.

29. Selkowitz, p. 277.

30. Approximately 35% of utility bill. Varies with location and user rate schedule. General Services Administaation, Energy Conservation Guidelines for Building Operations (Washington, D. C.: GSA, [1975]), p. 22.

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32. Assuming a gas, or oil fired boiler for heating.

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II.

DAYLIGHT IN THE INTERIOR VISUAL ENVIRONMENT

1. INTRODUCTION

Light in buildings serves two basic functions:

i. It enables the occupant to accomplish visual tasks such as: reading, writing, holding meetings, examining goods, etc. This "task lighting" can be considered broadly as "light to see by".

ii. It provides visual definition of spaces: a sense of orientation, drama, visual focus; and satisfies physiological and psychological needs. This "ambient lighting" can be broadly considered as "light to see".

In this chapter, the requirements of lighting for task performance and lighting for perception of space are examined, drawing particular emphasis to the suitability of daylight in fulfilling these two purposes.

2. TASK LIGHTING--"LIGHT TO SEE BY"

2.1 The Task Performing System

Lighting is only one of many components, albeit an important one, in the task performing system. An examination of these components is therefore useful as a means of placing the influence of lighting in context. Figure 3 [1] illustrates that

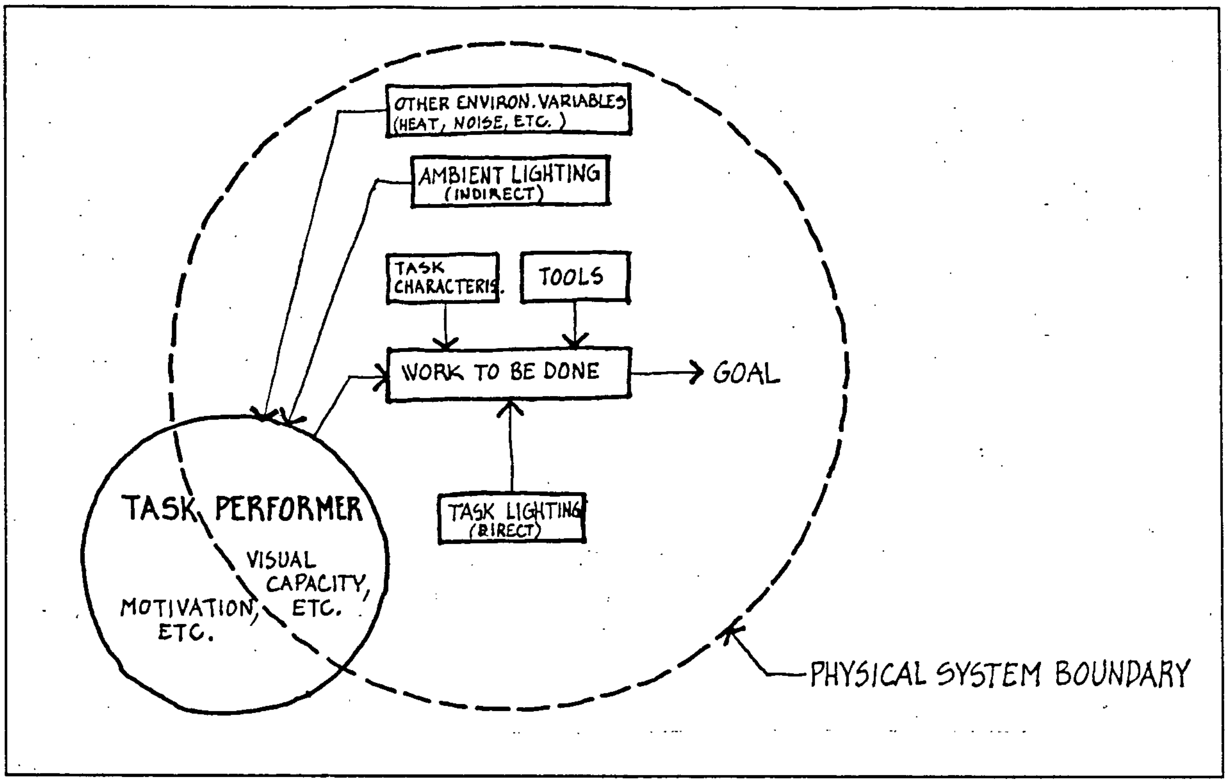

Figure 3 - Components of the task performing system

components in this system may affect task performance either indirectly or directly.

Components that influence task performance indirectly are:

i. environmental variables such as: heat, humidity, noise, etc.--by affecting physiological mechanisms of the task performer

ii. the ambient lighting--by affecting the comfort and sense of satisfaction of the the task performer with the visual environment

iii. the task performer's social environment, motivation, attitude, expectation, skill, etc.

The last of these components are non-physical variables that can only marginally be controlled by manipulation of the physical environment, yet they can substantially influence task performance[2].

Components that directly influence task performance do so by affecting the ability of the task performer to extract information from the visual environment. Such requirements for visibility may involve detection, recognition or identification[3], becoming progressively more stringent as one proceeds from detection through recognition to identification. There are three components whose characteristics affects task performance directly. These are:

i. the task

ii. response of the task performer

iii. the lighting

2.2 Characteristics Of Task

Table II , adapted from Harker[4], summarizes the effects of the physical characteristics of the task which affect task visibility. In general office situations, the size and contrast of the task are the most important task characteristics affecting visibility[5,6]. An increase in contrast and the resulting increase in visibility has a much greater influence on visual performance than corresponding changes in illuminance[7,8]. Levy[9] has even shown that increasing the illuminance on a task of low contrast may never be able to bring about the performance level of a task of higher contrast. Berman and Clear[10] have calculated that, for light levels above as little as 100 lux in a typical office situation, an improvement in contrast or

TASK ATTRIBUTE	DEFINING CHARACTERISTICS	COMMENTS
SIZE	ANGULAR SEPARATION, CYCLE FREQUENCY OF DETAIL	PREDICTABLE CONSEQUENCES FOR EASE OF SEEING
CONTRAST	ACHROMATIC, RELATIVE REFLECTANCES OF DETAIL AND BACKGROUND	PREDICTABLE CONSEQUENCES WHICH INTERACT WITH SIZE
	CHROMATIC, BIAS IN RELATIVE REFLECTANCE AT DIFFERENT WAVELENGTHS	KNOWN EFFECTS BUT DIFFICULT TO QUANTIFY
DEPTH	TWO DIMENSIONAL VERSUS THREE DIMENSIONAL TEXTURE	VARIANCE IN OFFICE TASKS IS NOT AS GREAT AS IN INDUSTRIAL TASKS
SPECULARITY	SELECTIVE REFLECTIONS AT DIFFERENT VIEWING ANGLES TO THE SURFACE, WICH ARE SPECIFIC TO THE VIEWING POSITION	SOURCE OF CONSIDERABLE VARIANCE
DENSITY OF DETAIL	DETAIL EMBEDDED IN A COMPLEX ARRAY	PROBLEM FOR DETECTION OF INFREQUENTLY OCCURRING ITEMS
PATTERN	REGULARITY	MAY AID IN LOCATION OF DETAIL
TIME AVAILABLE FOR VIEWING	DEFINITIONS OF RIGID, SEMI-RIGID PACING VERSUS THE UNPACED CONDITION	VERY RIGID PACING IS UNDESIRABLE FOR THE HUMAN OPERATOR
CONSISTENCY OF SENSORY INPUT	COINCIDENCE OF VISUAL AND OTHER SIGNALS	NEED TO IDENTIFY THE CRITICAL CUES

Table II - Task characteristics affecting visibility

contrast sensitivity is 3 to 10 times more cost effective than an increase in illuminance on task. This improvement may be accomplished, for example, by using forms with larger print, xerographic copies instead of carbon or mimeograph, etc.

2.3 Task Performer Response Characteristics

The response characteristics of the task performer directly affecting task visibility are summarized in table III [11]. These include visual capacity, position with respect to the task, visual adaptation, etc.

The ability of the human eye to adapt to a very wide range of luminances, is an important phenomenon in the design of interior lighting. The eye adapts to a general level of luminance and can perceive a range of brightnesses above and

PERFORMER RESPONSE	DEFINING CHARACTERISTICS	COMMENTS
VISUAL CAPACITY	· ABILITY TO FOCUS THE EYE · CONTRAST SENSITIVITY	· VARIES WITH INDIVIDUAL · DECREASES WITH AGE
VISUAL ADAPTATION	· ABILITY OF EYE TO ADAPT TO PREVAILING LUMINANCE LEVELS	· BRIGHTNESS RATIOS ARE IMPORTANT. ABSOLUTE LUMINANCE NOT IMPORTANT · INSTANTANEOUS PERCEPTION OF LIMITED LUMINANCE RANGE AS COMPARED WITH TOTAL RANGE OF EYE SENSITIVITY.
POSITION WITH RESPECT TO TASK	· DEFINED BY POSTURE OF TASK PERFORMER, POSITION OF TASK, ANGLE OF VIEW	· MAY GREATLY AFFECT VISIBILITY BUT OPTION TO CHANGE THIS PARAMETER IS NOT ALWAYS AVAILABLE
CONFLICT BETWEEN VISUAL AND ACTIVITY REQUIREMENTS	· REQUIREMENT FOR CONCURRENT MOTOR CONTROL AND VISUAL INSPECTION OF WORK	· MOSTLY IN INTERFACING WITH MACHINES – A PROBLEM IN ERGONOMICS

Table III - Task performer response affecting visibility

below this level[12]. Because of the phenomenon of adaptation, absolute luminance levels are not as imporant in task performance as the luminance ratios of the surfaces within the field of view.

2.4 Characteristics Of Lighting

Task lighting has been defined as[13]:

> a lighting installation which provides the correct quantity of light on the visual task, flowing from the correct direction, with respect to the worker and the working plane or planes involved, being of the appropriate spectral quality, and designed to provide good visibility.

Table IV , adapted from Harker[14], lists the various

LIGHTING ATTRIBUTE	MEASURE	COMMENTS
ILLUMINANCE	PLANAR ON WORK SURFACE	MOST FREQUENTLY USED STANDARD EFFECTIVE IN INCREASING VISIBILITY WHEN LEVELS ARE LOW BUT FOLLOWS LAW OF DIMINISHING RETURNS
DIRECTIONAL LIGHTING	CONTRAST RENDERING FACTOR (CRF) RELATES TO SPHERE ILLUMINANCE. SPECIFIC TO VIEWING ANGLE AND MATERIAL CHARACTERISTICS	IMPORTANT FOR MATERIALS WITH DEPTH AND SPECULAR COMPONENTS
	BALANCE OF GENERAL ILLUMINATION TO DIRECTIONAL COMPONENTS (VECTOR-SCALAR RATIO IS ONE MEASURE)	DIFFICULT TO MEASURE FOR MATERIAL POSITION BUT MAY BE IMPORTANT WHERE BOTH TRANSMITTED AND REFLECTED LIGHT ARE IMPORTANT
SPECTRAL QUALITY	FREQUENCY SPECTRUM OF LIGHT SOURCES	CHOICE OF SOURCE LIMITED TO A PREDETERMINED RANGE OF ALTERNATIVES.

Table IV - Characteristics of task lighting affecting visibility

parameters of lighting affecting visibility. These parameters are:

i. illuminance

ii. luminance distribution

iii. direction of light

iv. spectral quality

v. variability in time

2.4.1 <u>The Effect Of Illuminance Level On Visibility</u>

The importance of illuminance as a parameter influencing task visibility has been over-rated for many reasons[15],[16], mostly due to the promotion of exagerated light levels during the era of cheap fuels[17], the easy use of illuminance as a yardstick[18], and an erroneous identification of higher light levels with more productivity. It is widely understood now that above light levels of 200 lux, visibility, and hence performance, becomes progressively insensitive to an increase in luminance[19]. In fact, at light levels currently prescribed for buildings, performance does not appreciably change with luminance[20]. This is shown in figure 4 . Increases in

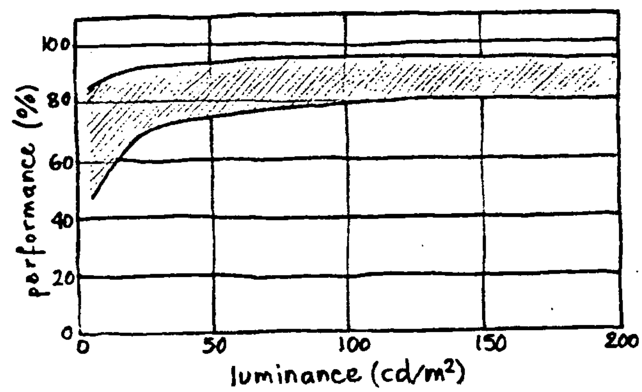

Figure 4 - Relationship between luminance level and performance

illuminance are very expensive[21], and current thinking is that it must result in improved visibility and, hence, improved performance to be justified.

Lighting installations delivering the same "raw" illuminance[22] can result in widely differing visibility on the task. This is because visibility is not only a function of illuminance, but also of light source design and location; of task and room reflectances; and of light source/task/task performer geometry. The Equivalent Sphere Illumination (ESI) is a reference lighting condition used to measure visibility[23]. It is designed to make the important distinction between "raw" illuminance levels and the resulting visibility[24] by quantifying the effects of the various factors affecting visibility[25]. It is used to compare the visibility produced by different lighting schemes. Some practitioners have expressed reservations about the use of (ESI) in field situations[26,27] but others have found it helpful in designing effective lighting while reducing lighting energy consumption[28,29].

The concept of visibility as a criterion of lighting performance is very important in interiors using daylight for task performance. The IES Daylighting Committee, in their 1979 edition of the "Recommended Practice of Daylighting", have written[30]:

> The distinction between the illumination level and any resulting visibility is especially important for daylighting analysis. In many applications, daylight is incident at the task from directions (side and back) which produce high contrast [and high visibility] and consequently, high ESI. Thus, it can happen that a small amount of daylight can produce the same task visibility as a larger amount of [overhead] electric lighting... The full possibility of daylight benefits can be difficult to demonstrate without the use of the ESI concept.

Griffith[31] has written:

> ...daylight illumination through windows has been shown to be 3 to 4 times as effective in increasing visual performance as equal illumination from conventional electric lighting if properly utilized... With proper layout of workplaces [daylight from the

> side] 20 to 30 footcandles of daylight can permit better visual performance than 70 to 100 footcandles of classical overhead lighting.

An extensive computer simulation study by Thrun[32] for Public Works Canada, on daylight illuminance levels available in typical office interiors, has shown that when all pertinent factors relating to task visibility are taken into consideration along with illuminance, and expressed as Equivalent Sphere Illumination, the ESI values for daylight from windows averaged between 2 to 4 times the value of the "traditional incident illumination"[33] (i.e. "raw" illuminance) throughout the room. The actual values are a function of the orientation, time of day, etc[34].

2.4.2 <u>The Effect Of Luminance Distribution On Visibility</u>

Visibility is in general governed by the total amount of light which may be seen within the visual field. This field is composed of the task, the immediate surround and the general surround[35], as shown in figure 5 . The total amount of light is a function of both the luminance of the visual field (which is proportional to the illuminance and the reflectivity of the surface), as well as its area. A change in luminance alone will have less influence on visibility than on visual comfort.

Contrast between task and immediate surround also affects visibility[36]. An extreme instance of this is disability glare, which substantially affects visibility, but this phenomenon is not very common in interior lighting situations[37]. Hopkinson

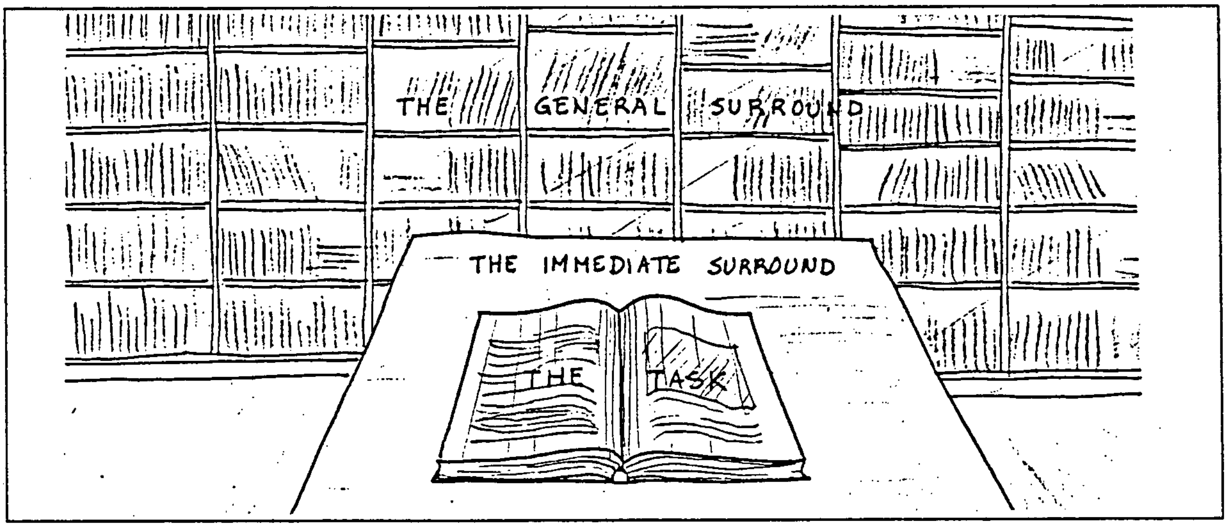

Figure 5 - Components of the visual field

and Collins[38], report that optimum luminance of the surround for task visibility is equal or somewhat less than that of the task itself. Visibility decreases very gradually as the luminance of the immediate surround is reduced, but decreases sharply as its luminance is increased above that of the task[39]. Visibility also improves by about 25% with an increase of surround area up to a subtending angle of about 6°. Examples of this are road signs, where a quite small immediate surround is sufficient to provide good visibility of the sign. Beyond the size of immediate surround indicated, improvement in visual performance is minimal[40].

In daylit interiors, locations remote from daylighting apertures may require electric task lighting supplementation. In other respects, daylight can provide luminance ratios within the visual field that enable good task visibility.

2.4.3 The Effect Of Light Direction On Task Visibility

The direction of light will affect task visibility[41], quite apart from its effect on visual quality of the space. Improvement in visibility is most marked for three dimensional tasks where a change in the direction of light will greatly influence the perception of form, depth and texture, but it will also affect two dimensional tasks having a degree of specularity.

The ratio between the level of the directional lighting and the level of the general lighting is called the Vector/Scalar ratio. In some situations, such as those involving model-making or the examination of objects having specular characteristics, an increase in this ratio--brought about, for example, by an increase in illuminance on the vertical plane--will improve task visibility[42].

In offices, the predominant mode of daylighting is through side lighting. This direction of light results in little or no veiling reflections for horizontal tasks and optimum modelling for three dimensional tasks. Griffith has demonstrated the advantage of side lighting in reducing veiling reflections and resultant contrast degradation, as compared with conventional top lighting[43].

2.4.4 The Effect Of Spectral Characteristics On Visibility

The spectral characteristics of the light source will naturally influence the colour rendering[44] of objects seen in its light. Thus, the ability to discriminate colour differences in some tasks will vary greatly under different light sources.

Beyond this effect, however, there is evidence that light sources with better colour-rendering characteristics (i.e. approaching the colour-rendering of natural light) provide greater 'visual clarity'[45] than sources of poorer colour-rendering characteristics. This means that a light source with a high colour-rendering index[46] can have lower illuminance--by as much as 40%[47]--and still provide equivalent visibility[48]. This phenomenon is known to the scientific community but has not been acknowledged in lighting standards[49].

Electromagnetic radiation that makes up daylight is evenly distributed within the range visible to the human eye, whereas the visible radiation from common light sources favours some colours over others. Therefore, there is a better colour perception under daylight, as compared with most of the commonly used electrical lighting[50], and a corresponding increase in visibility. The light is also perceived as pleasant[51], with a vibrancy and colour balance that can be simulated only with installations of rather expensive, "full-spectrum", fluorescent lamps[52].

2.4.5 The Effect Of Illuminance Variability On Visibility

A fluctuation in illuminance has an impact on visibility and task performance. The degreee of impact is a function of the rate and amplitude of fluctuation, as well as of the meaning attached to this fluctuation. The flicker produced by fluorescent lamps, for example, can impair the visibility of tasks that involve rapid motion, as well as reduce performance because of the distraction it causes. Other phenomena, such as staged switching of lights in response to fluctuating daylight levels, will not cause a reduction in visibility, but may nevertheless impair task performance because of their distracting effect.

Daylight is naturally variable, but its rate of variability and the amplitude of variability within short intervals are such that they do not impair visibility. Short term fluctuation in daylight levels--such as during partly cloudy days--are generally considered pleasant because of the positive associations they evoke, and do not impair task performance. In daylit buildings integrated with electric lighting, the continuous dimming of electric light, with time delay and dead-band characteristics[53], avoids distracting variations in interior light levels.

3. LIGHTING FOR USER SATISFACTION--"LIGHT TO SEE"

General lighting of interior space, or ambient lighting, fulfills the following roles:

i. responds to the physiological needs of the occupants

ii. influences (along with task lighting) the visual comfort, in psycho-physical terms, of the occupants

iii. promotes visual definition of spaces: a sense of orientation, guidance, visual focus, etc.

iv. influences the overall impression created by the space: spaciousness, privacy, etc.

To the extent that ambient lighting fulfills the above roles, it will indirectly, through the the satisfaction of the occupants with the visual environment, also affect task performance.

3.1 Lighting For Physiological Well-being

Light has extrasensory effects on all living organisms. In human beings, these effects occur mostly through the eye and the skin. Signals from light on the eye are interpreted by parts of the brain not associated with vision and these regulate normal biological rhythms[54,55]. The triggering wavelengths for some of these are in the visible portion of the spectrum, for others, in the near or mid-ultraviolet portion[56]. Light striking the skin is well known to aid in synthesizing vitamin D[57]. For this, the most active wavelengths are the mid-ultraviolet range[58]. Both mid and near-ultraviolet rays are known to have bacteriocidal effect on the skin's surface[59].

Although inconclusive, research results are making increasingly clear that "lighting exerts important effects upon human health and productivity, far beyond its requirements for vision"[60]. According to photobiological research, "it seems reasonable that the light sources to which we expose people should not deviate markedly from the lighting environment under which people evolved in nature. The fragmentary data now available suggests that working under such 'natural' conditions significantly decreases visual fatigue and may also increase productivity"[61].

There is, however, no consensus on this subject. Partly because of inconclusive evidence, but mostly because of vested commercial interests by the large lighting manufacturers, the importance of providing daylight, or daylight-simulating electrical lighting, in building interiors is much debated[62,63,64,65].

Light in the interior of buildings comes either from electric light sources or from daylight transmitted through daylighting apertures. These two light sources may be examined to determine to what extent these differ from outdoor sunlight and daylight, under which man has evolved.

Photobiological effect of electric light

Scientific opinion differs on the issue of health effects of artificial lighting sources: whether they are non-injurious, deffficient in some aspects or positively harmful[66,67]. The answer partly depends on the definition of these terms. Moderate amounts of ultraviolet rays and of the shorter wavelength visible rays appear to be beneficial to human health. The common fluorescent lighting exhibits a narrow-band light distribution and a general deffficiency in the UV wavelengths[68]. One concern is that people, working under these lights and exposed to very little daylight (especially during winters), become deprived of the catalytic energies present in the shorter visible, and UV wavelengths. Full spectrum fluorescent lamps, duplicating the spectral composition of daylight, are available[69], but these are 5 to 10 times more expensive than standard fluorescent lamps and there is considerable controversy in the industry concerning the usefulness of these lamps[70]. Some research even suggests that full-spectrum lamps have harmful side-effects[71].

Photobiological effect of daylight

The other way of receiving biologically desirable spectral balance in light is from daylight, coming through windows, skylights, etc. Although direct sunlight is the most potent photobiologically, overcast skies filter out only about 20% of the ultraviolet light[72,73] and hence, cloudy days are almost as beneficial.

The main issue, therefore, is whether or not window glass will transmit the wavelengths necessary for health. Clear glass transmits a large part of the near ultraviolet rays (320-

380nm) but that transmissivity falls off sharply at the mid-ultraviolet wavelengths (290-320nm)[74]. Since the photobiologically active wavelengths are in the visible, near-ultraviolet and mid-ultraviolet ranges (varying for different physiological processes), this means that ordinary clear glass is transparent to much, though perhaps not all, of these wavelengths. Low iron glass, having high transmittance to the mid and near ultraviolet rays, and higher transmittance in the visible portion of the spectrum than standard clear glass, is now being manufactured, so that the full benefit of these electromagnetic frequencies may be realized inside buildings[75]. Heat absorbing and especially heat reflecting glasses reflect most of ultraviolet rays; these also of course reduce the quantity of visible light transmitted[76].

The tentative conclusion one may draw from these facts is that naturally lit buildings, with clear window glass, are more able to provide their occupants with the kind of light that is necessary for biological health of the human organism, than totally electrically lit buildings that ignore the potential for daylighting.

3.2 Lighting For Visual Comfort

Lighting for ease of seeing, or visual comfort in strictly psychophysical terms, can be divided into the following goals:

i. control of brightness gradients

ii. avoidance of discomfort glare

iii. provision of visual rest centres

3.2.1 Brightness Gradients

The perception of brightness is governed by the phenomenon of lightness constancy[77]. Because of lightness constancy, an object will appear to be equally bright under a wide range of illuminance levels, and its perceived luminosity--or brightness[78]--will depend on the relationship to its surroundings. The practical result of this is that the absolute luminance of surfaces within the field of view (and hence, the illuminance on them), is of little consequence in judging brightness levels. It is the luminance ratios among these surfaces that is important. Table V.[79] lists recommended maximum luminance ratios between task and surroundings that will provide visual comfort conditions within office interiors.

Acceptable luminance ranges may be obtained in daylit interiors with careful detailing: relatively high room surface reflectances, contrast grading around daylighting apertures, glare control devices at daylighting apertures, etc. These techniques are examined in later chapters.

3.2.2 Discomfort Glare

Discomfort glare is an extreme situation of brightness contrast occuring when an object within the field of vision has a luminance exceeding the range to which the eye is adapted at

SURFACES BEING COMPARED	MAX. BRIGHTNESS RATIOS
TASK AND ADJACENT SURROUNDINGS	1 TO 1/3
TASK AND MORE REMOTE DARKER SURFACES	1 TO 1/10
TASK AND MORE REMOTE LIGHTER SURFACES	1 TO 10
FENESTRATION AND ADJACENT SURFACES	20 TO 1
ANY TWO SURFACES WITHIN THE NORMAL FIELD OF VIEW	40 TO 1

Table V - Recommended luminance ratios within the visual field

the time. Discomfort glare is a function of the luminance of the offending source, the solid angle subtended by it at the point of observation, its location within the visual field, the reflectances of the room surfaces and the general illuminance in the space[80]. As a result, glare control can be achieved by reducing the luminance of the glare source and/or reducing its perceived size; moving its location to the periphery of vision; increasing the general background luminance by increasing the ambient illuminance and the reflectances of major surfaces in the field of view; and in general, by decreasing the contrast between the light source and its surroundings[81]. Figure 6 [82] shows these relationships. Substantially greater luminance values are tolerated at the periphery of vision than at the centre of vision (by a factor of 4)[83], and therefore higher brightness levels can be tolerated for luminous ceilings, for example, than for wall areas, which are more prominent in the field of vision.

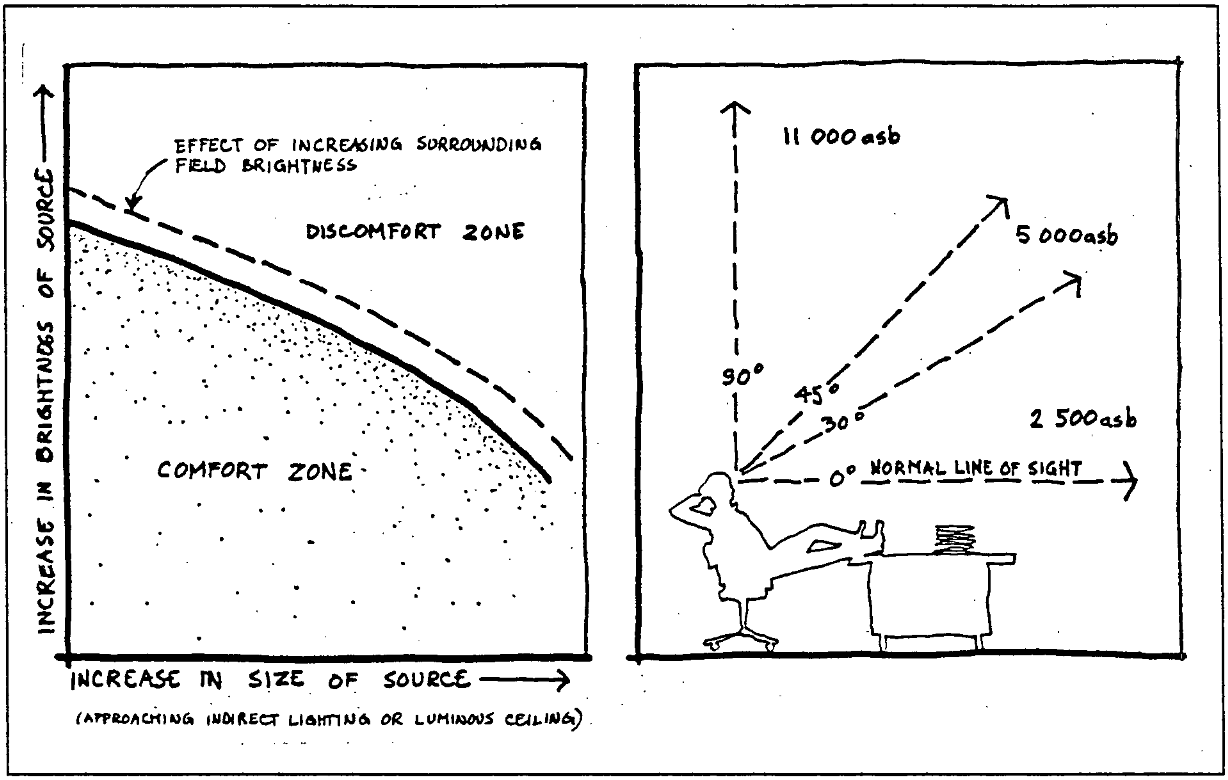

Figure 6 - Glare as a function of area and location of source

The perception of glare is not a constant factor, but is an inverse function of the adaptation reference level of the eye, which corresponds to the average illumination level at the task and the immediate task surround. Therefore, the higher the illuminance within a space and/or the higher the reflectances of the interior surfaces, the greater luminance a source of illumination--a window, for example--may have before it becomes a source of glare.

For the range of lighting levels of 300 to 1 000 lux found in present day offices, critical sky luminance is 6 000 and 20 000asb respectively[84]. This coincides with values obtained by Hopkinson and others, shown graphically in figure 7 [85,86].

In Vancouver, the luminance of a clear sky (excluding the

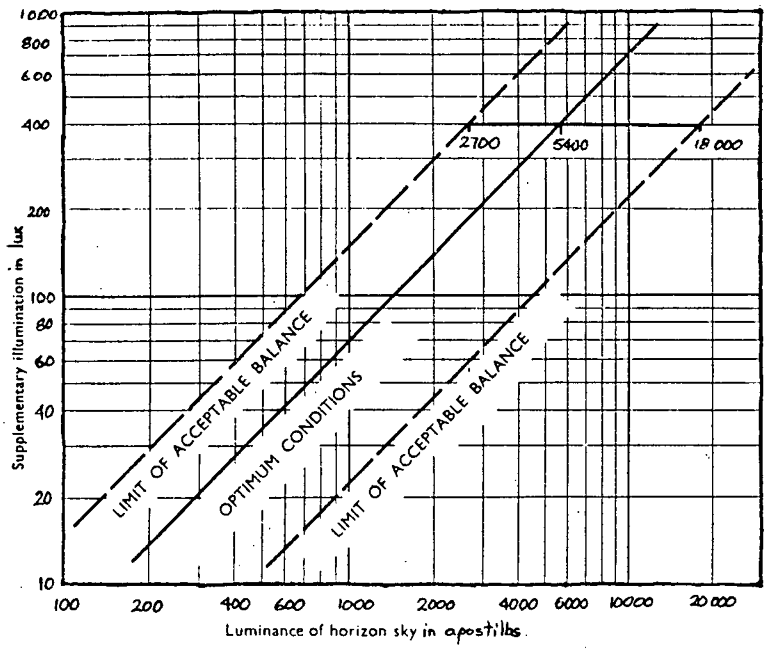

Figure 7 - Range of sky luminance acceptable with a fixed level of supplementary lighting

region near the sun, which is assumed to be shielded from the interior) is between 13 000 and 20 000asb, depending largely on angular altitude; the luminance of a cloudy sky is between 7 000 and 14 000asb[87]. Therefore, with high indoor illuminance levels and/or a partially obstructed skyvault, glare may not be a problem. This is also the conclusion of Galbreath[88] who has stated that when direct sunlight is excluded, a clear sky is seldom so bright as to cause discomfort. Matthews[89] concurs, saying that the problem of glare has been overemphasized in present-day design techniques.

In the worst case situations, such as those involving high exterior luminances and low interior luminances, the problem involves reducing the luminance through the window by a factor of about 3. This observation is confirmed by Selkowitz[90], who has observed that "glare is a problem of knocking down the brightness by a factor of 2 or 3".

Since higher brightness is tolerated at the periphery of vision, glare may be reduced by arranging working positions so that unscreened windows are not in the line of sight of workers[91]. This solution is not always as feasible in present day office situations as it was in the past due to increased complexity of office activities and increased densities. On the other hand, it may be possible, especially with work stations utilizing the newer office furniture systems, to arrange components to shield direct views of unscreened windows; movable bulletin boards, acoustic screens, shelves, hanging plants, can all be used for this purpose.

Lynes[92] has cautioned that glare limits appropriate for electric light sources--small or large--will be too conservative if applied to daylighting apertures, because of two phenomena:

i. Because of the "proximity effect", the sky, being perceived as further away, will feel less oppressive than a luminous source within the interior space, even when the luminance and solid angle subtended by both are the same.

ii. Because of the "habituation effect", most people find the sky, which they have known since birth, less objectionable as a glare source than electric lighting of similar luminous characteristics.

In a similar vein, Lam[93] has stated that when the stimulus is meaningful, relevant, and expected, much higher luminances are acceptable. Thus a pattern of light fixtures or a luminous ceiling may be judged as glaring or annoying, while under identical interior light levels, a window view of greater luminance may be perceived as sparkling and enjoyable. According to Lam, "people perceive information and relationships, not absolute intensity levels of light"[94].

Since the phenomenon of glare is an extreme situation of brightness differences, all methods that help in balancing the perceived brightness in a space, do also, to some extent, reduce the glare problem.

3.2.3 Visual Rest Centres

The provision of visual rest centres within a work space is another requirement for visual comfort. The eye muscles need periodic relaxation from the effort of close-up work; they can relax when the eye is focused on distant objects, termed "visual rest centres". In practice, objects or surfaces 6m or farther from one's location can serve the purpose.

The visual rest centre should preferably be an area of low phototropic attraction - i.e. of equal or lower brightness than the visual task, and having no conspicuous visual pattern that may seriously interfere with the eye's relaxation[95]. Examples are views out of windows (some are better for this purpose than others), long views across rooms, areas of clear colour, etc.[96]

Windows can serve well as visual rest centres, even though their brightness level is generally greater than that of the task, since they offer distant objects for the eye to focus on, and relief from the visual work being done. Windows that provide a view of soft landscaping, of sky and of simple visual patterns, serve best as visual rest centres, but windows overlooking active scenes can also be satisfactory for relatively static visual tasks, such as reading or writing, since a degree of psychological stimulation is acceptable for these activities.

3.3 Lighting For Visual Perception

There is general agreement among lighting designers that consideration of perceptual factors is necessary for good lighting design[97]. This is for the following reasons:

i. The overall visual impression that occupants have of their work environment will influence their satisfaction with, and acceptance of, the space, and this in turn, will affect work performance[98].

ii. Conscious use of perceptual factors in the design of lighting can heighten the perception of form and space for pragmatic as well as aesthetic ends.

Light may be used to create perceptual impressions that have immediate and practical purposes: to emphasize architectural focal points, clarify structure, draw attention to dangerous edges, etc. Light is thus consciously utilized to reinforce perceptual clues with a resultant increase in spatial clarity and easier use of the building. However, the use of light in this way can go beyond the pragmatic, and may be part of a larger purpose: to mould and interpret space and highlight its beauty.

Lam[99], Jay[100] and Boyce[101] have all discussed the role and importance of perceptual impressions in lighting design. Flynn[102] has devised research methodologies--factor analysis, multidimensional scaling and semantic differential techniques--that can systematically identify and scale these impressions. The principles for manipulating lighting to give desired impressions in spaces have been well formulated, and are of great value. Ultimately, however, their application involves synthesis and intuition. The detailed discussion of lighting in general, to achieve desired impressions in interiors, is beyond the scope of this thesis.

Daylighting and sunlighting in building interiors result in perceptual advantages which are due either to the mode of entry of daylight/sunlight into interiors or the inherent nature of these light sources. These are discussed under the following headings:

i. view

ii. spaciousness

iii. modelling

iv. drama of daylight

v. sunshine

3.3.1 View

View--or some contact with the outside world--is considered by occupants one of the most highly valued benefits provided by windows[103]. The ability to rest one's eyes on some distant object, to be aware of the time of day, of changes in weather and of unfolding events outdoors, all contribute to the value of view.

Whereas all windowed buildings provide view to a greater or lesser extent, daylit buildings can enhance that potential. In daylit buildings, windows are considered assets in the total energy picture; in conventional design, they are considered thermal liabilities requiring trade-offs between human satisfaction and energy use. The location of windows for daylighting may not coincide with the prefered location for view, but the very fact that in daylighting design windows are considered in their various functional aspects (rather than predominantly as elements in a visual composition) and window size is not minimized, will increase the likelihood of view being given due consideration. View and connection with the outdoors is enhanced further in daylit buildings by the increased perception of the subtle changes in the intensity of daylight and, in some designs, by the play of sunlight on some interior surfaces.

In many new office buildings, a large percentage of exterior wall area may be covered with reflective glass of very low (7-20%) transmittance. Some surveys have found that the reduced luminance of the outdoors created a sense of visual gloom that the occupants found to be depressing. Also, the glass, because of its low transmittance, turned into a mirror whenever illumination levels outdoors were relatively low in the daytime. This was found to be distracting[104]. At certain sun angles, reflective glass can also contribute to annoying glare (and substantial load on the AC system) in adjacent buildings. Thus, very low transmittance glass, although providing a solution to the problems of interior glare and solar heat gain, has adverse effect on the perception of the outdoors. It also eliminates the potential of daylighting in buildings where it is used.

3.3.2 Spaciousness

The presence of windows in a room make it seem more spacious [105], reduces feelings of enclosure and restriction and increases its apparent size[106]. It adds an important psychological dimension to a room, almost unrelated to such factors as view or sunshine. Windows need not be too large for this purpose but cannot be too small[107]. This may perhaps be because the modelling effect of daylight, which is a factor in the perceived spaciousness of a space, disappears when the window is too small.

Spaciousness of interiors due to the presence of windows is not limited to buildings purposely designed to take advantage of daylighting, but daylighting will enhance this quality. Flynn's study[108], summarized in table VI , testifies to the positive effect of peripheral lighting in general. The spaciousness created by windows, may be seen as an example of this more general phenomenon.

SUBJECTIVE IMPRESSION	LIGHTING CUES
IMPRESSION OF PERCEPTUAL CLARITY	• BRIGHT, UNIFORM LIGHTING. • PERIPHERAL EMPHASIS, SUCH AS WITH HIGH REFLECTANCE WALLS, OR WALL LIGHTING.
IMPRESSION OF SPACIOUSNESS	• UNIFORM, PERIPHERAL (WALL) LIGHTING. • BRIGHTNESS IS A REINFORCING FACTOR, BUT NOT A DECISIVE ONE.
IMPRESSION OF RELAXATION	• NON-UNIFORM LIGHTING. • PERIPHERAL (WALL) EMPHASIS, RATHER THAN OVERHEAD LIGHTING.
IMPRESSION OF PRIVACY	• NON-UNIFORM LIGHTING. • TENDENCY TOWARD LOW LIGHT INTENSITIES IN THE IMMEDIATE LOCALE OF THE USER, WITH HIGHER BRIGHTNESSES REMOTE FROM THE USER. PERIPHERAL (WALL) EMPHASIS IS A REINFORCING FACTOR, BUT NOT A DECISIVE ONE.
IMPRESSION OF PLEASANTNESS	• NON-UNIFORM LIGHTING. • PERIPHERAL (WALL) EMPHASIS.

Table VI - Reinforcement of subjective impressions by lighting cues

3.3.3 Modelling

In offices, the predominant modelling requirement is that of seeing peoples' faces during conversations. Lynes[109] has found that for this requirement, there was a distinct preference for lighting with some directional character and close to the horizontal--15-45° above the horizontal being the range of the most preferred directions. The least acceptable direction was found to be lighting directly overhead. It is clear from this that daylighting apertures located in exterior walls, at or above the work plane, provide preferred modelling characteristics.

3.3.4 The Drama Of Daylight

Current environmental design practices aim at uniform temperatures and unvarying light levels in our buildings, and as such, the variability of daylight may at first thought appear to be undesirable. However, experience and research suggest that the changes and variability introduced into a space by daylight are valued by the occupants and even preferred over uniform lighting conditions[110,111,112].

Larson[113] has written:

> Good lighting, in terms of efficiency of work and psychological interest must be suitably variable but constantly adequate... For relatively static visual tasks, constancy on the work surface and variation within the space are conducive to a healthy visual situation. The worker and not the work is the final reason for lighting a particular way: lighting should be designed with the best physiological, psychological and esthetic interests of the worker in mind.

The short term variations have been found to add a dynamic quality to daylit interiors, contributing to an avoidance of the monotony that electrical lighting installations sometimes evoke[114]. This characteristic variability is sometimes called the "living quality" of daylight[115].

There is a marked difference in the "feel" of daylit spaces, as compared to those lit by electric lighting[116]. They have a "more pleasing and natural character"[117]. Surveys made on lighting preferences have revealed a widespread belief that daylighting is a better light source than electric lighting[118]. In some innovative daylit buildings there has been "overwhelming worker enthusiasm for daylight and the concept of natural light as the preferable source of office lighting"[119].

In Great Britain, when the system known as the Permanent Supplementary Artificial Lighting Installation (PSALI) was conceived in the 1950's for commercial and institutional buildings, it was deemed important that most of the illumination be provided by daylight, with electric lighting supplementing it. It was felt that "daylight in all its variety and stimulation must be provided, and must be the dominant feature of the room lighting, rather than it should be shut out by blinds or merely allowed to peep through small view windows"[120]. Evans[121] identifies that moderate changes in illuminance promote "comfort and agreeableness" and that the introduction of daylight into interiors is "the simplest and most effective way to provide these valuable [changes]...of reasonably subdued surface-brightness variations, with some visual flexibility and stimuli".

Variations in illuminance level are known to have a relaxing effect on the eyes and to promote positive psychological reactions[122]. It has also been found to assist concentration, as measured by the span of attention[123].

3.3.5 Sunshine

Daylit buildings are not the only ones that can admit sunshine into their interiors; all buildings with windows or skylights can potentially do so. However, in the design of most commercial buildings, sunshine is treated as a problem: the additional heat introduced places a burden on the HVAC system; glare is a nuisance; furniture and fabrics fade. Therefore, effort is made to screen out the sun. In spite of this, experience shows that sunlight introduced judiciously and sparingly--as a "wall wash" or other similar means of highlighting surfaces of interest--can make a worthwhile addition to the interior space.

Sunshine, as differentiated from daylight from the sky-vault, has been found to create a set of distinct psychological reactions[124]. The desirability of sunshine in interior spaces has been found by researchers to vary with the type of activity: hospital patients and housewives found sunshine extremely important (85-91% wanted it); school teachers and hospital workers less so (52-60%); office workers were in between (73% wanted sunshine)[125]. The nature of the visual task being performed and the degree of freedom individuals have in the space, undoubtedly affects their preference for sunshine: the more individuals are able to control glare and overheating by the use of shading, or to move around in their task, the more likely they will appreciate sunshine[126].

The desire for sunshine in the interior of buildings has also been found to be strongest in maritime regions and northern latitudes, where the duration of sunshine is most limited[127]. The B.C. Lower Mainland for example, with its "dreary" winters, is an appropriate geographical area for the introduction of sunlight sparkle inside buildings. Lam has argued that "most people view sunlit surfaces as desirable points of interest, because of the importance of sunlight in man's biological history"[128].

Although less experienced designers have been cautioned against use of sunlight in task oriented interiors, because of grave penalties associated with design errors [129], examples of successful solutions are very dramatic and appealing[130]. In conclusion, according to available research on the subject, the quality of illumination provided by both daylight and sunlight has a "tremendous psychological impact upon people in buildings"[131].

4. NOTES

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29. Isaac Goodbar, "The Application of the ESI System to Office Lighting," Proceedings of the Symposium on "The Integration of Visual Performance Criteria into the Illumination Design Process", January 25-27, 1982. Ottawa: Public Works Canada, 1982, pp. 123-183.

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31. James W. Griffith, "Benefits of Daylighting: Energy and Cost Savings," ASHRAE Journal 20, January 1978, p. 55.

32. Public Works Canada, Levels of Performance Related Illumination Available from Daylight in Typical Office and School Interiors (Ottawa: Public Works Canada, [1980]).

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Architectural Lighting Graphics (New York: Van Nostrand Reinhold, 1962), p. 58. Luminance values twice as high may be acceptable if relatively high surface reflectances are used throughout the room, thus reducing distracting contrasts and raising adaptation levels (Flynn and Mills, p. 58).

83. Ibid.

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III.

PROMOTE DAYLIGHT ACCESS

1. INTRODUCTION

Daylight, unlike electric light, originates outside the building, and as such, it must penetrate into the building through apertures in the envelope. By increasing the exposure of the daylighting apertures in this envelope to daylight--i.e. improving the building's daylight access--potentially greater amount of daylight can reach task areas within the interior.

1.1 The Three Sources Of Daylight

There are three light sources through which daylight impinges on the building envelope, as shown in figure 8 . These are:

i. the sky

ii. the sun

iii. the ground

The sky as a light source

Daylight from the skyvault, or atmospherically diffused sunlight, is usually termed the Sky Component(SC). It is the principal channel for indoor daylight in most designs. When compared with the sun, the sky has a large visual area and relatively low luminance. The luminance distribution varies

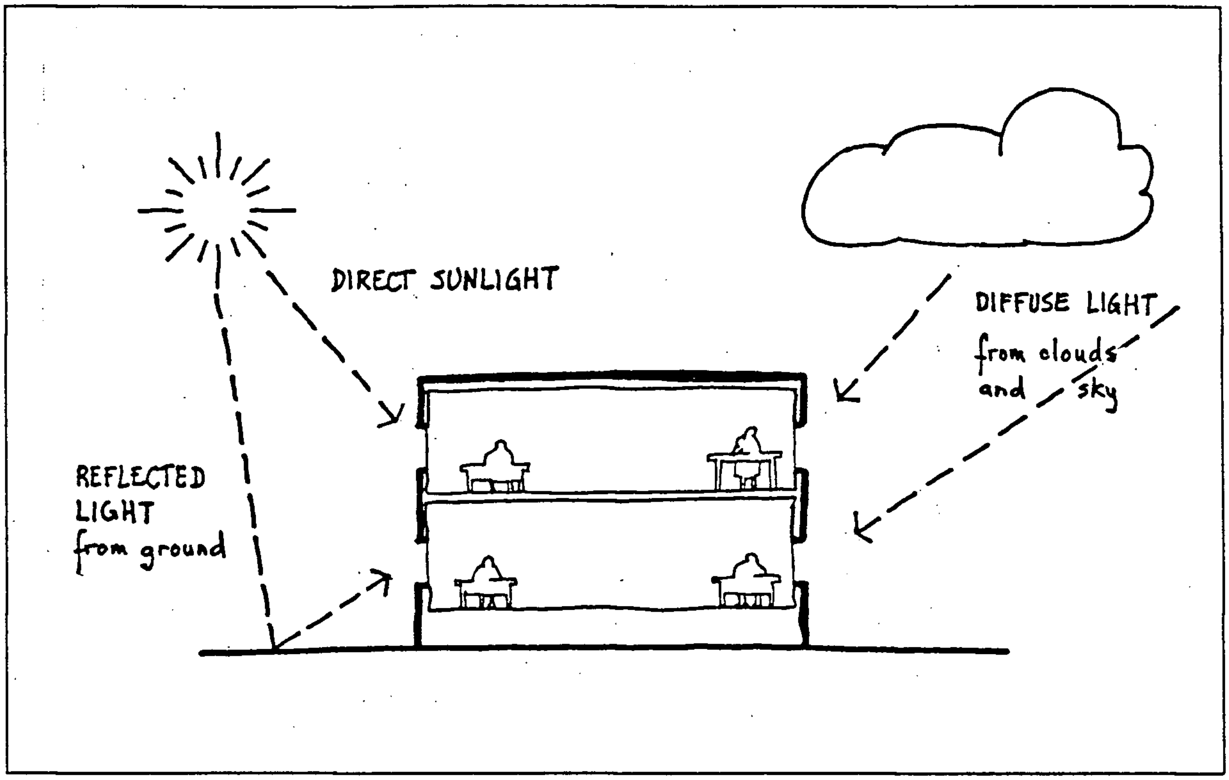


Figure 8 - The three sources of daylight

with latitude, time of day, cloudiness, and turbidity[1] of the atmosphere. Overcast and clear skies have different, but predictable, luminosity distribution across the skyvault. Thus, luminosity values for any given time can be predicted with reasonable accuracy and the SC of daylight calculated for various orientations and outdoor illuminance levels.

Most techniques that aim at maximizing the potential for daylighting in a building, do so by increasing access of the building envelope to the skyvault: manipulating massing and layout and strategically locating daylighting apertures for maximum interior daylighting.

The sun as a light source

In terms of its luminous properties and geometrical relationship to buildings, the sun may be described as a point source of light[2], of extreme luminous intensity, moving across the skyvault in a varying, but predictable, path. The illuminance produced by the sun on an exterior surface is a function of the altitude angle of the sun; the angle between the incident sunlight and the surface receiving the light; and the turbidity of the atmosphere. Since the luminous efficacy of sunlight is very high[3], the sun would be a very desirable source of light, were it not for its movement in the skyvault. The movement makes distribution of sunlight within the interior of buildings difficult to achieve; and without the ability to distribute this concentrated light, it becomes a glare and/or heat gain problem. For this reason, sunlight is screened out most of the time in larger buildings, either by opaque control devices or by tinted glazing. However, it is possible to introduce sunlight into office building interiors, using techniques that can control and distribute it appropriately.

The ground as a light source

Daylight from the ground--here meaning adjacent buildings, bodies of water and landscaping--is usually termed the Externally Reflected Component (ERC). It is a secondary source of indoor daylight. Unlike diffuse daylight and sunlight, this component is readily influenced by the activities of man, and thus may be subject to short-term, as well as long-term changes at a given site. It may also be seasonally variable (e.g. snow cover). Although the inclusion in design of the ERC can thus be problematic, it can nevertheles have an influence on the quantity of light in some interiors, and an even greater impact on the quality of light.

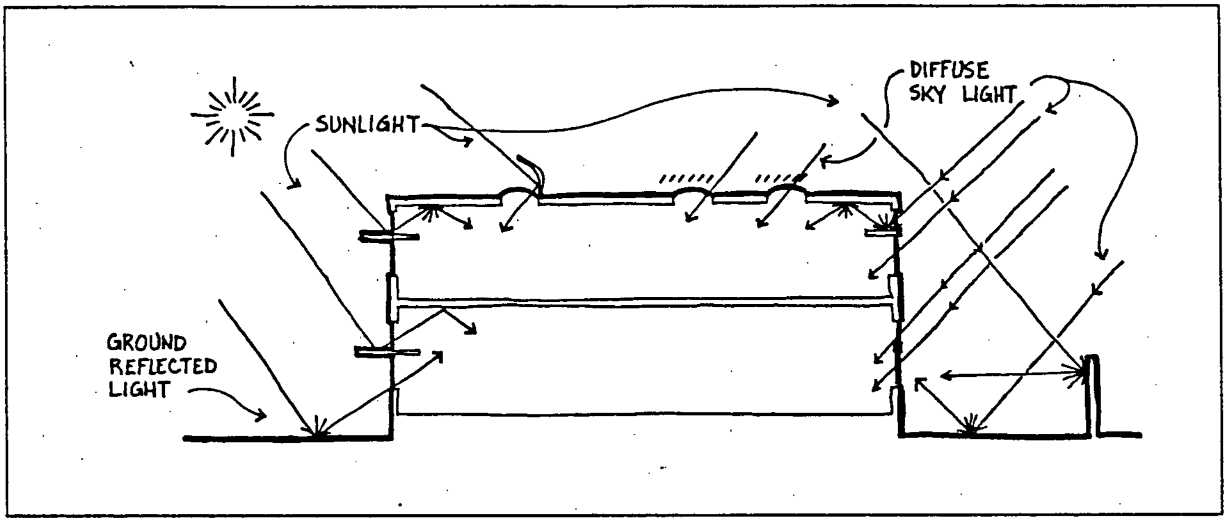


Figure 9 - Daylighting techniques using the three sources of daylight

Figure 9 shows typical techniques that can access one or more of these three sources of daylight.

1.2 The Three Daylight Design Conditions

A building must respond to one or more of three predominant daylight conditions:

i. overcast sky

ii. clear sky, with direct sunlight excluded from the interior

iii. clear sky, with direct sunlight admitted into the interior

Overcast sky

This sky condition is common in much of Europe and in maritime climates generally, and thus design methods for this condition have been well developed.

Figure 10 a. shows that a uniformly overcast sky is approximately 3 times as bright at the zenith as at the horizon[4]. Although cloudiness is a variable factor, the luminance distribution of a fully and uniformly overcast sky is independent of solar position and latitude[5]. Only absolute luminance levels are thus variable for a given orientation and therefore the overcast sky condition is relatively simple to model.

The clear sky, with direct sunlight excluded

Figure 10 b. shows the approximate luminance distribution of a clear sky[6]. The luminance distribution is the reverse of the overcast sky situation, with the luminance near the horizon approximately three times as high as that at the zenith. In addition, the sky is very bright in the proximity of the sun and a minimum luminance occurs in the quadrant of the sky opposite the sun. Although the luminance of the clear sky at any time of day can be predicted, the distribution pattern is more complex and varies with solar altitude and azimuth.

Under clear sky conditions, even with direct sunlight

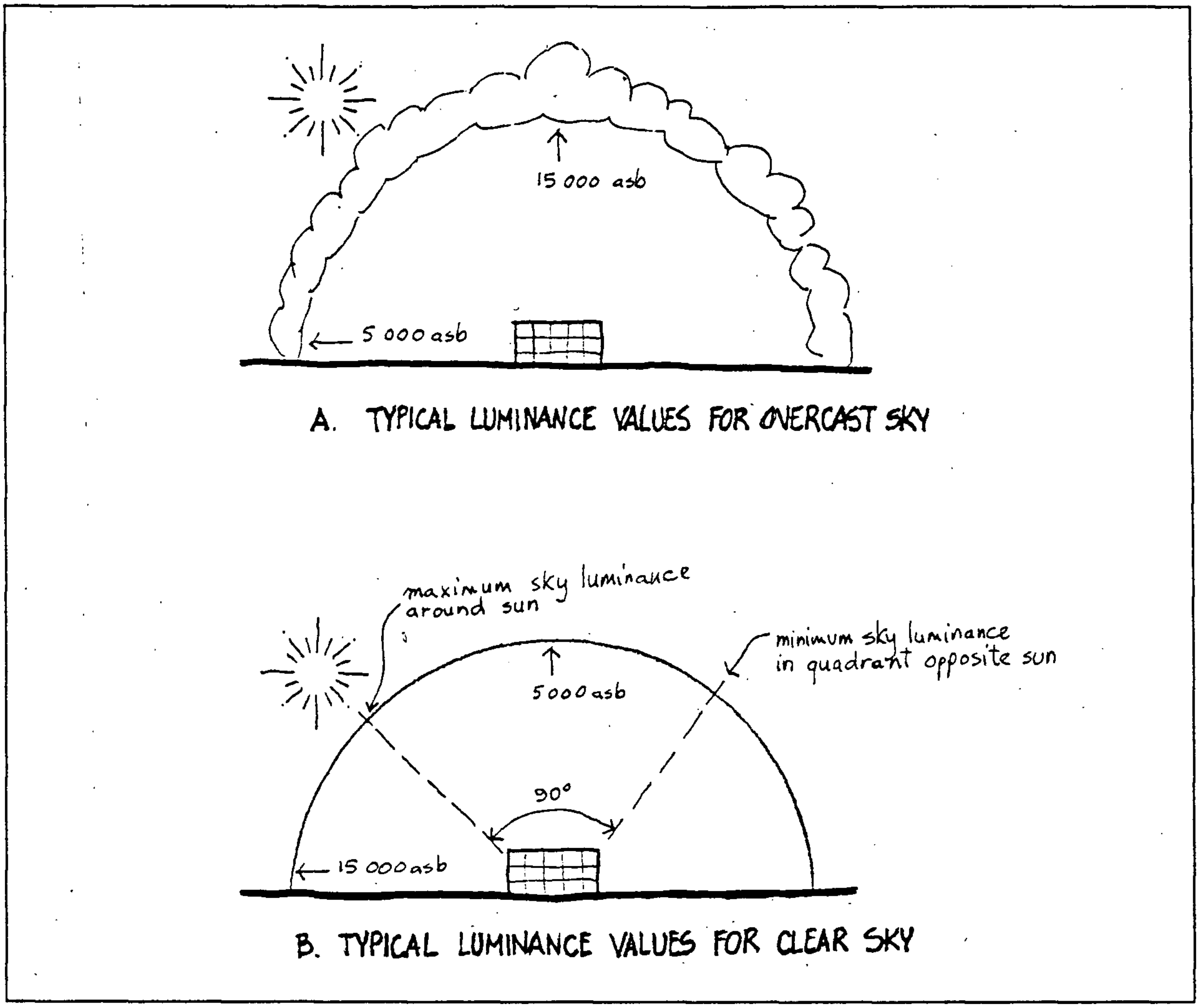


Figure 10 - The luminance distribution of the overcast and the clear sky

excluded, building orientations facing east, west and south, will, on the average, experience higher daylight levels than those oriented towards the north. Surfaces facing the sun thus receive 3-5 times the illuminance received by surfaces facing away from the sun[7], varying somewhat with the time of day and the season. The variation is mainly due to the difference in sky brightness, but also to the higher reflected component at sunward orientations.

The clear sky, with direct sunlight admitted

Direct sunlight may be admitted successfully into building interiors, without thermal and glare penalties, but as this involves accurate simulation techniques and more or less elaborate distribution mechanisms, the luminous design of office interiors using direct sunlight requires design skill and experience to implement. Nevertheless, some existing solutions create interior luminous environments of great human appeal[8].

Table VII summarizes the design responses required under each of the three design conditions discussed above. It may be

DAYLIGHT CONDITION	LUMINANCE DISTRIB.	RESPONSE BY ORIENTATION	SOLAR CONTROL	GLARE CONTROL
OVERCAST SKY	PREDICTABLE AND CONSTANT	ALL ORIENTATIONS SIMILAR	NOT REQUIRED	MAY OR MAY NOT BE REQUIRED
CLEAR WITHOUT SUN	PREDICTABLE AND VARIES WITH SOLAR ALTITUDE AND AZIMUTH	ORIENTATIONS TO SUN BRIGHTER EAST AND WEST DIFFICULT TO CONTROL	SUN BLOCKED CONTROL VARIES WITH ORIENTATION	CAN USUALLY BE ACCOMPLISHED BY SOLAR CONTROL NORTH EXPOSURE REQUIRES SEPARATE ATTENTION
CLEAR WITH SUN	— " —	SPECIAL DISTRIBUTION TECHNIQUES ON SOUTH SIDE DIFFICULT ON EAST AND WEST	REQUIRES SUNLIGHT DISTRIBUTION TECHNIQUES IN INTERIOR	STRICT ATTENTION REQUIRED MAY BE RESOLVED AS PART OF SUNLIGHT DISTR. TECHNIQUES

Table VII - Design responses required under different daylighting conditions seen that the number of variables characterizing each condition increase progressively, and therefore the design response becomes progressively more complex, and requires more elaborate analysis and prediction techniques for successful luminous and thermal performance.

1.3 Measurement Of Indoor Daylight

Clear or overcast sky--direct sun excluded

It has been found that the ratio between the daylight level at a given point in a building and the daylight level of the unobstructed sky is constant over a very wide range of exterior daylight levels. This constant has been termed the Daylight Factor (DF)[9]. The most common reference is to the horizontal working plane between 0.7-1.0m from the floor, but vertical reference planes may also be used[10], if the function of the space requires the investigation of illuminance levels on these planes.

As has been seen in the previous chapter, above illuminance levels of 100 lux, visual comfort conditions, as well as visual performance, depend more on the luminance ratio within the visual field than on absolute illuminance levels. Because the eyes will adapt to the prevailing luminance, the perceived brightness ratios within a room will remain constant, regardless of the fluctuating illuminance levels. The concept of the DF can be used to explore these ratios.

Daylight factors have been historically given for overcast sky conditions (e.g. the standard CIE overcast sky). Recently, the concept of the DF has been extended by Bryan et al.[11] to include clear sky conditions. Because the illuminance impinging on an exterior surface under clear sky conditions varies with solar altitude and azimuth, comparative evaluation of various design options can only be done for identical orientations and specific time of day.

Clear sky--direct sunlight admitted

In innovative, deep daylighting techniques, admitting direct sunlight to the interior, the concept of DF as an index of luminous performance is no longer accurate or useful, since illuminance levels will change not only with solar altitude and azimuth, but will also vary within short intervals with the specific technique used to project sunlight/daylight into the interior. The luminous environment is in this case best predicted by measuring illuminance levels in physical models, obtaining distribution at various solar altitudes and azimuths, at more or less frequent intervals, and comparing them for different design configurations.

2. TECHNIQUES FOR DAYLIGHT ACCESS

The techniques presented in this chapter are summarized in figure 11 .

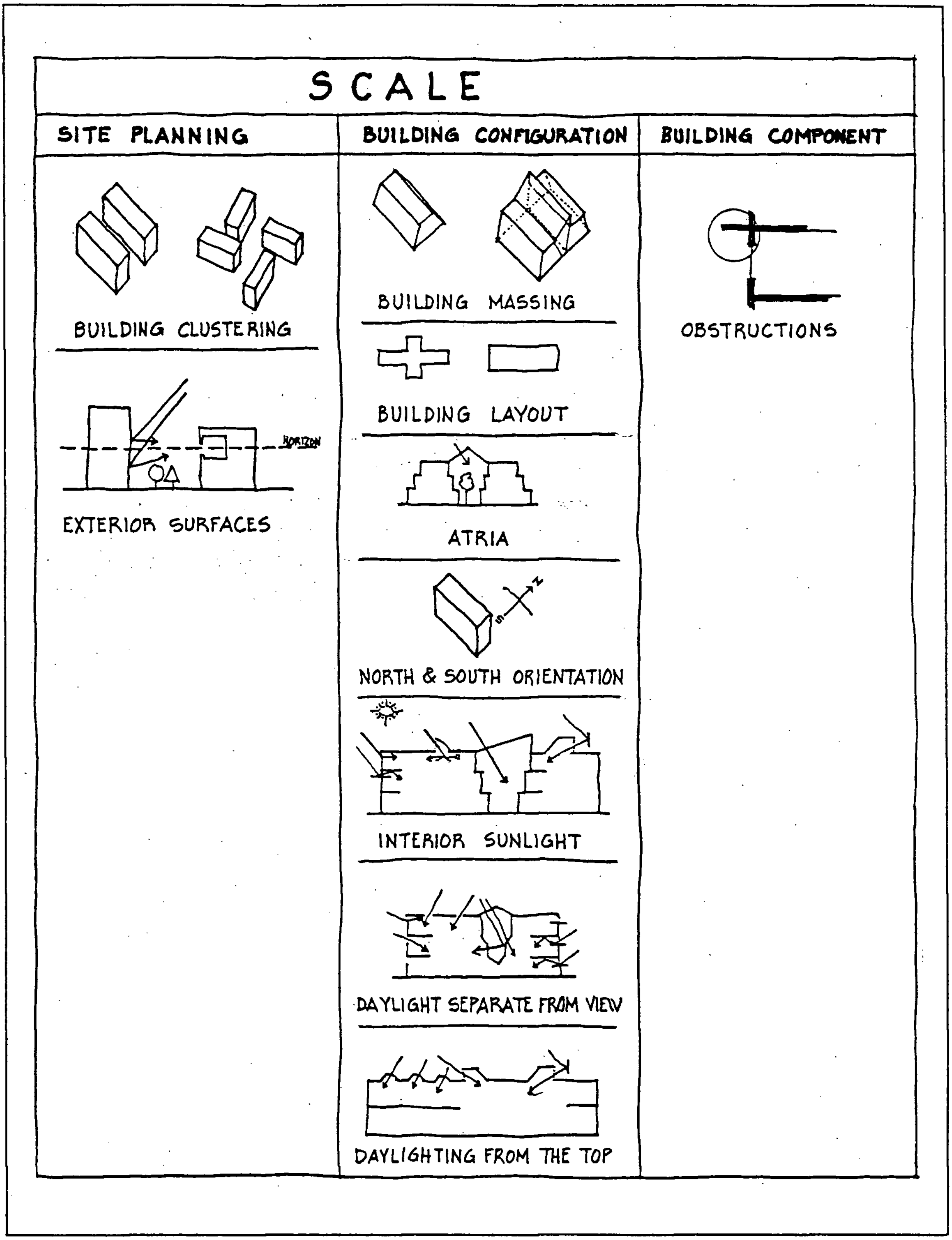


Figure 11 - Summary of techniques of daylight access

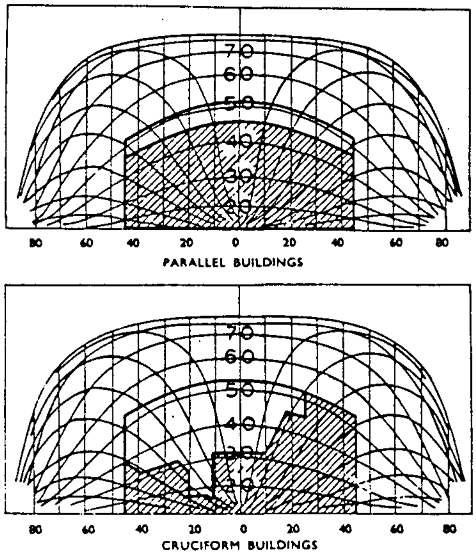
2.1 Building Clustering

In medium to high density urban areas, adjacent buildings will, to a greater or lesser extent, obstruct each other's access to the sky component of daylight. For a given density of development (total floor area for the site), some planning strategies will result in better daylight access for buildings than others[12].

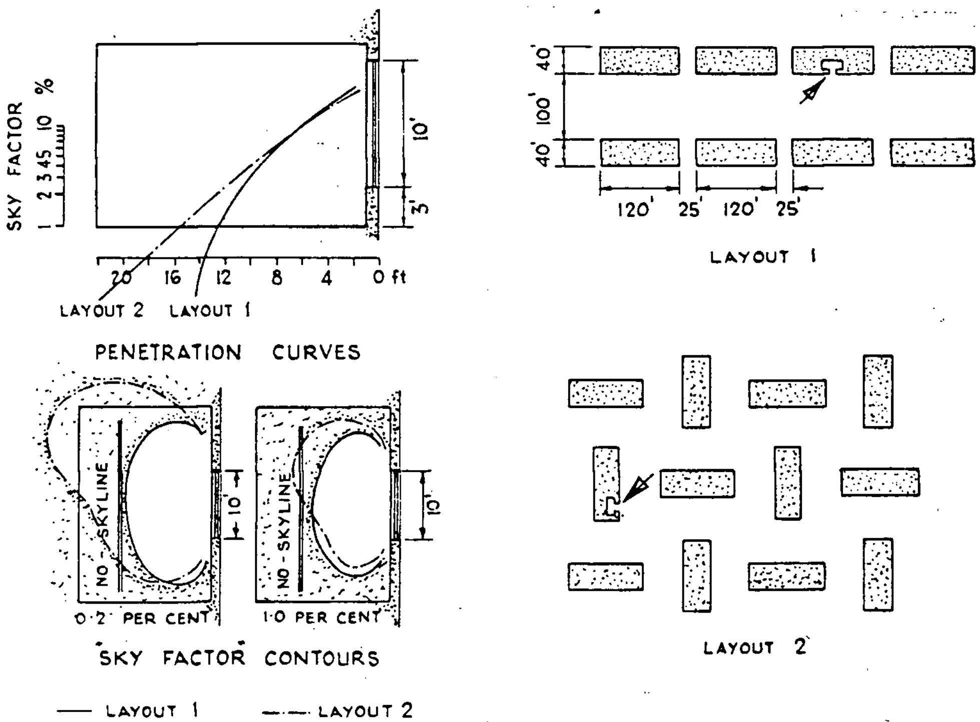
In the 1940s, the Building Research Establishment of Great Britain carried out a number of investigations[13] on the way clustering of discrete, repetitive buildings affected daylight access to interiors. Density was kept constant throughout these experiments; site layout, building plan and building height were varied.

i. In one study, plan and height of buildings were kept constant and only the arrangement of buildings on the site was varied. It was found that certain arrangements were superior to others in terms of daylighting. The Waldram diagrams in figure 12 [14,15,16] show that the better daylight penetration in the case of layout no. 2, is due to the increased sky component (SC) visible and also because the sky is visible at a much lower angle. Thus, the SC contributes to the daylight available deeper inside the room and also to a balance of brightness in the room[17].

ii. In another study, the height of the buildings were kept constant, and the plans were varied[18]. The hollow square layout, which was a common plan type in urban areas during



Waldram diagrams to show the view of sky obtained with comparative arrangements of buildings.



Daylight penetration with parallel and with cruciform layout of buildings. The latter gives better penetration of light from the low-angle sky

Figure 12 - Daylight penetration and Waldram diagrams for parallel and cruciform layouts

the 1940s[19], was contrasted with the alternating slab arrangement of the previous example and a cruciform arrangement[20]. As figure 13 shows, plans no.2 and no.3 provided better daylight access for typical rooms[21],[22].

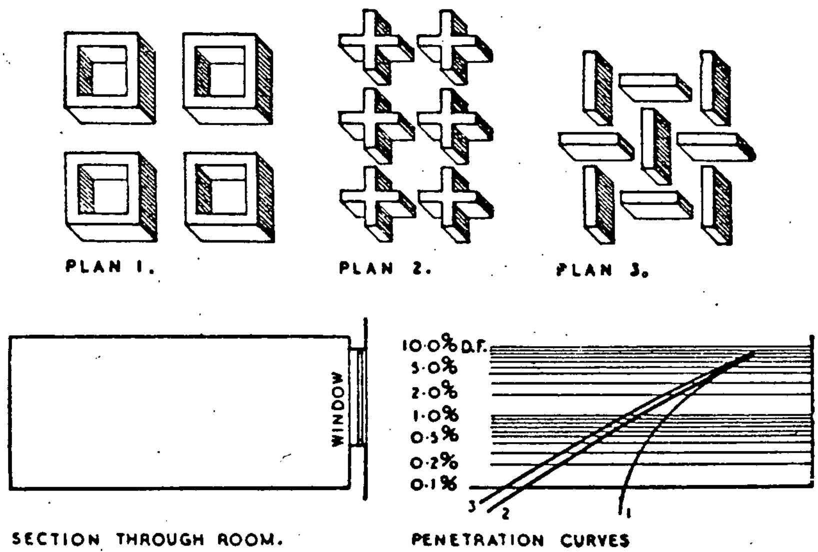


Figure 13 - Comparison among different building layouts of equal height and density

iii. In a third study, the plan shape was kept constant, while the height and spacing of the buildings was varied. It was found that for an equivalent density, tall blocks, wide apart, resulted in more favourable daylight access than low-rise blocks. The effect is shown in figure 14 , where the angle of obstruction decreases as spacing increases[23].

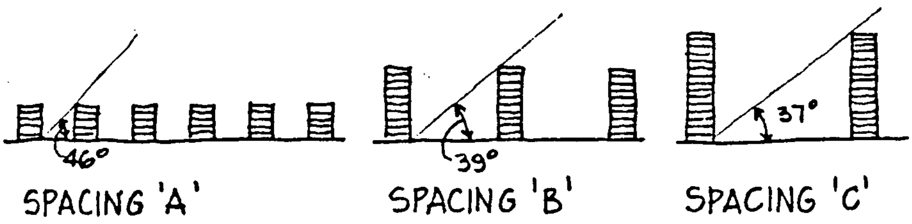


Figure 14 - Tall blocks wide apart ensure better penetration of daylight

Therefore, in medium to high density situations, medium or high-rise blocks are superior to low-rise buildings in terms of daylighting. It is to be noted from the diagram that when the spacing between buildings is increased, the first few increments of change are more productive than subsequent steps[24]. Thus, when social and technical consequences of high-rise buildings are considered along with daylighting, medium-rise buildings are, in many instances, an optimum choice.

iv. In a fourth study, both building plan and height were varied. Figure 15 shows two layouts on identical size lots; the height of the cruciform plan is greater than that of the hollow square plan to allow the Floor Area Ratios (FAR's) to be the same for both. Even though the cruciform building is taller, the daylight access for most of the rooms in this layout is superior to the daylight available in the hollow square plan; also, neighbouring

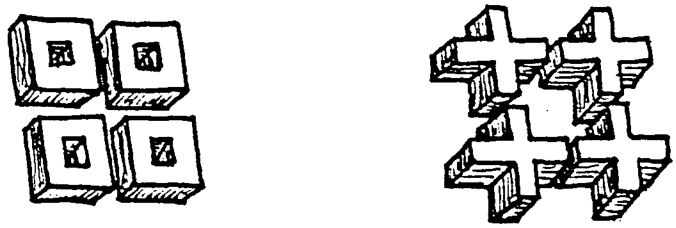


Figure 15 - Daylight availability for two building layouts

buildings enjoy a less obstructed skyvault with the cruciform arrangement than with the hollow square. Therefore, for a given density of development, and even allowing for different heights of buildings, the plan form is the main factor in determining daylight availability indoors[25].

It may be noted that the above mentioned studies of building clustering, using discrete, repetitive forms, are an oversimplification of most design situations. More complex building massing, interconnected buildings, buildings with suitably proportioned atria, etc. were not studied. However, the experiments do indicate generally how the variables at this broad scale affect daylight access.

It may also be observed that the importance of the foregoing "open planning" principles increases with greater densities. At densities of less than 1.0 Floor Area Ratio, the angle of light entering through windows will be low enough so that acceptable light penetration can be obtained with any layout and height of building. At densities above 1.25 FAR, the open plan forms can substantially improve the general daylight availability in the development[26].

2.2 Exterior Surfaces

Where possible, the location and detailing of neighbouring land forms, structures and vegetation should minimize obstructions and promote the best use of externally reflected daylight. The Externally Reflected Component (ERC) within a

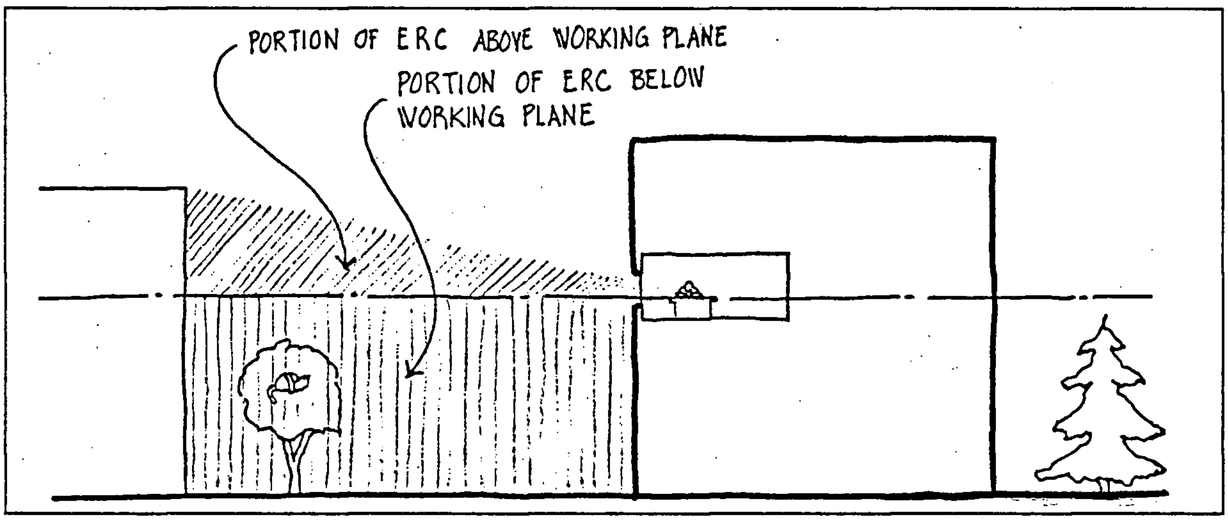


Figure 16 - The ERC is comprised of surfaces both above and below the working plane

daylit interior--i.e. reflected from the ground and other exterior surfaces--represents about 15% of the total daylight reaching the windows on sunny exposures (may be higher with light vegetation, snow cover, etc.) and on northern elevations, may account for over 50% of the total daylight reaching windows in low-rise buildings[27]. In the lower floors of buildings surrounded by high-rise development, the ERC will comprise an even larger proportion of the total accessible daylight. A high value for the ERC correspondingly increases the internally reflected component (IRC) of daylight, which in the previous chapter has been seen to be the dominant component at the back of daylit spaces[28,29,30].

As shown in figure 16 , the ERC may be considered as being comprised of surfaces both above and below the working plane. The portion of ERC above will contribute to the direct component on the working plane, whereas the portion below will enhance the daylight on the working plane after being reflected from room surfaces. Surfaces in the portion of ERC above the working plane, obstruct part of the sky (which has a much greater luminosity) and therefore reduce daylight access to the interior of adjacent buildings. If the location of these obstructions is within the control of the designer, he should attempt to relocate them in order to improve daylight access. Very often though, relocation of these obstructions is not possible for various reasons, and the only other option that can be considered is to maximize, if possible, the reflectance of these surfaces. The portion of the ERC below the working plane cannot, by definition, be eliminated, but increasing the reflectance of surfaces visible from daylighting apertures will always increase the access of building interiors to daylight. Whenever reflectances for the ERC are within the control of the designer, a high, but diffuse reflectance can be selected--and maintained by cleaning and painting. These measures will also reduce the harsh contrast between sky and exterior surfaces[31].

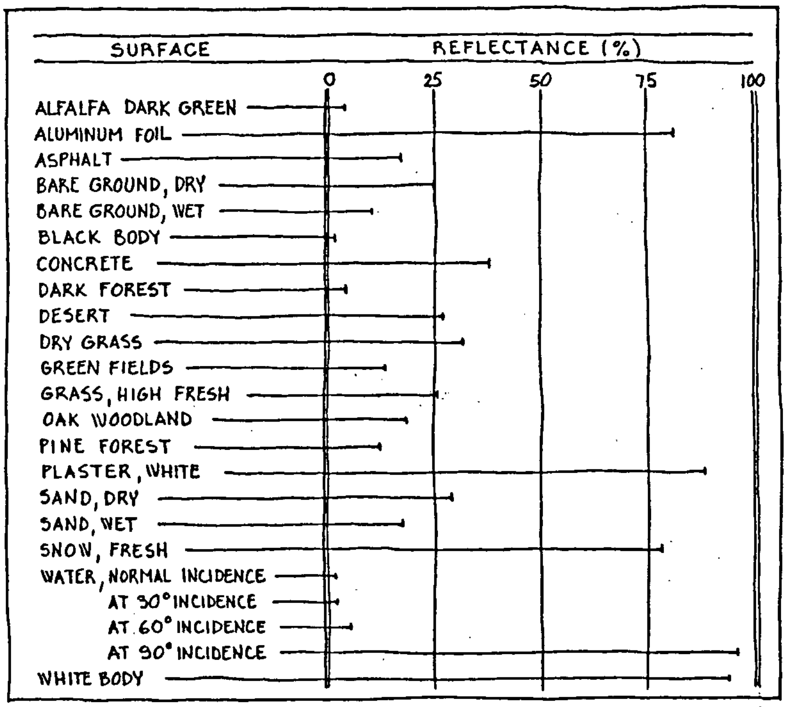


Table VIII - Reflectances of various outdoor surfaces

Table VIII [32] shows reflectances for common ground surfaces:

Figure 17 shows possibilities for using the ground and external surfaces as secondary light sources. It is shown how non-specular reflection of southern sunlight by landscaping features can introduce more intense and warmer light from the south into north-facing windows.

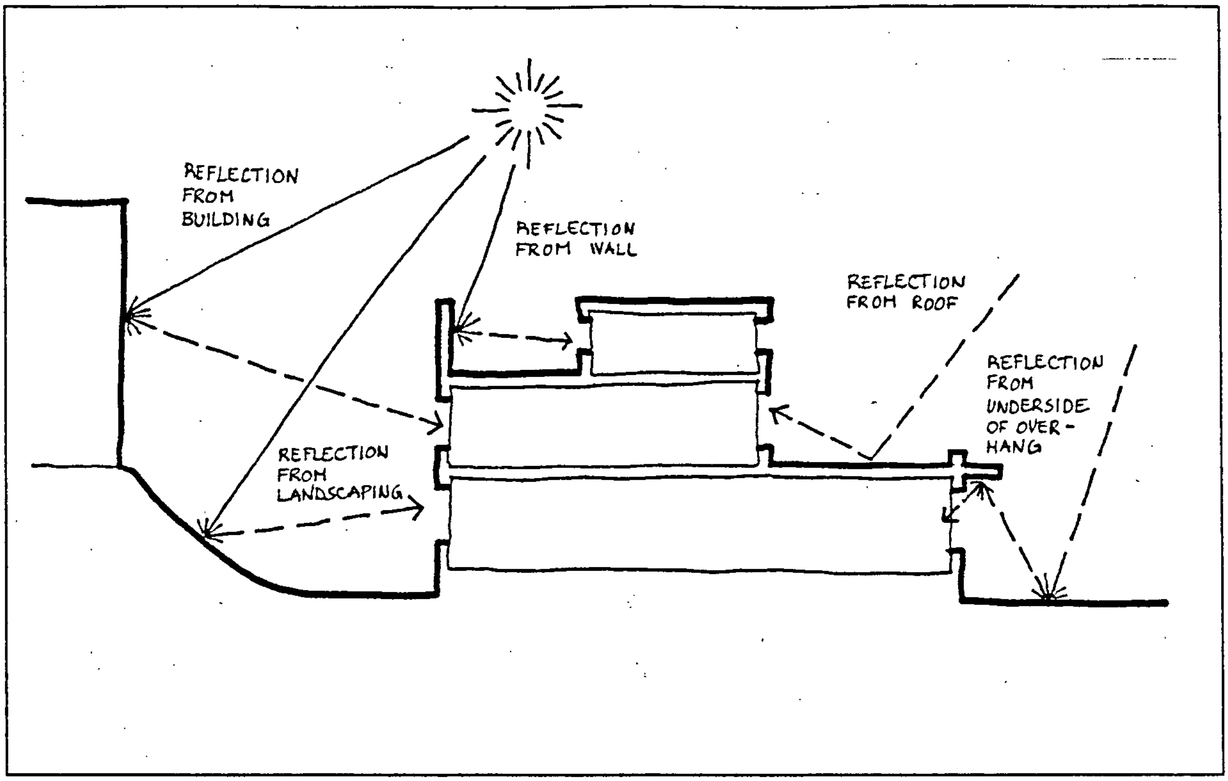


Figure 17 - Exterior surfaces as secondary light sources

2.3 Building Massing

Certain building forms will provide access to more daylight than other forms, the key determinants being the skin to floor area ratio and the area of sky that may be "seen" by the external surfaces. Figure 18 [33] and figure 19 [34], illustrate that buildings whose massing provides good daylight access to their own interior spaces also tend to obstruct less the daylight access of their neighbours. Conversely, buildings whose massing reduces daylight access to their own interior spaces, will also tend to reduce the daylight access to their neighbours.

Buildings massing may be resolved at the detail scale in

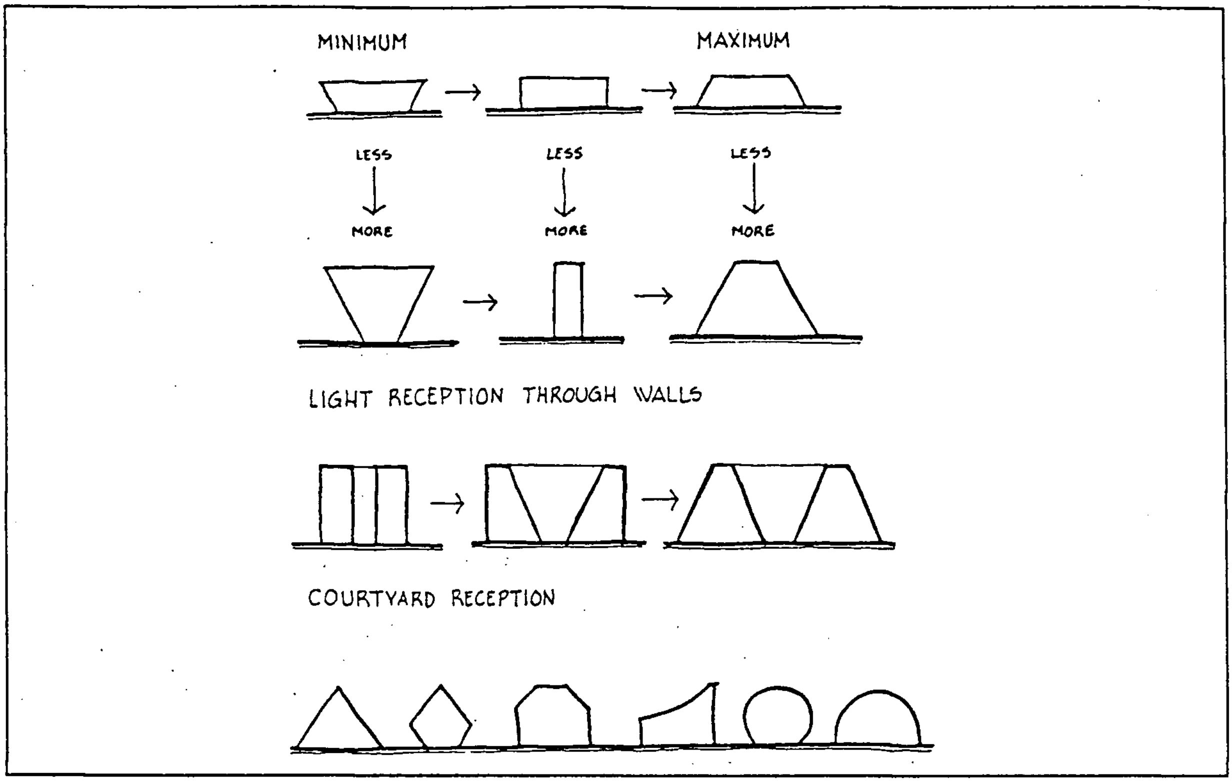


Figure 18 - Building form responses to light

various ways that reconcile daylighting needs with other requirements. For example, figure 20 shows that a pyramidal mass may be resolved into a stepped pyramid integrating structural, HVAC and other functional requirements.

2.4 Building Layout

For office buildings of more than one storey, window openings in walls are the predominant mode of daylighting. Some building layouts, such as those with a high ratio of exterior envelope area to floor area, provide access to daylight to a greater percentage of a given floor area than other building layouts. This means that long and relatively narrow layouts, for example, have greater potential for daylighting

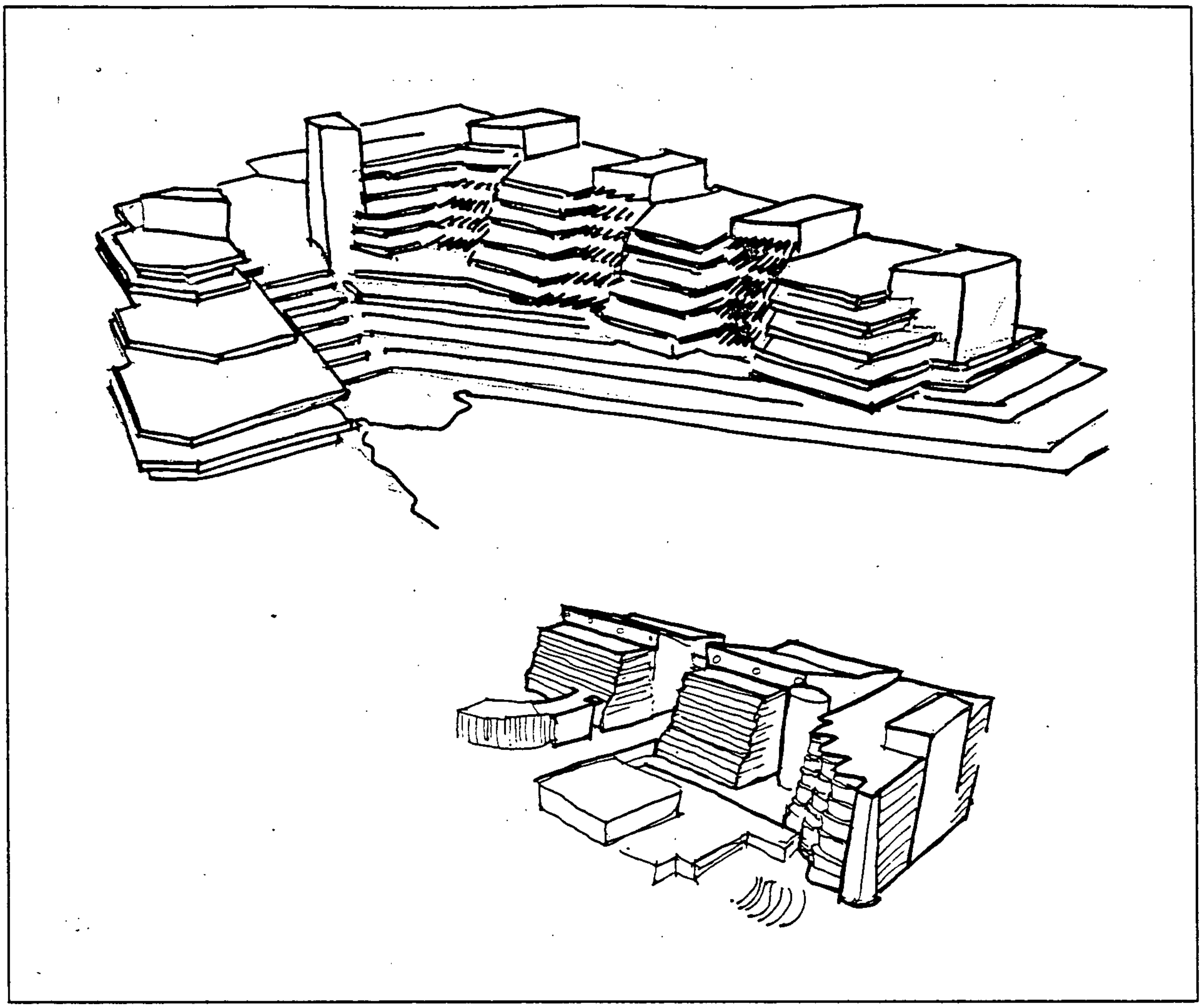


Figure 19 - Typical buildings whose massing responds to daylight

than square shaped plans (layout c. vs. layout a., in figure 21). Figure 22 illustrates schematically layouts of existing buildings that respond to daylighting needs[35].

An excellent example of the impact of daylighting consideration on building form (both massing and floor layout) is found in Alvar Aalto's Finnish National Pensions Institute, Helsinki, built between 1952 and 1956, an aerial view of which is shown in figure 23 [36]. Here, Aalto built a large office complex within a high density business district of the city.

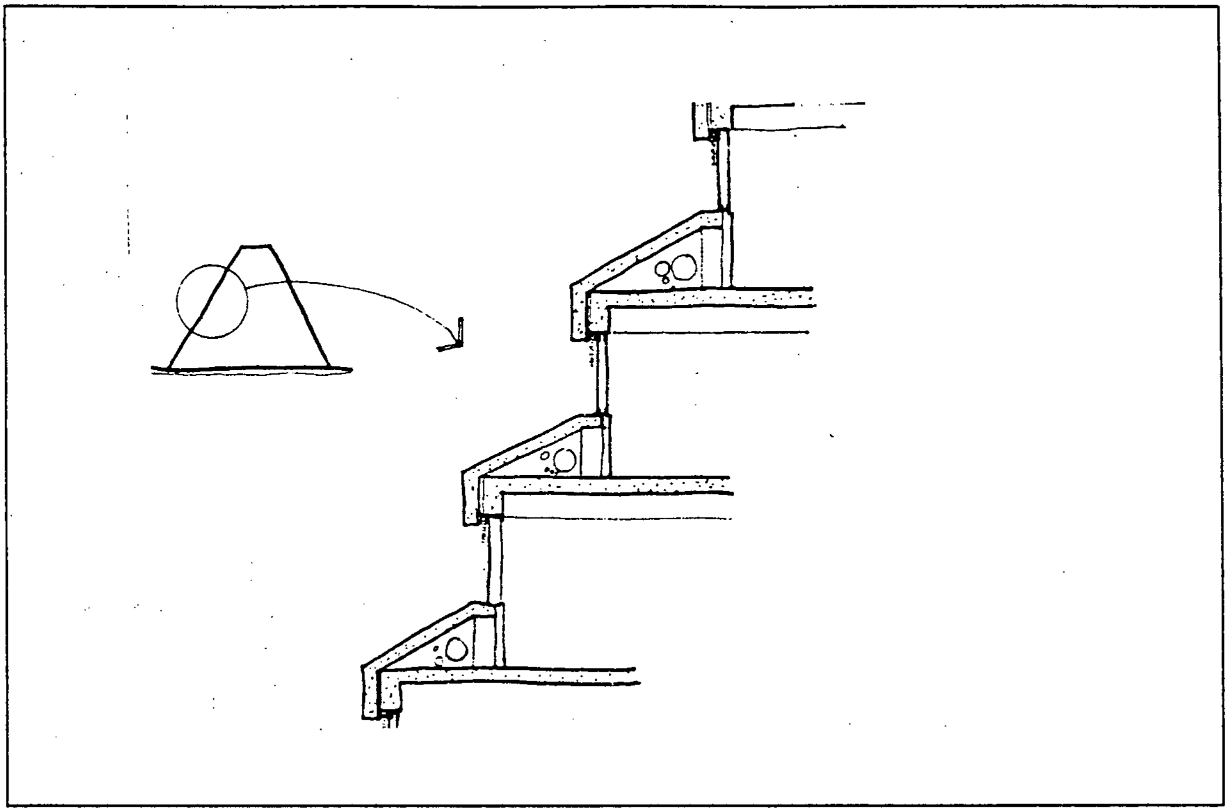


Figure 20 - An example of daylight-responsive massing and its resolution in detail

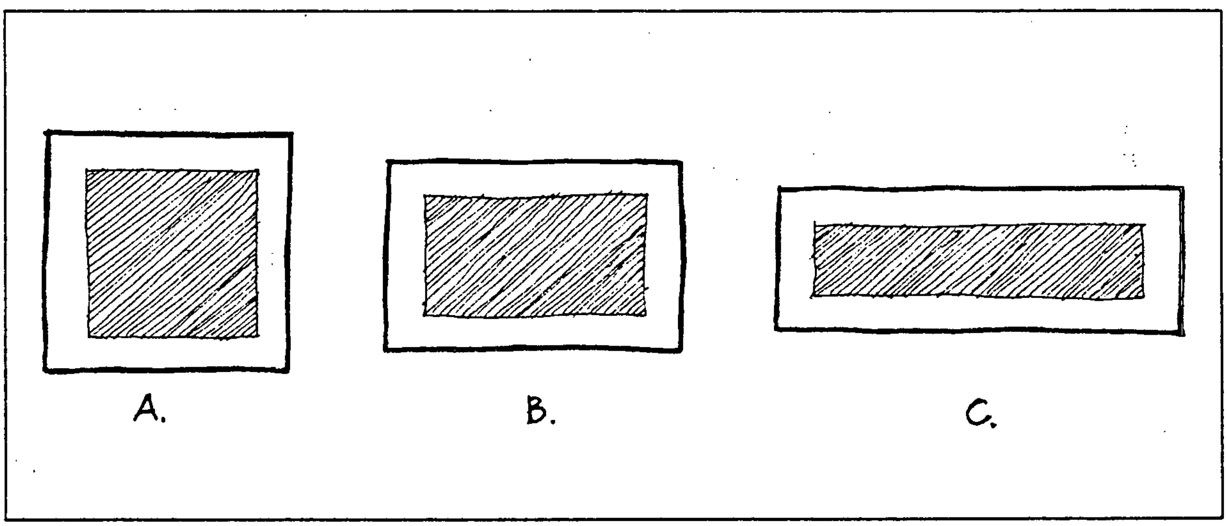


Figure 21 - The effect of building plan on daylight access

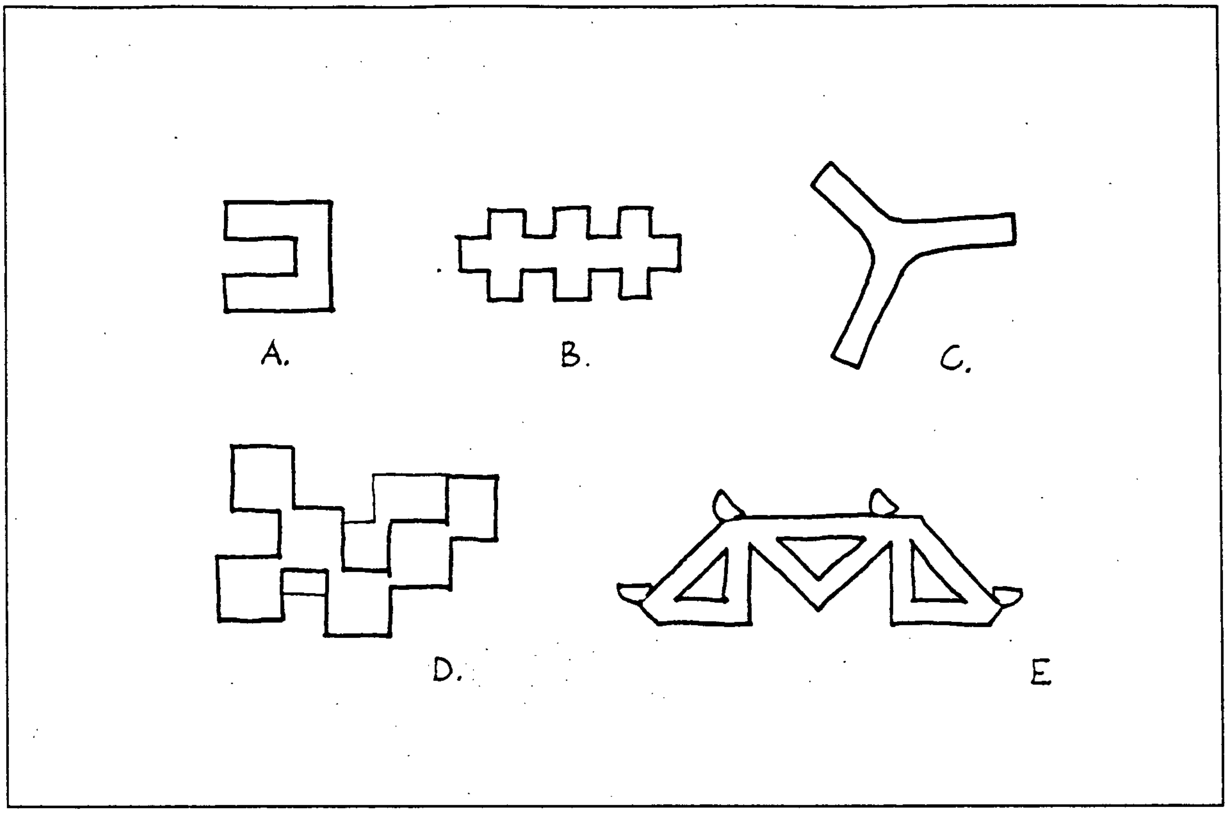


Figure 22 - Examples of existing buildings whose layout responds to daylighting needs

Building massing and layout respond to program requirements, while at the same time providing narrow plan depths and increased perimeters that enable good daylighting. The top floors of the low rise masses are daylit through skylights; four very large skylight structures light up an atrium on the main floor[37].

An increase in perimeter to accommodate daylighting is not without consequences:

i. The increase in perimeter may cause higher building cost since corners and exterior walls are generally expensive. However, while the cost of the building envelope may increase, the total building cost in a well integrated

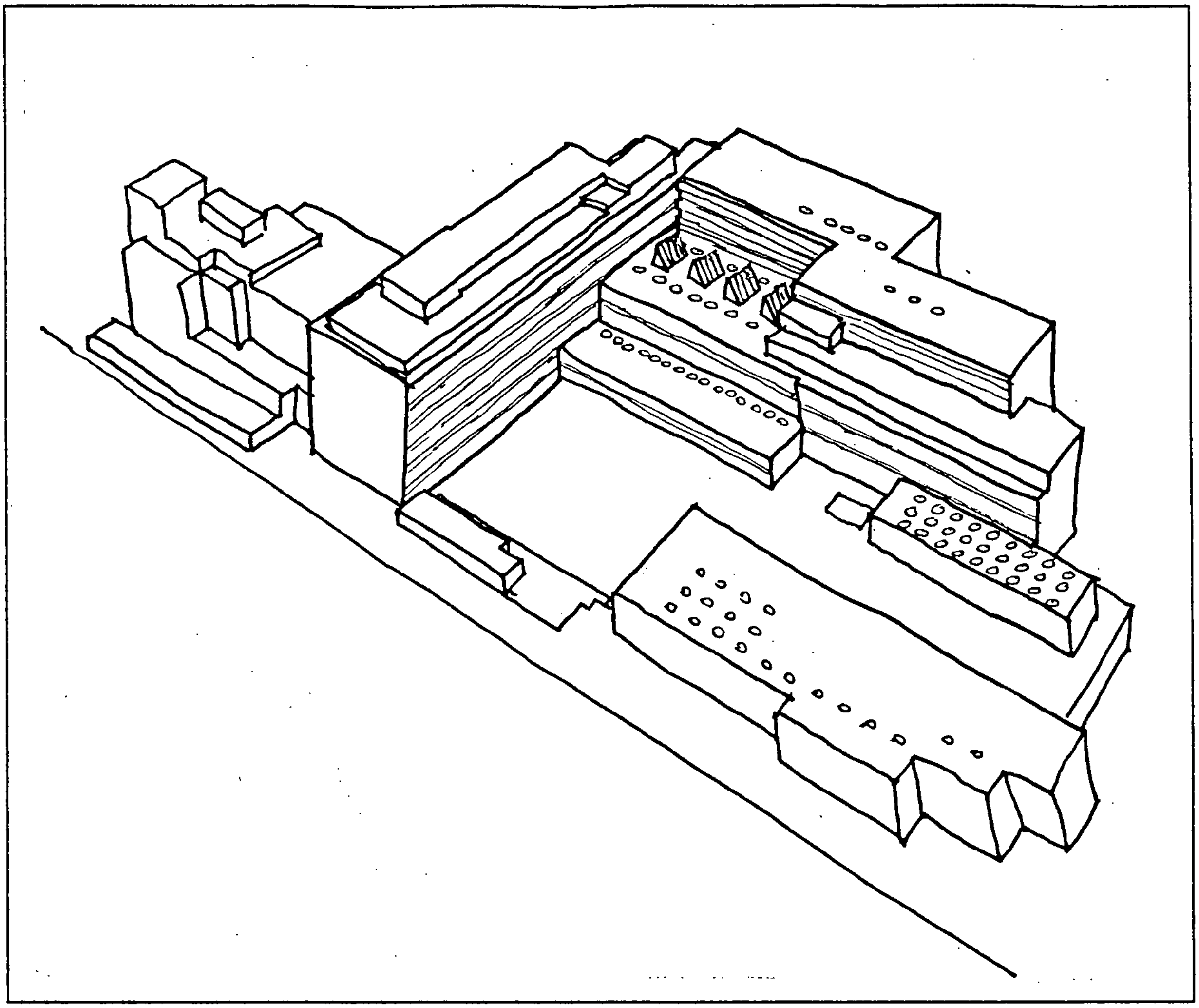


Figure 23 - Aerial view of Aalto's Finnish National Pensions Institute

design may be unchanged or even reduced[38].

ii. An increase in perimeter will lead to increased heat loss in winter and possibly, to increased solar gain in summer[39], unless their major orientation is north and south. However, with proper orientation, a larger envelope area created by narrower building shape or other manipulations of the plan to accommodate daylighting, carries at the very least no penalties and, in a mild climate, offers substantial net savings in energy cost.

According to Matthews and Calthorpe[40], office buildings, being generally internal load dominated, are not in fact, very sensitive to an increase in the ratio of envelope to floor area. This means that penalties of increased heat loss in winter and increased solar gain in summer can be more than offset by energy savings through daylighting. Bazjanac[41], using extensive computer studies on building energy use, indicates that office buildings actually benefit from a larger skin area in warm and temperate climates. In cold climates, there is only minimal advantage in choosing a rectangular plan over a square plan insofar as the total energy use of the building is concerned[42], but the advantage of a rectangular plan in terms of daylighting remains.

iii. Technical considerations may in many instances not be the predominant factors determining floor layout. The social organization of the owners/tenants and the site configuration may make a preferred layout from a daylighting point of view an inappropriate response. In this connection, Lynes, writing in the 1960s[43], has pointed out that "the future shape of office buildings may well depend more on ... social consequences than on the daylight factor". Nevertheless, the impact of building form on daylighting considerations have to be understood, even if these considerations may in many instances be overridden by other requirements.

2.5 Atria

If properly dimensioned and detailed for daylighting, atrium designs can increase the building perimeter having access to daylight. At the same time they avoid the heating and cooling penalties attendant with large exterior surface area (high perimeter) solutions.

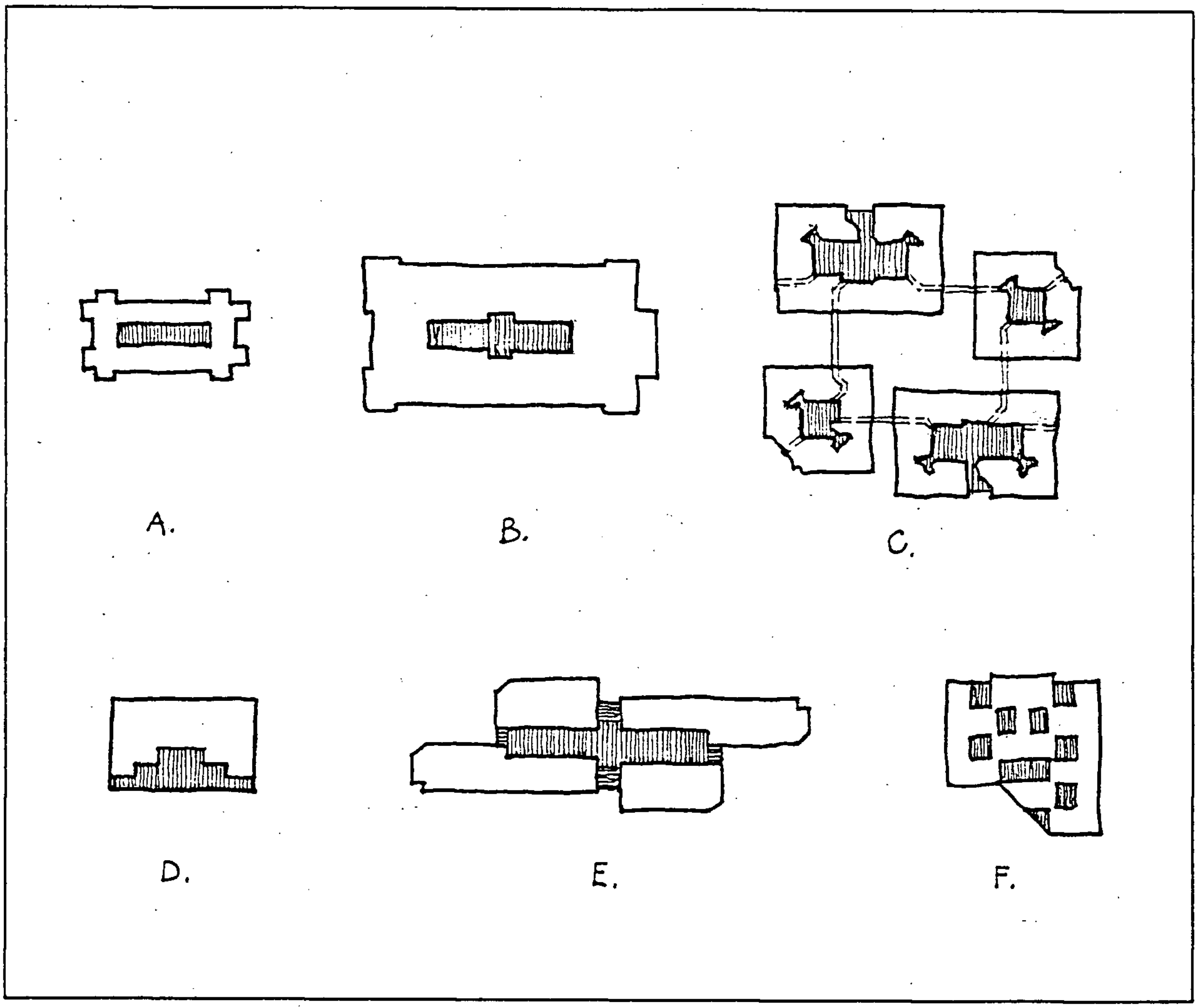


Figure 24 - Examples of existing daylit buildings with atrium plans

A study of the design concepts of the buildings plans shown in figure 24 [44], (as well as of other atrium buildings) reveals that the atria play a key role in resolving constraints of site, structural requirements, circulation, general program needs, as well as requirements for daylighting and energy saving. Daylighting requirements are, therefore, an important, but not sufficient reason for choosing an atrium concept.

In the late 1970's atrium plans became popular as innovative solutions to energy related issues in office building design--in particular, the issue of daylighting. Matthews and Selkowitz[45] have reported that generally they have not performed as anticipated: the energy dynamics in atria are complex and there is sometimes a poor match between predicted and actual energy behaviour. The contribution of atria to energy saving is now found to be questionable[46].

In some cases, atria do not significantly contribute to energy savings even in office lighting[47]. This however does not mean that the daylight reaching offices through such atria does not contribute to an improvement in the quality of light; only that it contributes little to the horizontal illumination. Atria, whatever their energy saving potential may be, can be interesting and delightful spaces to be in and look into; and many designers now agree that this should be the major criterion for their design[48,49].

2.6 North And South Orientation

Optimized plan shapes from the point of view of daylighting will have a relatively high perimeter to floor area ratio. The high perimeter may result from crinkling of the envelope of a basically compact layout or it may result from an elongated layout.

For office building layouts that have the length of the building substantially greater than the width, as well as for atrium type designs, an orientation in which the major facades face north and south is preferable. As Calthorpe[50] argues:

> When you begin to grapple with problems of daylighting a building and shading it against heat gain at the same time, orientation becomes very important. East and west facades are extremely difficult to deal with as light sources because they are, of course, so critical from the point of view of heat gain.

Sanchez[51] concurs, stating that for cooling load dominated buildings, such as offices, a north/south orientation results in the least total energy used by the building.

Two buildings that demonstrate the advantage of orienting the building facades to the north and the south are the Lougheed Missiles no. 157 building and the TVA building in Chattanooga, Tennesee. In both, the major axis is oriented east-west and essentially, they are both daylit from the north and south. Both have atria along their length, with daylight blocked at the east and west ends, thus avoiding the problems inherent with daylit east and west elevations[52,53].

Situations may arise in which a predominant east-west axis is not feasible. The conflict between daylighting and other requirements may be resolved, as shown in figure 25 , at various scales. At the building configuration scale, this may be resolved by reconsidering the massing concept or by reorganizing the plan; at the envelope scale, by letting in daylight separate from view and thereby providing greater potential to control the undesirable side effects of east and west facing apertures; or, at the element scale, by the resolution of the conflict between shading and daylighting requirements using accessories such as automatic venetian blinds, architectural projections, etc.

2.7 Interior Sunlight

As shown in figure 26 , sunlight in office buildings may be admitted into one of the following areas:

i. the work area

ii. the periphery of the work area

iii. non-task areas

The function of sunlight is different in each case.

Sunlighting the work area

While sunlight indoors is in general found to be a desirable amenity, there appear to be differing opinions whether direct sunshine should be allowed within the office workspace. This is because sunlight, if uncontrolled, can lead to substantial overheating and/or glare problems[54]; the former

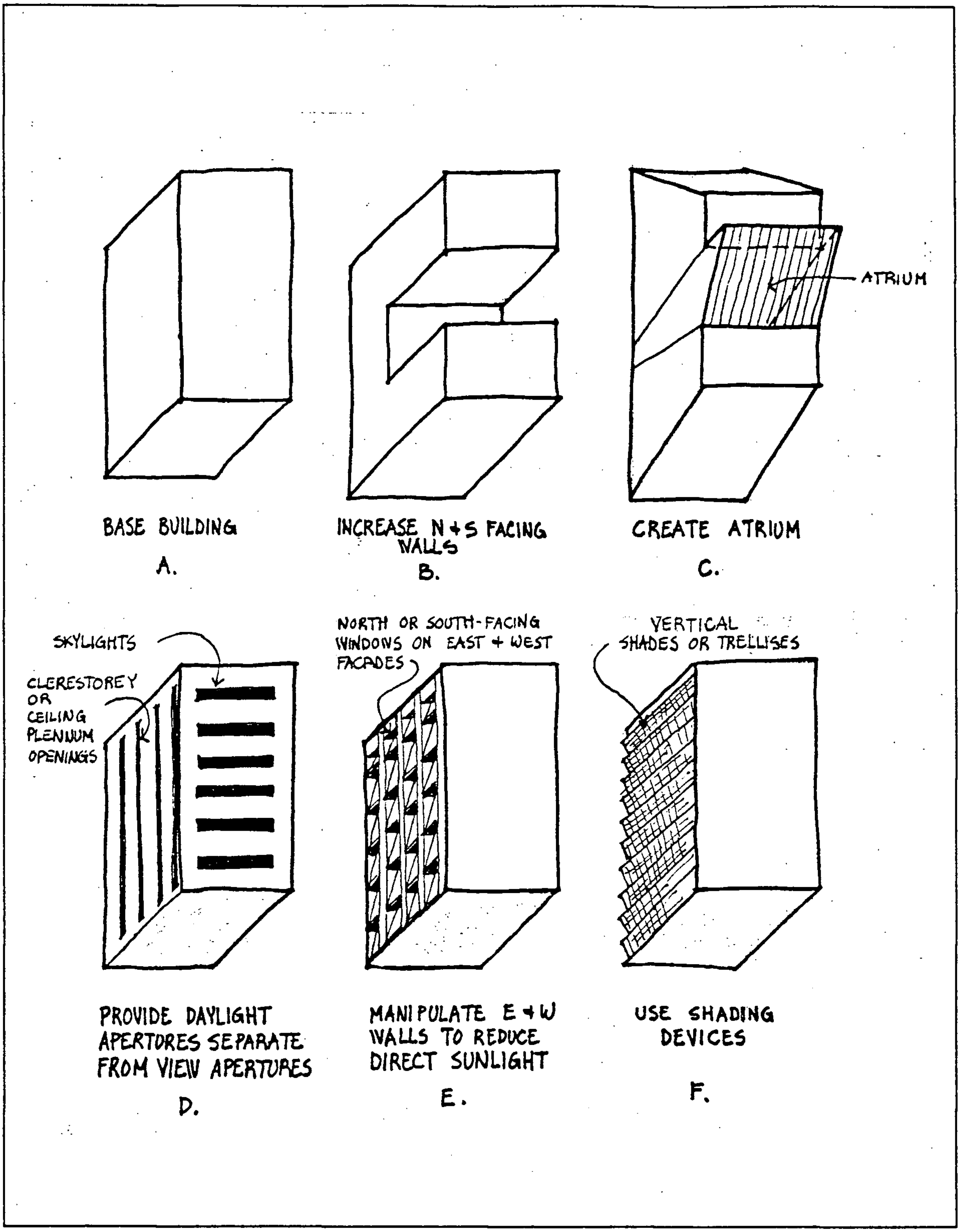


Figure 25 - Response to daylighting in buildings that must have a dominant north-south axis

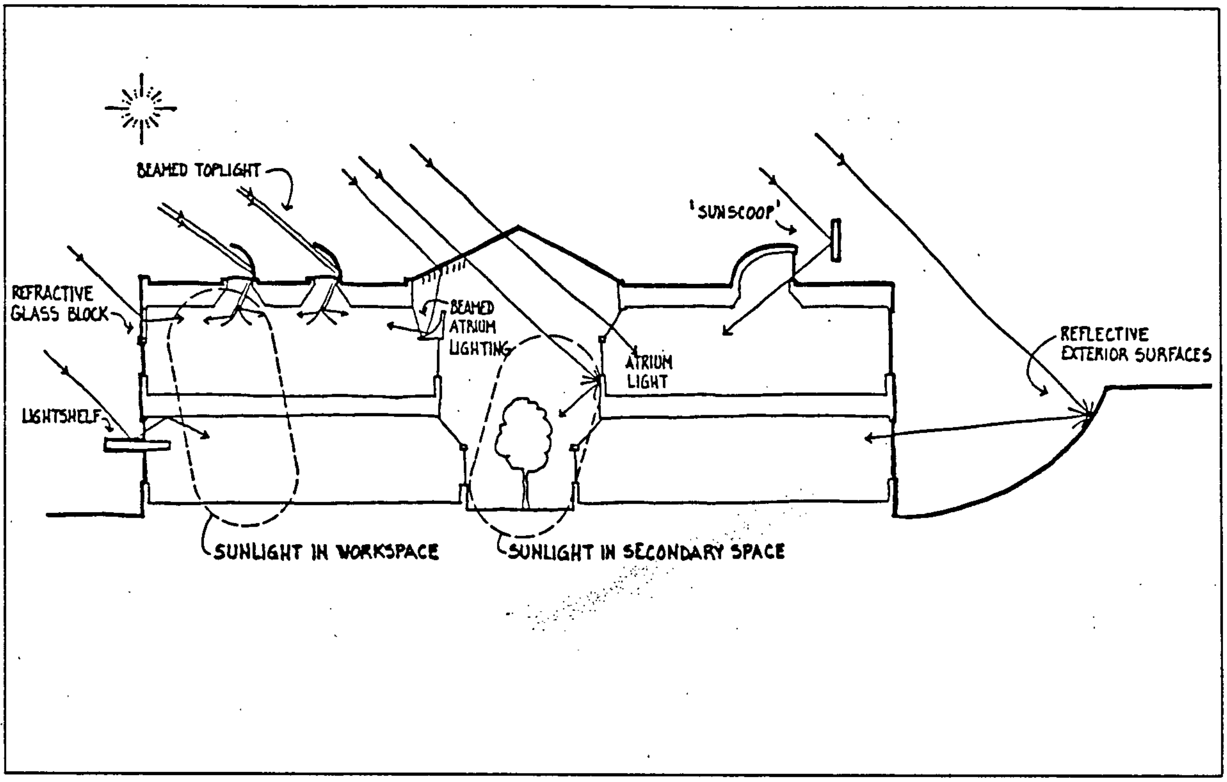


Figure 26 - Techniques for admitting sunlight into interiors

resulting in costly air conditioning, and the latter in worker discomfort and an attendant reduced performance. However, sunlight is an illuminant of high luminous efficacy: 100-120 lumens/watt[55] as compared with 11-22 lumens/watt for incandescent lamps, and 40-80 lumens/watt for fluorescent lamps[56]. If distributed uniformly, the lumens contained in $1m^2$ of sunlight could provide 500 lux of illumination over an area of $195m^2$ [57]. The problem is, therefore, one of distribution and control.

Sunlight is admitted into task areas primarily to raise the horizontal task illuminance within the space. Traditional daylighting techniques are generally unable to distribute and control the great intensity of sunlight near the fenestration and therefore direct sunlight is generally screened out in order to provide an acceptable luminous environment in the interior.

There are exceptions to this. At certain times of the day--early winter mornings for example--sunshine may be allowed inside an office building to assist in heating up the building[58] and providing a lively play of light for an hour or so as the workday begins. An example of this is the CIGNA building in Bloomfield, Connecticut[59]. Ordinarily, however, only innovative sunlight "beaming" systems can effectively project and distribute sunlight deep into spaces, and can also deal with the problem of heat gain and glare inherent in the manipulation of direct sunlight.

Sunlighting the periphery of the work area

Sunlight is introduced into the periphery of the working area to provide ambient light for circulation, create points of interest and balance the level of brightness at locations away from daylighting apertures. Sunlight for these purposes need not have as stringent distribution and control since the illuminance levels are not critical. The use of daylight in this way takes advantage of the fact that "most people view sunlit surfaces as desirable points of interest because of the importance of sun light in man's biological history"[60]. The strong positive associations that people in cold climates have for sunlight, as well as the variability and dynamic quality of sunshine, can thus be an asset. The Johnson Control offices in Utah (by Donald Watson Architects)[61] is an example of sunlight used as wall washer, creating a luminous plane providing supplementary illumination and a visual focus, as well as aiding orientation within the building.

Sunlighting in non-task areas

Sunlight is admitted in non-task areas--such as lounges, cafeterias, stairwells, entrance foyers, etc.--to celebrate the drama of sunshine, to create a strong biological connection with the outdoors and to contrast the exhuberance of these areas with the controlled visual environment in task areas. Sunlight introduced in these areas needs little or no control and may be distributed by simple techniques, such as the use of high reflectance surfaces to bounce light around. Because visual performance is not critical in these areas, the amount of sunlight and the means of bringing it into such spaces is determined by the limits for overheating and envelope heat loss that are considered acceptable. It is in these secondary and transitional areas that the lighting can be contrasted with the daylighting schemes within work areas requiring a more disciplined design approach. Fine examples of these kind of spaces are the AAL building cafeteria in Appleton, Wisconsin[62,63] and the entrance lobby of the Ventura Coastal Corporation building in Ventura, California[64].

2.8 Daylighting Separate From View

View windows are the most common method of daylighting offices, because the combination of daylighting and view to outdoors is obvious and low in cost, and because offices, being generally multi-storey and monolithic, provide opportunities for daylighting mostly through the walls. However, daylighting through view apertures can encounter some of the following difficulties:

i. If windows are of optimum size for daylighting (and even if below the optimum), there may be a problem of glare that requires special accessories and/or detailing to control.

ii. Windows sized optimally as daylighting apertures can be a solar heat gain and/or an envelope heat loss liability.

iii. The location and shape of windows for view is generally not the optimum location and shape for daylighting apertures: apertures higher, closer to the ceiling, and responsive to obstructions due to the building shape and other surrounding buildings, will optimize daylighting, thus often conflicting with requirements for view.

iv. Restricting daylighting apertures to view windows means that a large percentage of the building envelope having access to daylight is not being used for this purpose; this represents a lost opportunity.

Figure 27 shows buildings utilizing daylighting apertures separate from view windows.

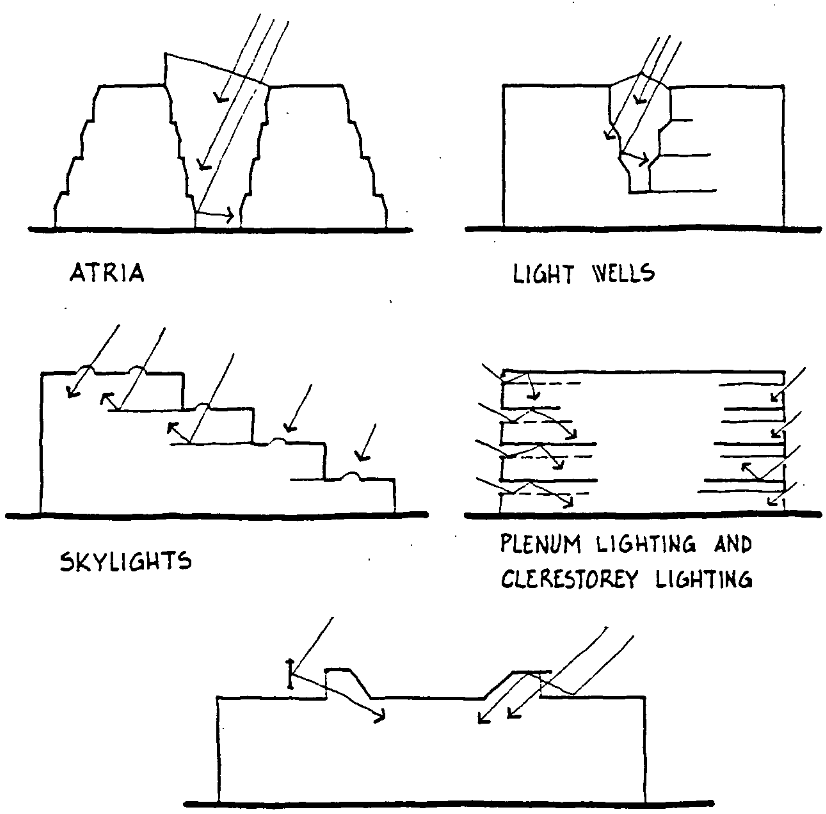


Figure 27 - Buildings utilizing daylighting apertures separate from view

2.9 Daylighting From The Top

Small office buildings of two storeys are the median size for North America[65], and single storey commercial buildings make up 58% of USA non-residential building stock[66]. Although side lighting is of necessity predominant in most office buildings[67], top lighting can easily provide a substantial portion of the lighting for the top floors of office buildings during working hours and can save energy as well[68,69]. The opportunities for top lighting are thus substantial, and mostly unrealized, at present.

Top lighting can deliver large quantities of daylight with minimum sized openings, because the illumination falling on the horizontal plane of the roof is generally many times that which falls on the vertical plane of typical windows[70]. While more appropriate in lighting top floors of buildings, top lighting through lightwells can bring light to lower floors as well, as shown schematically in figure 28 [71,72].

Top lighting may be roughly divided into two categories: skylights and roof monitors. Skylight may be defined as daylighting apertures parallel to the roof plane, whereas roof monitors are daylighting apertures in the vertical plane.

Typical skylight solutions are shown in figure 29 [73]. In a., the skylight well is splayed to increase spread of daylight for a given skylight area. In b., a typical skylight is shown fitted with an adjustable reflector/shade to increase the daylight/sunlight penetration. In c. , the device is adjusted to provide shading, and reduce solar heat gain. In the above examples, a distinctly separate mechanism for controlling glare and increasing daylight penetration is installed on a standard skylight. The examples shown in figure 30 [74] are roof monitors that have the glare, solar heat gain and heat loss controls integrated with the daylighting aperture. The control devices are an extension of the building envelope and surfaces: an overhang controls unwanted solar heat gain and high reflectance surfaces distribute the light.

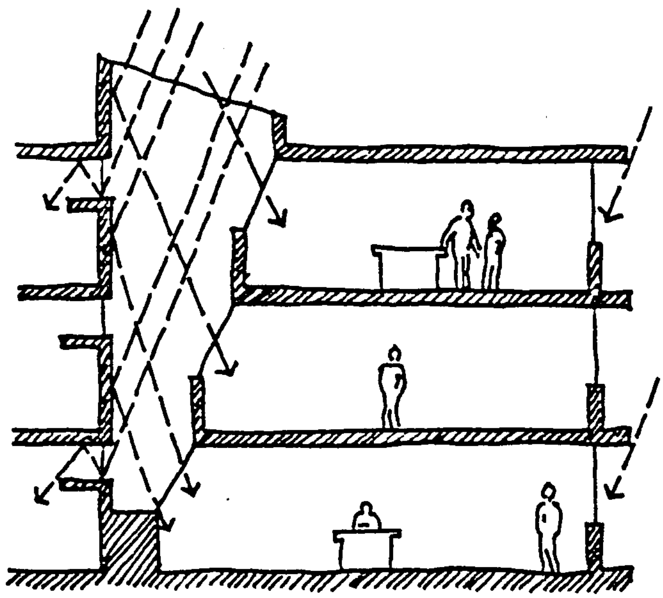


Figure 28 - A skylight with a lightwell can deliver light deep into interiors

The choice between roof monitors and skylights is usually made not only on the basis of the quantity of light and thermal tradeoffs involved with each type, but also on the impact of each type on the building form and the modulation of the resulting interior light. Thus, skylights provide more light per glazed area than roof monitors and result in less expensive roof construction and simpler roof shapes. However, skylights on flat roofs, because they are oriented to the zenith, require special attention to glare and solar heat control. Because skylights are incorporated in the roof plane and do not generally involve additional projecting planes, they can be economically be laid out in patterns that result in an even

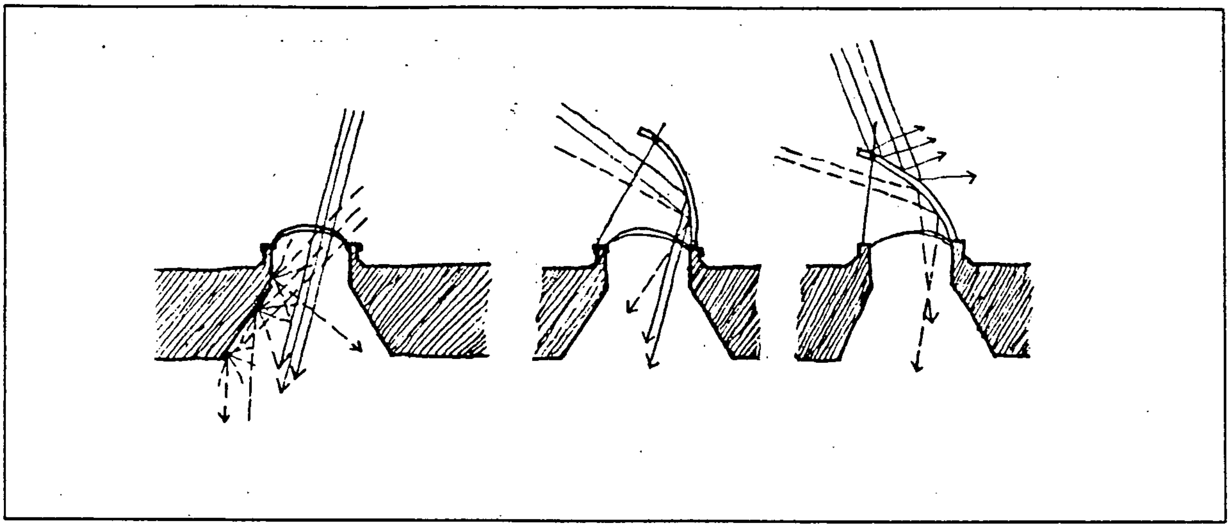


Figure 29 - Daylighting and sunlighting with standard skylights

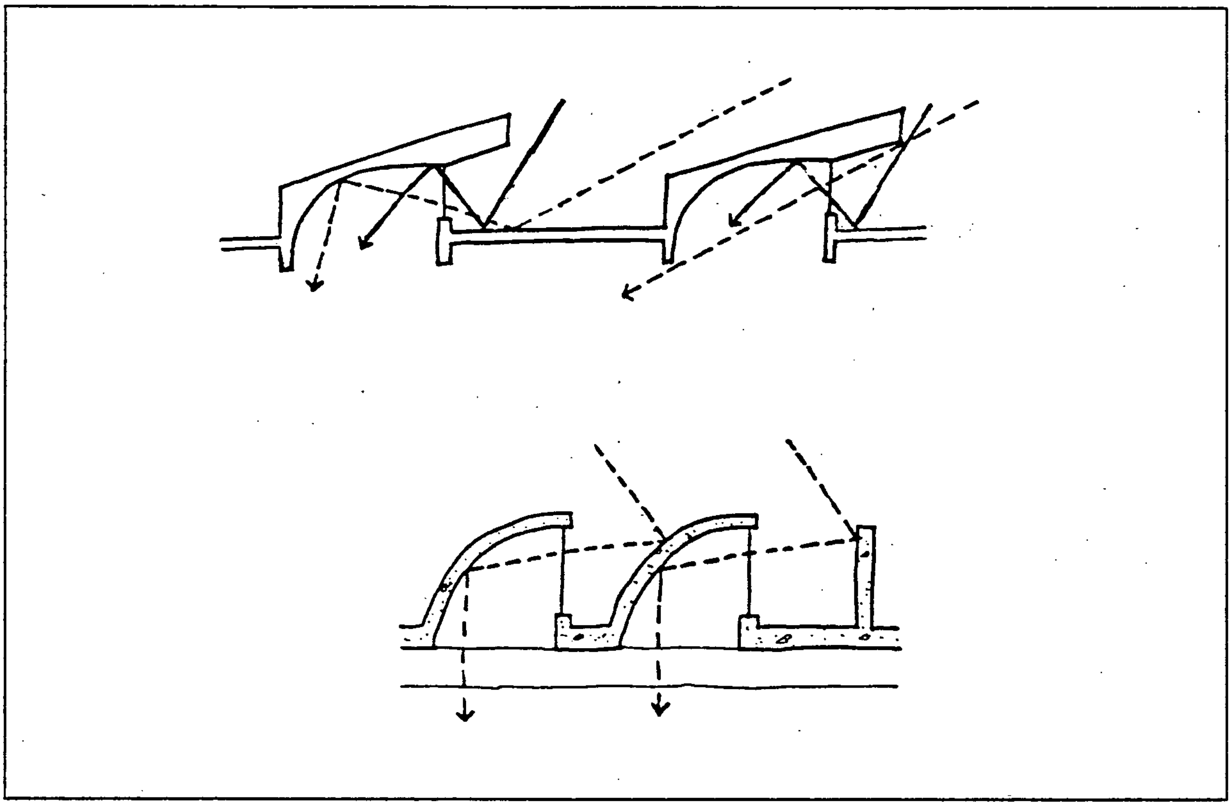


Figure 30 - Integrated toplighting examples

daylight distribution on the horizontal work plane. Roof monitors can be used as large, dramatic, semi-indirect daylighting apertures (two examples are shown in figure 30). They can be oriented to any direction, and can thereby avoid solar heat gain, if this is undesirable. Lam[75] has used "sun catcher baffles" to reflect sunlight into roof monitors facing north, thereby taking advantage of the sun's light without the attendant heat gain. South-facing monitors can similarly incorporate solar controls, either as baffles or as overhangs. For reasons of economy, roof monitors will generally be large architectural elements. As such, they will deliver large pools of light into the interior, but this light will not be as evenly distributed as is possible with skylights. Depending on the end use intended, this may, or may not be a problem.

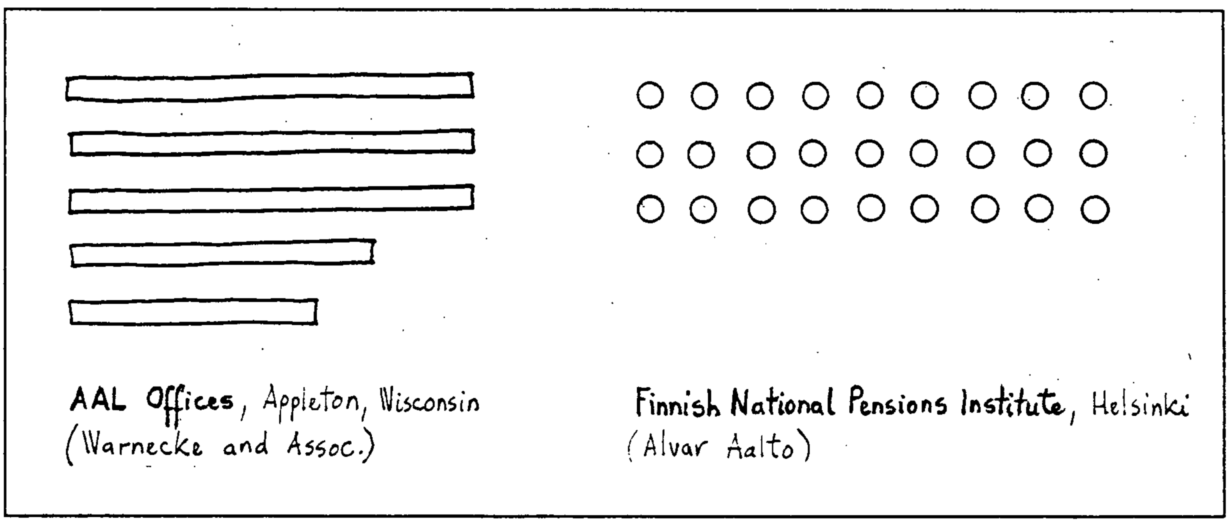


Figure 31 - Typical toplighting layouts

Daylighting a substantial portion of a floor with skylights may involve the use of either linear skylights or compact circular, square or rectangular ones on a grid pattern as shown in figure 31 [76]. The choice is generally determined by concerns of aesthetics, structure, and integration with other environmental concerns. Both layouts shown can potentially provide good daylight penetration.

2.10 Obstructions

Obstructions to daylight access may occur either at the bottom of the daylighting aperture (generally due to the presence of nearby buildings or landscape elements) or at the top (generally due to elements of the building itself). This is shown in figure 32 . Further, obstructions to daylight access above daylighting apertures may occur either at the massing or component scale, as shown in figure 33 . Obstruction at the massing scale has been discussed in a previous section; the focus in this section is on obstruction to daylight access at the component scale. Consideration of overhead obstructions is especially important when window openings are already obstructed by other buildings or landscape features[77].

Types of obstruction

Obstructions above a daylighting aperture are of three types:

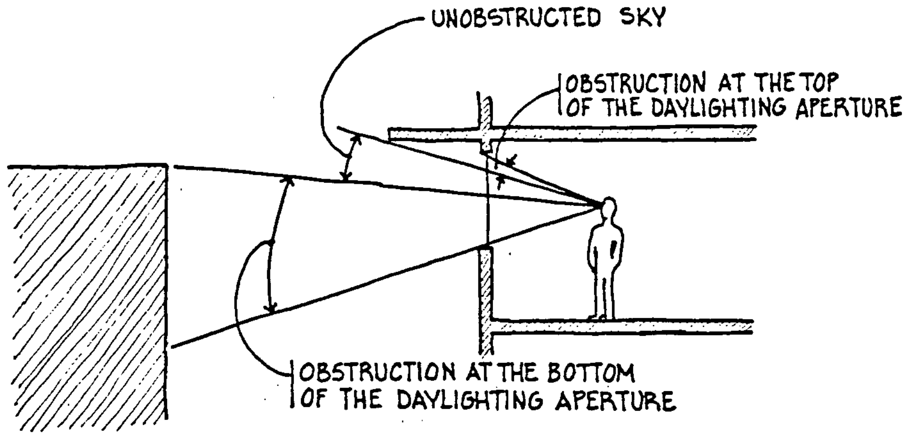


Figure 32 - Obstructions at the bottom or the top of a daylighting aperture

i. The first type of obstructions are those created by external shading devices. Partial obstruction of the skyvault by exterior horizontal sun control devices is, in practice, unavoidable, since in screening out the sun, they invariably mask a portion of the sky. However, sun control devices which are equally effective in screening out the sun, can vary widely in luminous performance. Therefore, it is possible to select sun control devices that perform their primary function with a minimum obstruction of daylight.

ii. The second type of obstructions are due to geometry of the facade. Once this geometry is chosen, obstruction of the

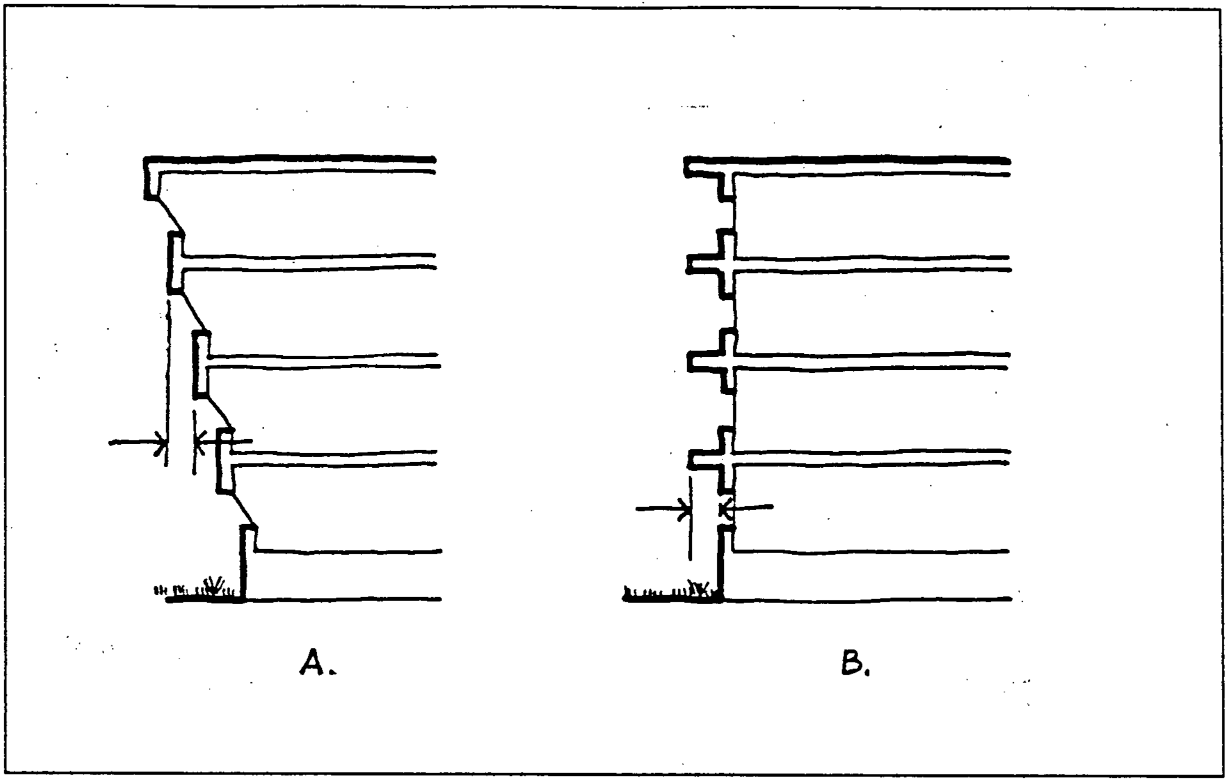


Figure 33 - Obstructions at the massing scale (a.) and the component scale (b.)

skyvault above daylighting apertures due to this choice is unavoidable. Figure 34 shows three typical cases. In a. a bay window is shown. This type of daylighting aperture provides a pool of light near the aperture, with little daylight penetration[78]. Its luminous performance is equivalent to that of a daylighting aperture in the plane of the facade with a trapezoidal shading device overhead[79,80]. Therefore, bay windows are not effective daylighting elements and should be chosen only if they are found to be desirable in modulating elevations and floor areas.

Figure 34 b. shows a corner window. The luminous performance of this design is equivalent to that of a daylighting aperture across the opening, with a pointed hood (shading device) overhead[81].

Figure 34 c. shows a daylighting aperture with sloped glass. In this case, as shown in the drawing, the luminous performance of this daylighting aperture is equivalent to that of an aperture with vertical glazing at the same location as the base of the original daylighting aperture and a shading device overhead. The slope of the glass will reduce glare from the skyvault, but by itself has a small effect on daylight penetration[82]. However, the effect of the "overhang" is to reduce daylight access.

iii. The third type of obstructions above daylighting apertures are those created by floor areas projecting beyond the line of the daylighting aperture (eg. cantilevered floors, balconies, etc.).

Effect of obstruction parameters

Four obstruction parameters may be identified as affecting daylight access:

i. Obstruction depth has a major effect on daylight access from the interior. It may be seen in figure 35 [83], that a shallow obstruction affects points near the daylighting aperture but not further away, whereas deeper obstructions reduce daylight levels progressively further in the interior. This is because the deeper obstructions reduce the sky visible and hence also the interior reflected component[84,85].

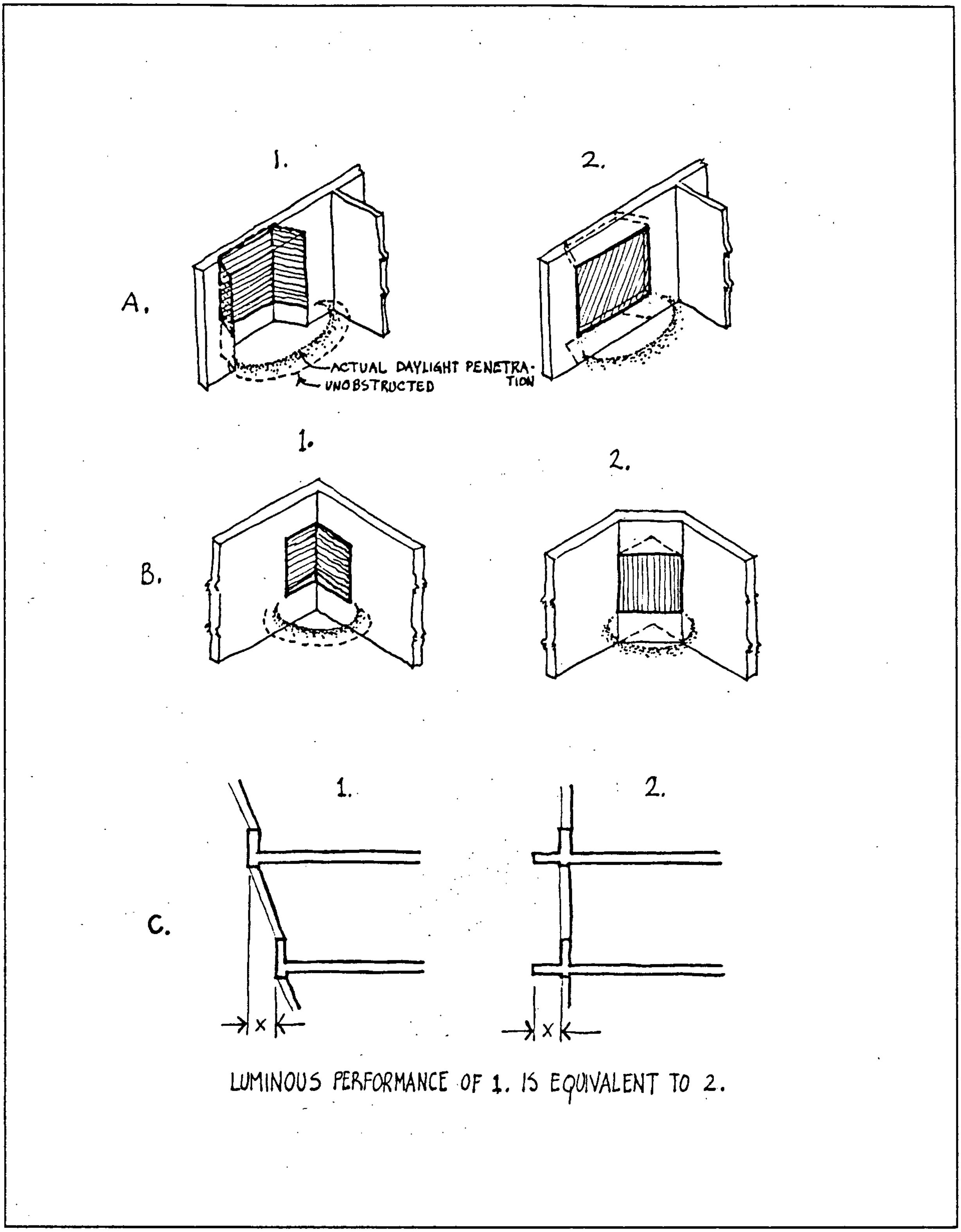


Figure 34 - Obstructions above daylighting apertures due to facade geometry

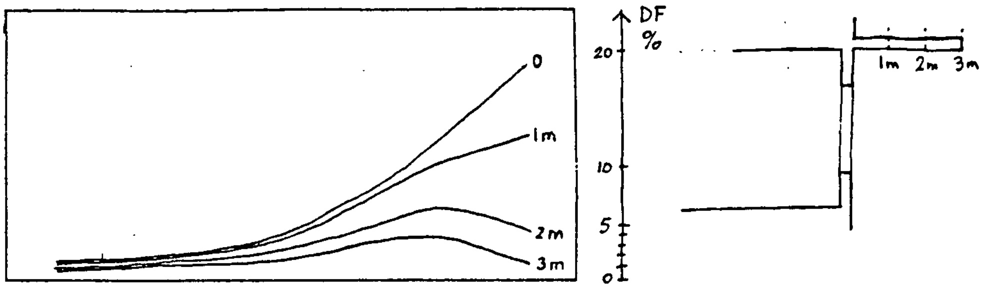


Figure 35 - Relationship between obstruction depth and daylight penetration

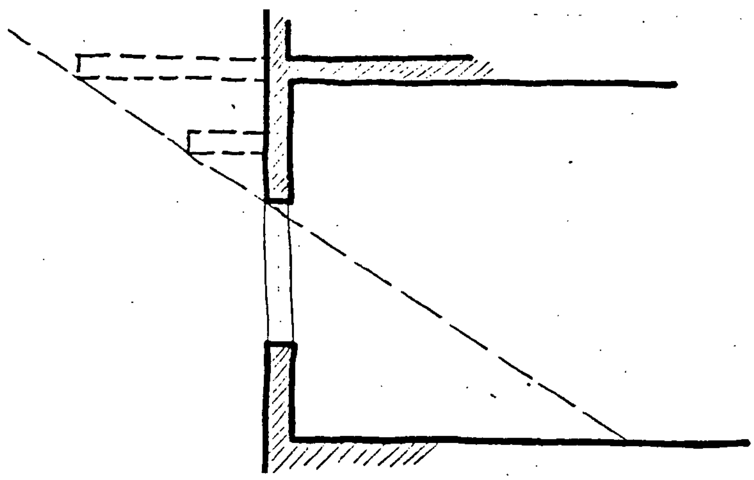


Figure 36 - Obstructions at different heights above a daylighting aperture having identical effect on daylight penetration

ii. Height of obstruction above the daylighting aperture is a second parameter affecting daylight access. Figure 36 shows two obstructions, of different depths and different heights above the daylighting aperture. They block access to daylight from the skyvault equally: the location in the room of the "no-sky line"[86] is the same in both instances.

iii. The reflectance of the underside of obstruction is a third parameter affecting daylight access. It is possible to compensate to some extent for a reduced daylight access due to an obstruction above the daylighting aperture by increasing the reflectance of its underside surface. Experiments by Aschehoug et al.[87] show that with a low reflectance foreground, an increase from 30% reflectance (grey concrete) to 75% reflectance, (near white paint) increases the DF by one tenth in the front of the room and reduces it by one tenth at the back.

iv. Ground reflectance is the fourth parameter affecting daylight acccess with a daylighting aperture obstructed overhead. Reflectance of the ground is very important, as it can mitigate to a large extent the inherent daylighting disadvantages of overhead obstructions. It can be seen in figure 37 [88], that with an obstruction over the daylighting aperture, an increase in ground reflectance from 5% (blacktop) to 85% (light paint, fresh snow) can approximately triple the DF at the back of a room and generally reduce the DF gradient. An increase in the reflectance of the underside of the obstruction can add a further 10% to the DF all across the room[89], with even greater increase near the window.

It is important to note, that when a daylighting scheme relies on high reflectance for the ground surface, this

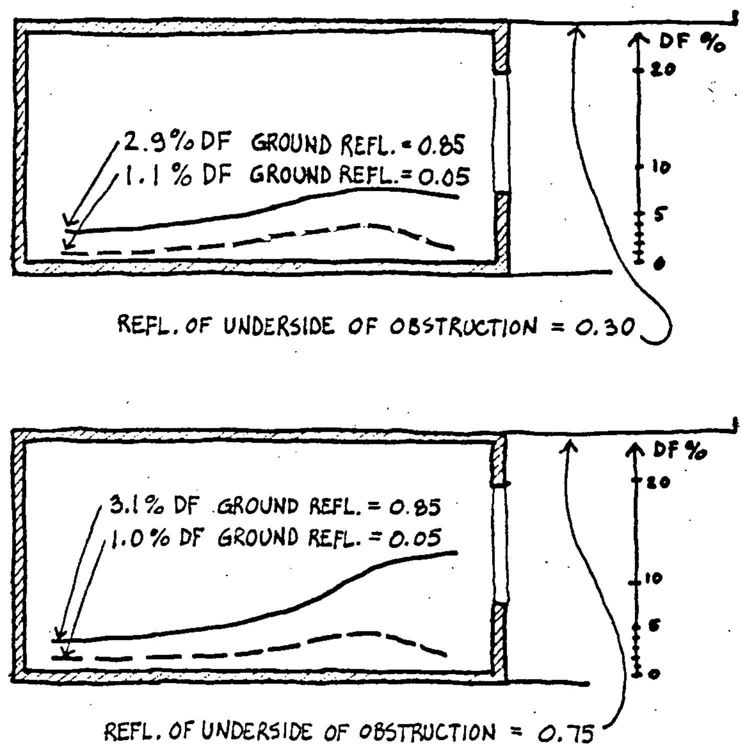


Figure 37 - The effect of ground reflectance on daylight access, with an obstruction above the daylighting aperture

reflectance value will need to be maintained in practice to ensure the success of the scheme. Ground reflectance values are, however, difficult to maintain for the life of the building, unless the "ground" is a roof or similar surface, covered with high reflectance material which can reasonably be expected to maintain this property with time.

3. NOTES

1. Rays of sunlight are parallel because the source is very far away.

2. Turbidity is an index of the haze in the atmosphere--either due to natural causes (eg. water vapour, fog) or man-made causes (eg. smog).

3. Up to 120 lumens/Watt. Arthur H. Rosenfeld and Stephen E. Selkowitz, "Beam Daylighting: An Alternative Illumination technique," Energy and Buildings,1(1977):44.

4. IES Daylighting Committee, "Recommended Practice of Daylighting," Lighting Design and Applications, February 1979, p. 33.

5. R. G. Hopkinson, Architectural Physics: Lighting (London: Her Majesty's Stationery Office, 1963), p. 166.

6. IES Daylighting Committee (1979), p. 33.

7. IES Daylighting Committee, Recommended Practice of Daylighting (New York: Illuminating Engineering Society, 1962), p. 9.

8. William Lam, "Sunlighting as Formgiver for Architecture," Proceedings of the 1983 International Daylighting Conference, 16-18 February 1983 in Phoenix, Arizona. Washington, D. C.: 1983 International Daylighting Conference, 1983, pp. 77-80.

9. The concept of the Daylight Factor (DF) is a useful index in assessing the relative daylight levels available at various points in building interiors. The DF is the sum of three components: the sky component (SC), the exterior reflected component (ERC) and the internally reflected component (IRC).

10. J. A. Lynes, Principles of Natural Lighting (London: Elsevier, 1968), p. 184.

11. Harvey Bryan et al., Quicklite I: A Daylighting Program for the TI-59 Calculator (Berkeley, California: Lawrence Berkeley Laboratory, 1981).

12. J. W. T. Walsh, The Science of Daylight (New York: Pitman, 1961), p. 233.

13. Building Research Board, The Lighting of Buildings (London: His Majesty's Stationery Office, 1944), pp. 22-25.

14. Ibid., pp. 23.

15. Hopkinson, p. 34.

16. See also Walsh, p. 214-15.

17. Building Research Board, p. 24.

18. Walsh, pp. 233-35.

19. Building Research Board, p. 25.

20. Ibid., p. 24.

21. Ibid., p. 27.

22. The performance of 'T' and 'L' shaped buildings is similar to that of the cruciform plans studied (Building Research Board, p. 24).

23. Building Research Board, p. 26.

24. Lynes, p. 156.

25. Building Research Board, p. 26.

26. Ibid.

27. IES Daylighting Committee, Recommended Practice of Daylighting, 1962, p. 9.

28. B. H. Reed, "Effects of Nearby Walks and Concrete Areas on Indoor Natural Lighting," Illuminating Engineering, July, 1956, p. 532.

29. R. G. Hopkinson, Architectural Physics: Lighting (London: Her Majesty's Stationery Office, 1963), p. 178.

30. Robert S. Hastings and Richard W. Crenshaw, Window Design Strategies to Conserve Energy (NBS Building Science Series 104, Washington D.C.: Department of Commerce, 1977), p. 16.

31. R. G. Hopkinson and J. D. Kay, The Lighting of Buildings (London: Faber and Faber, 1969), p. 88.

32. Gary O. Robinette, Plants, People and Environmental

Quality (Washington, D. C.: Department of the Interior, 1972), pp. 70-71.

33. A. Bowen, "Fundamentals of Solar Architecture," in Solar Energy Conversion: An Introductory Course, edited by A. E. Dixon and J. D. Leslie, eds. (Toronto: Pergamon, 1979), p. 500.

34. Plans are: A.--GSIS building, Manila, Phillipines from Architectural Record, "Terraced Pods Invite Daylight and Breezes," Architectural Record, Mid-August 1981, p. 52.; B.--TVA building, Chttanouga, Tenn., from Scott Matthews and Peter Calthorpe, "Daylight as a Central Determinant of Design," AIA Journal, September 1979, p. 87.

35. The plans are: A.--Wainwright building, St. Louis, Mo. (Louis Sullivan); B.--typical European office building in 1950s; C.--UNESCO, Paris (Breuer and Zehrfuss); D.--B.P. Headquarters, Hamburg,(proposal only, A. Aalto); E.--Shell Oil Co. Exploration and Production Offices, Houston,Texas (CRS, arch.).

36. Quantrill, pp 119-20.

37. Flieg, Karl, ed., Alvar Aalto (New York: Praeger, 1971), p. 120.

38. AIA Journal, "Measuring Performance of Energy Design: DOE studies a set of Owens-Corning Award Winners over Time," AIA Journal, January 1983, p. 44.

39. Max H. Leu, "Energy Conservation in Office Buildings," Master's Thesis at University of British Columbia, 1980, p. 121.

40. Matthews and Calthorpe, p. 87.

41. Vladimir Bazjanac, "Energy Analysis: One Year Later," Progressive Architecture, April 1981, p. 154.

42. Ibid.

43. Lynes, p. 159.

44. The plans are: A.--Larkin building, Buffalo, N. Y. (F. L. Wright); B.-- Lockheed Missiles no. 157 building, Sunnyvale, Calif. (L. Daly); C.-- Atria North Complex, Toronto (Thom Partnership); D.-- Enerplex, Plainsboro, N. J. (SOM); E.-- CIGNA building, Bloomfield, Conn. (Architects Collaborative); F.-- State Office building, San Jose, Calif. (State of Calif., Arch.).

45. Scott Matthews and Stephen Selkowitz, plennary session, The 1983 International Daylighting Conference, 16-18

February 1983 in Phoenix, Arizona .

46. Ibid.

47. Scott Matthews, "Proving the Benefits of Daylighting," Architectural Record, Mid-August, 1981, p. 49.

48. Ibid.

49. Stephen Selkowitz, talk given at the plennary session, The 1983 International Daylighting Conference, 16-18 February 1983 in Phoenix, Arizona .

50. Architectural Record, "Round Table: A Realistic Look at The Passive Approach--Using Natural Means to Conserve Energy," Architectural Record, Mid-August 1983, p. 98.

51. Nestor E. Sanchez and William Rudoy, "Energy Impact of the Use of Daylighting in Offices," ASHRAE Transactions, 1981, pt.2, pp. 145.

52. Peter Calthorpe, "More Than Just Energy," Progressive Architecture, April 1983, p. 119.

53. Lee Stephen Windheim and Kyle V. Davy, "The Substitution of Daylighting for Electric Lighting in a Large Office Building," Proceedings of the 6th National Passive Solar Conference, September 8-12, 1981 in Portland, Oregon, Newark, Delaware: American Section of the International Solar Energy Society, 1972, p. 878.

54. Architectural Record, "A Perspective on Daylighting Design," Architectural Record, Midaugust 1981, p. 45.

55. Rosenfeld and Selkowitz, p. 44.

56. A. W. Levy, "Interior Lighting Design and Energy Conservation," Division of Building Research, National Research Council of Canada, Canadian Building Digest 192, 1977, p. 3.

57. Rosenfeld and Selkowitz, p. 43.

58. Marietta S. Millet, "Daylighting Design Guidelines for Pacific Northwest Buildings," Proceedings of 'Solar 79 Northwest' Conference, August 10-12, 1979 in Seattle. Seattle: Pacific Northwest Solar Energy Association, 1979, p. 52.

59. Architectural Record, "Partitions and Lights Work as a Modular Pair to Create Luminous Space," Architectural Record, April 1983, pp. 160-167.

60. Lam, p. 78.

61. D. Watson, "Johnson Controls Salt Lake City Office Building Design: Daylighting studies," <u>Proceedings of the 1983 International Daylighting Conference, 16-18 February 1983 in Phoenix, Arizona</u>. Washington, D. C.: 1983 International Daylighting Conference, 1983, p. 96.

62. Architectural Record, "On the Wisconsin Prairie a Reposeful Building with Strong Presence," <u>Architectural Record</u>, February 1978, pp. 126-132.

63. Architecture, "Ingeniously Daylit Seaside Offices," <u>Architecture</u>, January 1984, pp. 64-67.

64. Scott Ellinwood, "Daylight in the Design Process," <u>Proceedings of the 1983 International Daylighting Conference, 16-18 February 1983 in Phoenix, Arizona</u>. Washington, D. C.: 1983 International Daylighting Conference, 1983, p. 149.

65. Solar Age, "Huzzahs for Daylighting," <u>Solar Age</u>, February, 1984, p. 17.

66. Ibid.

67. Hopkinson and Kay, p. 95.

68. Solar Age, p. 17.

69. Dan Lewis, "Good News on Skylight Performance," <u>Solar Age</u>, pp. 24-25, .

70. Evans, pp. 63-64.

71. Figure after Benjamin H. Evans, <u>Daylight in Architecture</u> (New York: McGraw-Hill, 1981), p. 64.

72. However, it has been shown, both theoretically and experimentally, that daylighting with lightwells is very unsatisfactory, unless their horizontal dimension is large compared to their depth--Walsh, p. 88.

73. Adapted from Zomeworks Corporation trade literature.

74. Figures show roof monitors in (top) Solarus Square, Grand Junction, Colorado (Milburn Sparn, architects), adapted from Jennifer A. Adams, "A Design Team's Success with Computers," <u>Solar Age</u>, March, 1983, pp. 27. Also shown (bottom) roof monitors at Dallas City Hall (I. M. Pei, architects) adapted from Evans, p. 174.

75. Lam, p. 80.

76. Plan views derived from: (left) Aid Association for

Lutherans building, Appleton, Wisconsin (Warnecke and Assoc.), as described in Architectural Record, February 1978, supra; (right) Finnish National Pensions Institute, Helsinki (A. Aalto), as described in Flieg, p. 120.

77. Walsh, p. 88.

78. Hopkinson, Architectural Physics, p. 32.

79. Oyvind Aschehoug et al., Vindu, Rom og Dagslys--Del II (Windows, Room and Daylight--Part II) (in Norvegian, Trondheim, Norway: Norges Tekniske Hogskole, 1982), text pp. 5,22; diagrams pp. 19-22.

80. Building Research Board, p. 15.

81. Ibid.

82. Evans, p. 76.

83. Aschehoug, p. 21. Figures assume 0.75 reflectance for the underside of overhang and 0.05 reflectance for ground.

84. Walsh, p. 88.

85. Building Research Board, p. 15.

86. The no-sky line is the line beyond which no sky may be seen. It is generally referenced at desk height.

87. Aschehoug, diagrams pp. 15-16.

88. Ibid. diagrams pp. 17-18.

89. Ibid.

IV.

PROMOTE DAYLIGHT PENETRATION

1. INTRODUCTION

Once the potential for accessing daylight has been maximized, it is necessary to provide means that will, in turn, promote daylight penetration into building interiors. The term "daylight penetration" is a widely used metaphor denoting the phenomenon whereby daylight is refracted and/or reflected by various means into interiors of buildings. Daylight penetration can be provided by:

i. traditional daylighting techniques

ii. innovative daylighting techniques

2. TRADITIONAL DAYLIGHTING TECHNIQUES

Traditional daylighting techniques for lighting task areas in offices may be identified by two characteristics:

i. They utilize only diffuse daylight from overcast or clear sky; direct sun is excluded from the interior. This is because the introduction of sunlight into task areas of office buildings requires methods of distribution and control that are outside the scope of traditional daylighting techniques.

ii. Components whose sole purpose is to promote daylight penetration are not used. Daylighting aperture geometry,

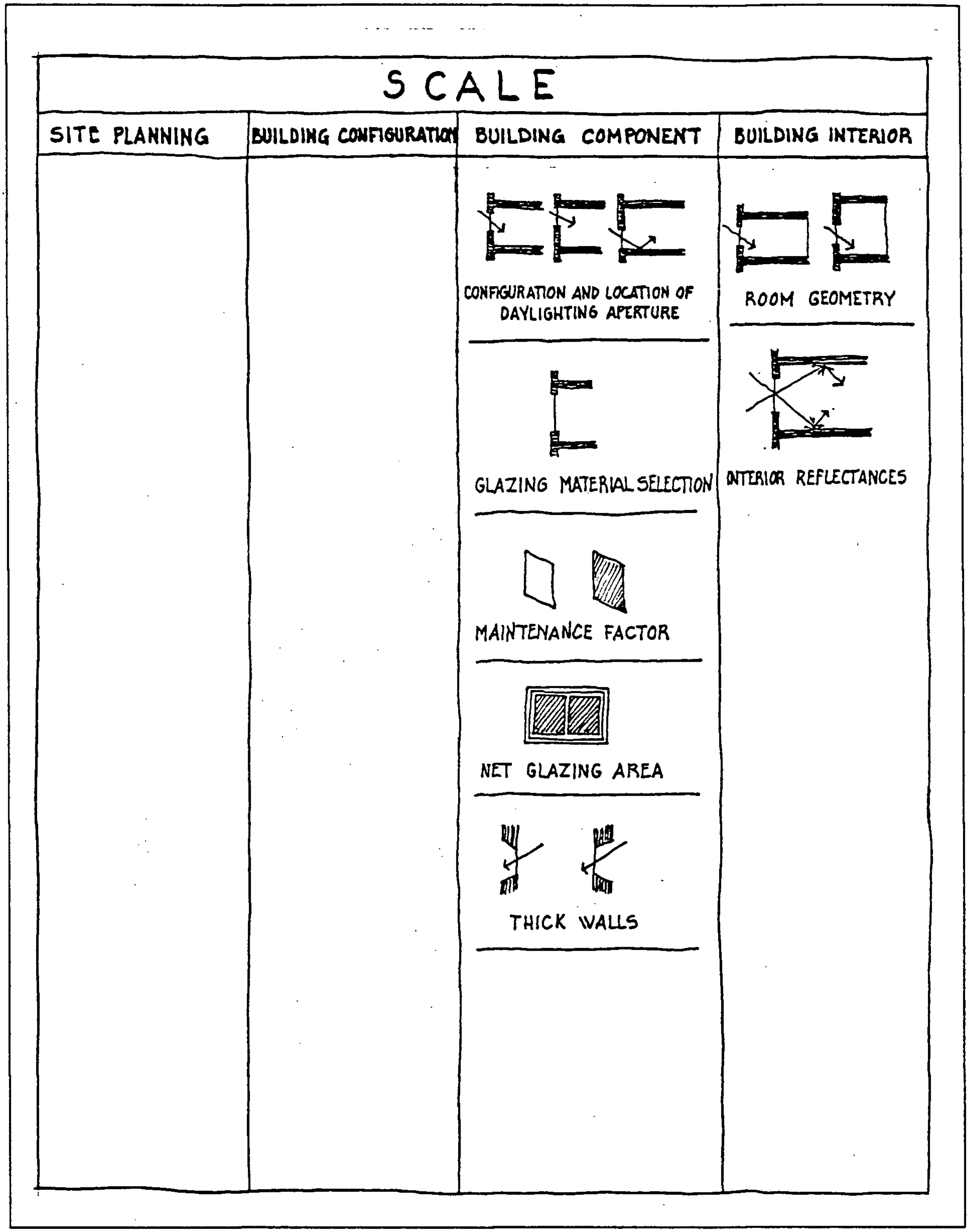


Figure 38 - Summary of traditional techniques promoting daylight penetration

room geometry, and detailing of surfaces are the only means utilized to increase daylight penetration.

A summary of traditional daylighting techniques included in this chapter is shown in figure 38 .

2.1 Configuration And Location Of Daylighting Aperture

An important means of promoting daylight penetration is by the appropriate sizing and location of the daylighting aperture. In an unobstructed situation, definite relationships can be established between the size or placement of the daylighting aperture and daylight penetration. These relationships are modified, to a greater or lesser degree, by external obstructions.

Unobstructed situation

The following are results of parametric studies done by Aschehoug[1] and Evans[2]. In this series, summarized in figure 39 , the configuration and/or location of the window on the exterior wall was varied, while the geometry of the room remained constant.

i. The size of the daylighting aperture has an obvious effect on daylight penetration. The increase in the DF with an increase in area is not, however, linear since this depends on surface reflectances, the location of the window with respect to the work plane, etc. Treating the window component below the work plane separately from the component above the work plane, will enable easier

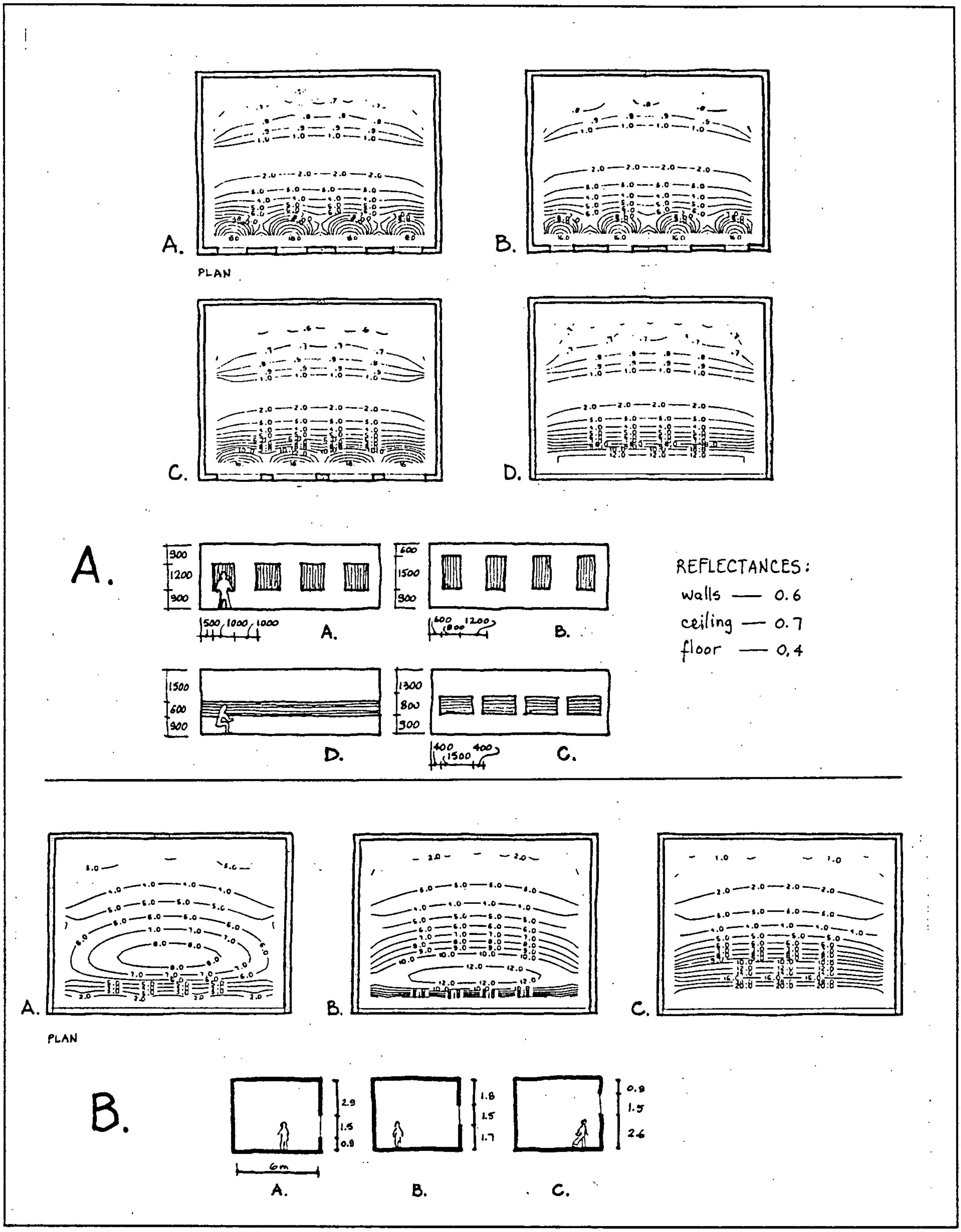


Figure 39 - The influence of size and location of the daylighting aperture on daylight penetration

optimization of window size from the point of view of daylight penetration, because it is the component above that contributes most of the light that reaches the work plane.

ii. Location of the window also affects daylight penetration. As measured by the Daylight Factor, daylight penetration increases as the height of window is increased (figure 39 b.). This is due to the increased sky component as well as to the fact that more illuminance is available on the horizontal plane. The amount of increase is dependent on the sky conditions, on reflectances of external surfaces, and on internal surface reflectances.

iii. A third parameter affecting daylight penetration is configuration of the window. Tall windows provide more light penetration than lower, wider windows of equivalent area.

iv. Windows below the work plane are useful in balancing the light within a room, especially if floor reflectances are in the higher ranges, but do not contribute substantially to the light on the work plane[3].

<u>Obstructed situation</u>

Under obstructed conditions, the effect of different daylighting aperture configurations must be re-examined. Obstructions may be classified as either primarily horizontal or vertical. Further, as indicated in the previous chapter, obstructions may occur either at the bottom of the daylighting aperture (generally due to the presence of nearby buildings or landscape elements) or at the top of the daylighting aperture (generally due to elements of the building itself).

i. Horizontal obstructions at the bottom of the daylighting aperture have a horizontal sky-line, resulting, for example, from a continuous row of buildings opposite the daylighting aperture. The maximum penetration of daylight directly from the skyvault will be determined by a line drawn through the top of the obstruction and the head of the aperture. Where this line cuts the working plane, a line can be drawn, beyond which no sky can be seen. This is called the no-sky line. For a parallel and horizontal obstruction, the no-sky line will be parallel to the daylighting aperture, as shown in figure 40 a.[4] A horizontal and parallel obstruction will affect daylight penetration more than the lateral spread of light. Figure 40 b. shows how the penetration of light is affected by the increasingly higher obstruction, but the side spread is reduced to a lesser extent[5]. Because of these phenomena, vertical daylighting apertures will provide better daylight penetration and lower peak intensities near the aperture, than a horizontal daylighting aperture with equal glazing area[6]. This is indicated in figure 40 c.

ii. Horizontal obstructions above the daylighting aperture are created by elements of the building itself (eg. balconies, overhanging floors). In these instances, horizontal apertures will deliver more light than vertical apertures

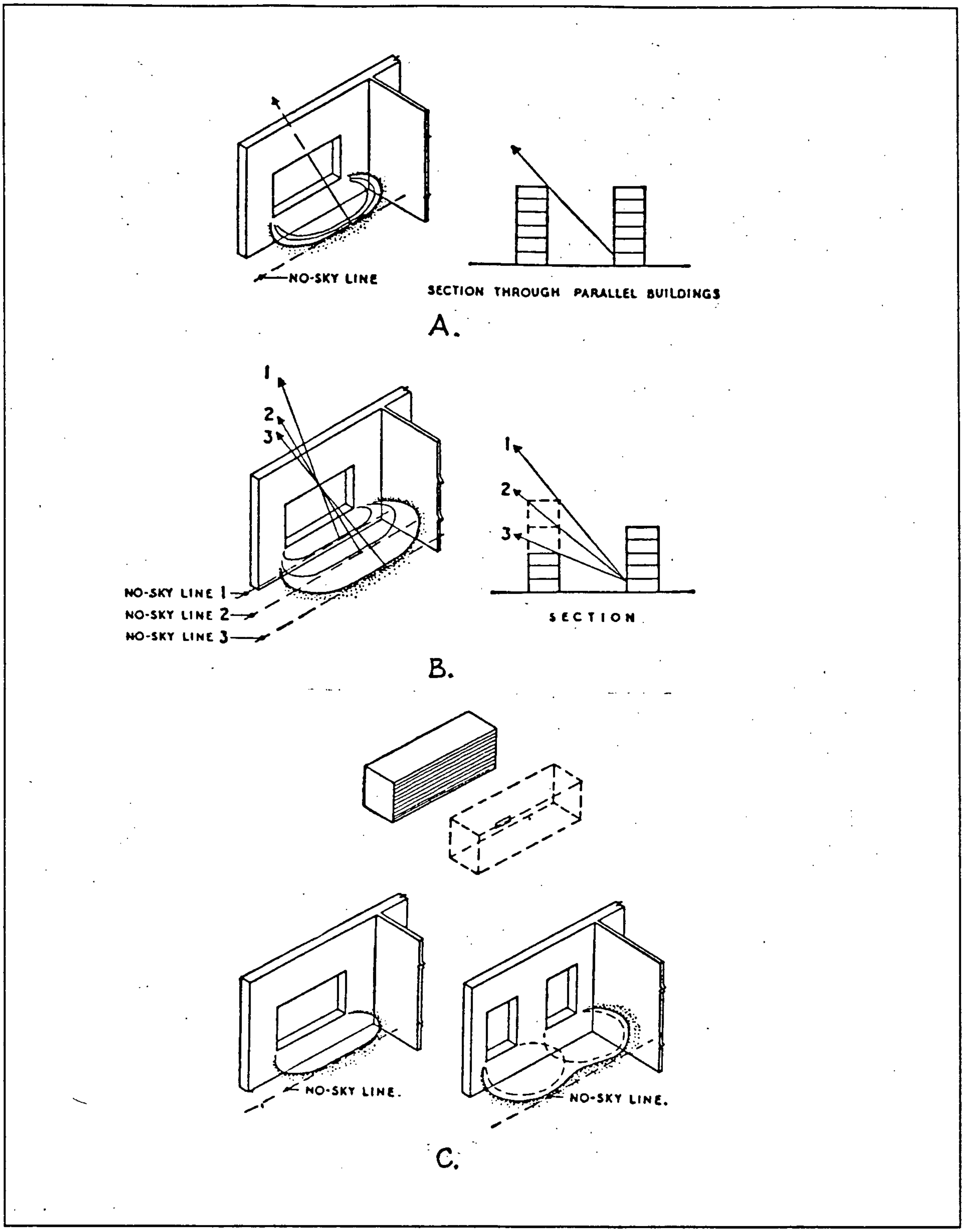


Figure 40 - Daylight penetration with horizontal obstruction

of equivalent area, because the upper portion of the sky is blocked by the obstruction. This is the reverse of the previous situation.

iii. Vertical obstructions have a vertical sky-line, such as might be produced, for example, by external return walls, large scale vertical shading devices, or a vertical gap between tall buildings opposite the daylighting aperture. The effect of a vertical obstruction is the opposite of a horizontal obstruction occuring at the bottom of the aperture, in that the spread of daylight is reduced, but the daylight penetration is not much affected. Figure 41 a.[7] shows the effect on daylight penetration of an external return wall, while in figure 41 b. the effect of a vertical gap between two buildings opposite the daylighting aperture may be seen. The broken daylight contours represent the theoretically unobstructed condition; the solid contour, the actual obstructed condition[8].

Figure 41 c. shows the effect on daylight penetration of different window shapes with daylight blocked by a vertical obstruction. In this instance, the vertical daylighting apertures create strong beams of light across a room, whereas the horizontal daylighting aperture provides more uniform illuminance[9].

These general observations should be supplemented in every project by model studies or mathematical explorations that accurately simulate the location of the obstructions. Only

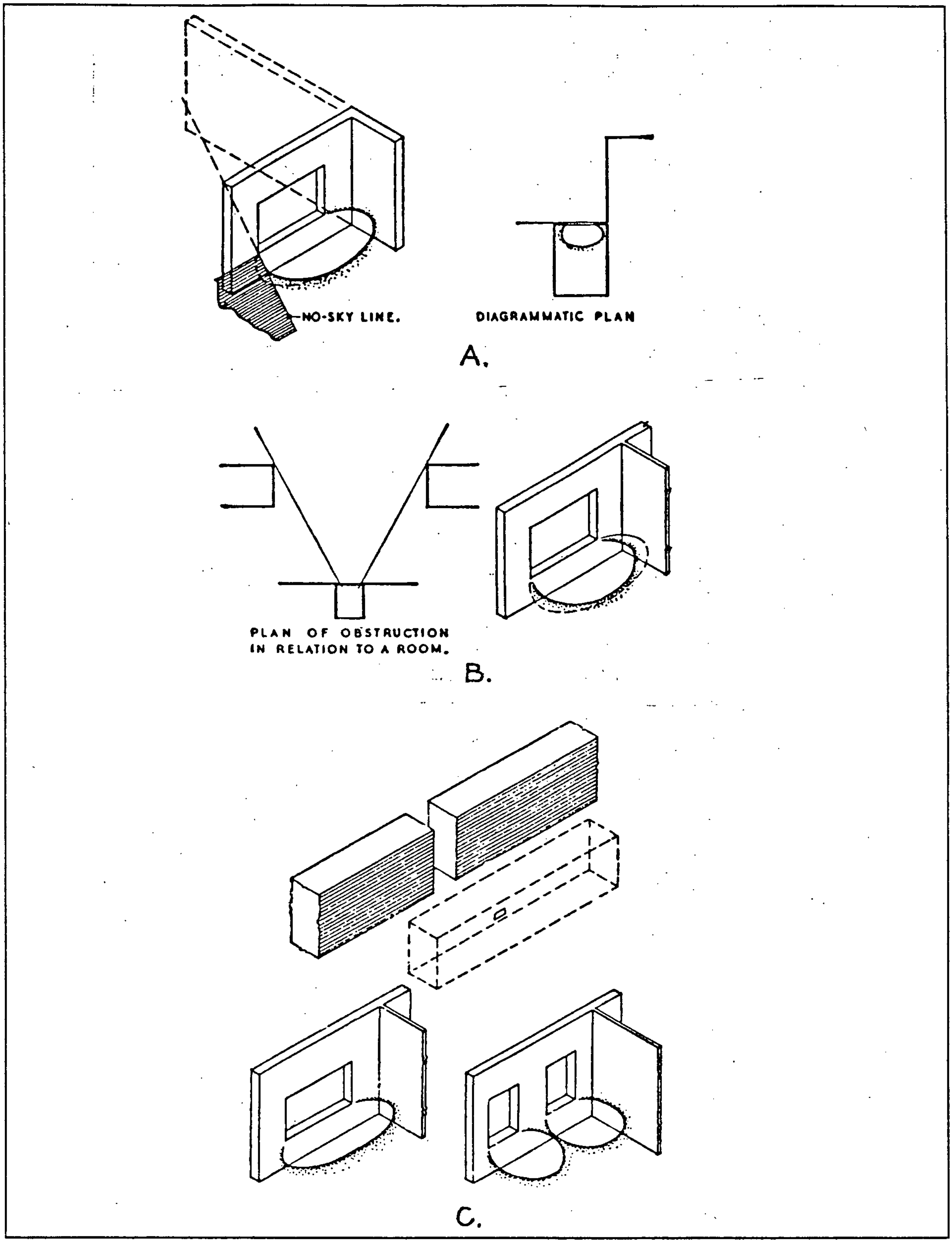


Figure 41 - Daylight penetration with vertical obstruction

thus can more specific information be obtained on the effect of obstructions on daylight penetration.

2.2 Glazing Material Selection

The thermal and luminous performance of a daylighting assembly may be described by three coefficients, which once known, enable an evaluation of the total energy performance of that assembly in a building, as well as a comparison with other daylighting assemblies.

i. Light transmittance (T) is the ratio of the amount of light transmitted through a material, or an assembly of materials, to the amount of light striking it. This characteristic of the glazing assembly in a daylighting scheme, therefore dictates the amount of light that penetrates into the interior. Table IX [10] lists light transmittance values of the more common, as well as of some new, glazing materials and assemblies.

ii. The shading coefficient (SC) for a glazing assembly is the ratio of the total solar heat gain through it to the total solar heat gain through a standard sheet of clear glass under exactly the same conditions[11]. Table IX indicates SC values for various glazing assemblies.

   It is generally understood that the SC varies approximately in inverse ratio to the light transmittance (T)[12]. However, some daylighting assemblies exhibit a relatively low SC and high T when compared with other assemblies. For example, some new products, such as the "heat mirror"

GLAZING ASSEMBLY	% VISIBLE TRANSMISSION	% TOTAL SOLAR TRANSMISSION	SHADING COEFFICIENT	WINTER 'U' VALUE METRIC (IMPERIAL)
SINGLE GLAZING				
3mm WATER-WHITE CRYSTAL	91.6	91.6	1.05	6.46 (1.13)
3mm LOW-IRON SHEET	91.1	89.1	1.03	" "
3mm CLEAR FLOAT	91.	85	1.00	" "
6mm CLEAR FLOAT	89	80	0.95	" "
6mm BLUE-GREEN FLOAT	74	48	0.70	" "
6mm BRONZE FLOAT	50	48	0.68	" "
6mm GRAY FLOAT	43	46	0.66	" "
6mm PYROLYTIC BRONZE	21	26	0.45	" "
6mm CHROME 8% CLEAR	8	10	0.26	5.14 (0.90)
6mm CHROME 8% BRONZE	8	9	0.34	5.54 (0.97)
DOUBLE GLAZING - 13mm AIR SPACE				
3mm CLEAR + 3mm CLEAR	82	71	0.88	2.79 (0.49)
6mm " + 6mm "	78	60	0.80	" "
6mm BRONZE + 6mm CLEAR	44	36	0.54	" "
6mm GRAY + " "	37	34	0.53	" "
6mm PYRO. BRONZE + " "	19	20	0.34	" "
6mm CLEAR 8% CHROME + 6mm CLEAR	7	8	0.18	2.33 (0.41)
6mm " 8% GOLD + " "	8	3	0.07	1.77 (0.31)
6mm BLUE GREEN + 6mm CLEAR	67	40	0.60	2.70 (0.48)
6mm CLEAR + LOW E. CLEAR**	74	52	0.71	1.80 (0.32)
6mm BRONZE + " "	43	32	0.49	" "
6mm GRAY + " "	38	31	0.46	" "
6mm GREEN + " "	64	32	0.47	" "
TRIPLE GLAZING - 13mm AIR SPACES				
3mm CLEAR + 3mm CLEAR + 3mm CLEAR	74	60	0.78	2.10 (0.36)
6mm " + 3mm " + 6mm "	73	53	0.73	1.90 (0.33)
6mm " + H.M. 55 * + " "	48	25	0.39	1.26 (0.22)
" " + H.M. 77 + " "	66	40	0.58	1.31 (0.23)
" " + H.M. 88 + " "	69	45	0.65	" "
6mm BLUE-GREEN + H.M. 55 + " "	40	16	0.28	1.26 (0.22)
" " + H.M. 77 + " "	56	26	0.41	1.31 (0.23)
" " + H.M 88 + " "	58	29	0.46	" "
6mm BRONZE + H.M. 55 + " "	27	14	0.27	1.26 (0.22)
" " + H.M. 77 + " "	37	23	0.38	1.31 (0.23)
" " + H.M. 88 + " "	39	26	0.42	" "
6mm GRAY + H.M. 55 + " "	40	16	0.28	1.26 (0.22)
" " + H.M. 77 + " "	56	26	0.41	1.31 (0.23)
" " + H.M. 88 + " "	58	29	0.46	" "

** LOW E. = LOW EMISSIVITY COATING ON GLASS * H.M. = 'HEAT MIRROR' FILM

Table IX - Table of performance data for glazing assemblies materials, either deposited on film[13] or on glass[14], have selective transmittance characteristics and when used in glazing assemblies, exhibit a very low SC, while maintaining a relatively high transmittance. From a life-cycle point of view, these glazing assemblies can be very cost effective[15].

In standard double-glazed assemblies as well, different light transmittances may be obtained for a given SC. For example, a double-glazed blue-green glass assembly will have about 46% higher light transmittance for the same SC as a similar bronze glass assembly[16].

iii. The 'U'-value (U) is the rate at which heat is transferred through a unit area of window when there is a difference of one degree between the air temperature outside and the air temperature inside a building[17].

As a very general trend, it may be observed that the 'U'-value of glazing assemblies varies directly with their transmittance; i.e. the lower the heat loss of an assembly, the lower its light transmittance. In fact, the relationship between these two coefficients will vary widely with the glazing materials used, their assembly, their orientation, and to some extent with the time of year. The 'U'-value itself is a function of the number and width of air spaces in a glazing assembly, as well as of the light transmittance/reflectance of the glazing materials used.

Traditional methods of lowering 'U'-values involve the use of multiple glazing and of exterior or interior accessories parallel to the glazing, such as roller blinds, fabric shades, venetian blinds, etc. The advantage of such operable accessories in general, and especially of the exterior mounted types, is their ability to optimize transmission, and the control of solar heat gain, glare, and heat loss at different times of the day in response to changing thermal and luminous conditions outdoors.

Ideally, considering light penetration alone, the glazing assembly should have the highest transmittance. However, in order to improve the thermal performance requirements, the transmittance must be compromised to some extent. The amount will depend on the particular daylighting scheme, as well as on the building energy load, the location and orientation of the building, its thermal mass, the cost of money, the utility rate structure, etc. In a daylit building therefore, the aim is to optimize light transmittance, solar heat gain, conductive heat loss and maintenance, from the point of view of life-cycle cost and occupant comfort. Interior and exterior appearance and ease of operation are other, less tangible, factors to be considered.

The many types of glasses and control devices on the market[18],[19], are the components of conventional daylighting/sun control schemes. There are also some new products, which will soon be, or have just begun to be, marketed, which may have a profound influence on daylighting design, since they do not exhibit the traditional trade-offs between transmittance and heat transfer (T and U) or between transmittance and solar heat gain resistance (T and SC). Examples are:

i. A material called "aerogel" exhibits higher transmission characteristics than clear glass double glazing, when used in 6" thickness--at which its 'U'-value is that of an opaque insulated wall of same width[20].

ii. An air-entrained acrylic plastic glazing material attenuates infrared wavelengths while maintaining visible transmittance, thus reducing the SC, and resulting in reduced solar heat gain[21].

iii. Development is complete on "optical shutter" materials that change phase, with a change in outdoor temperature, and in the process vary their transmission to solar radiation[22]. Matthews[23] has stated that, in his opinion, these phase change materials will "revolutionize daylighting".

According to Selkowitz[24], there are as yet no simple methods of choosing glazing options that will be most effective for large office buildings, because the interrelationship of variables is complex. However, guidelines for glazing selection may be given. The general principle is that for each facade orientation of a building, a different glass type is required to obtain a minimum heating, cooling and lighting load[25].

i. For north-facing daylighting apertures, select glazing with high light transmittance. Shading coefficient need not be as low as for other orientations. Window assemblies having matching colours when viewed from outside, but

DOMINANT ENERGY NEED IN ZONE SHOWN	PERFORMANCE REQUIREMENTS						EXAMPLES OF GLAZING ASSEMBLIES				
	ORIENTATION	SHADING COEFFIC.(1)	SUN CONTROL REQ'D(2)	GLARE CONTROL REQ'D	LOW 'U' VALUE	VISIBLE ENERGY AS % OF TOTAL ENER GAIN	CHOICES OF ASSEMBLIES	% VISIBLE TRANSMIS.	% TOTAL SOLAR TRAN.	S.C.	RANK(3)
MAXIMUM COOLING REQUIRED (SHADING IMPORTANT)	E, W, S	LOW >0.1 - 0.5	YES	POSSIBLY	(4) IMPORTANT	HIGH > 70%	1. BLUE-GREEN + H.M.55 + CLEAR	40	16	0.28	GOOD
							2. " + LOW E. CLEAR	64	32	0.47	GOOD
							3. CLEAR + H.M.55 + CLEAR	49	25	0.39	GOOD
							4. BRONZE + CLEAR	45	36	0.54	FAIR
							5. PYROLYTIC BRONZE + CLEAR	21	26	0.45	POOR
							6. DOUBLE CLEAR	78	60	0.80	POOR
	N (5)	HIGH >0.7	NO	POSSIBLY	NOT IMPORT. >5.4 (1.0) IMP.	MAY BE LOW < 60%	1. SINGLE CLEAR	89	80	0.95	GOOD
							2. DOUBLE CLEAR	78	60	0.80	FAIR
							3. SINGLE BRONZE	50	48	0.68	FAIR
BALANCED SHADING AND DAYLIGHTING	E, W, S	MEDIUM 0.5 - 0.7	YES	LIKELY	IMPORTANT	MEDIUM 60-70%	1. BLUE-GREEN + CLEAR	67	40	0.60	GOOD
							2. CLEAR + H.M.77 + CLEAR	66	40	0.58	GOOD
							3. BRONZE + CLEAR	44	36	0.54	FAIR
							4. PYROLYTIC BRONZE + CLEAR	21	26	0.45	POOR
	N	HIGH	NO	POSSIBLY	IMPORTANT	MAY BE LOW < 60%	1. DOUBLE CLEAR	78	60	0.80	GOOD
							2. CLEAR + H.M.77 + CLEAR	66	40	0.58	GOOD
							3. BLUE-GREEN + CLEAR	67	40	0.60	FAIR
							4. BRONZE + CLEAR	44	36	0.54	POOR
MAXIMUM HEATING REQUIRED (SUN PENETRATION ACCEPTABLE WITH CONTROL)	E, W, S	HIGH	YES	VERY LIKELY (IF WINDOWS LARGE)	VERY IMPORTANT	HIGH > 70%	1. CLEAR + LOW E. CLEAR	74	52	0.71	GOOD
							2. CLEAR + H.M.88 + CLEAR	69	45	0.65	GOOD
							3. TRIPLE CLEAR	73	53	0.73	FAIR
							4. BRONZE + CLEAR	44	36	0.60	POOR
	N	HIGH	NO	VERY LIKELY	VERY IMPORTANT	MAY BE LOW < 60%	1. CLEAR + H.M.88 + CLEAR	69	45	0.65	GOOD
							2. TRIPLE CLEAR	73	53	0.73	GOOD
							3. DOUBLE CLEAR	78	60	0.80	FAIR
							4. BRONZE + CLEAR	44	36	0.54	POOR

NOTES:
1. MAY BE ACHIEVED BY GLAZING ASSEMBLY ALONE OR IN COMBINATION WITH ACCESSORIES.
2. OPTIMUM CONFIGURATION OF SUN CONTROL MECHANISM VARIES WITH ORIENTATION, LATITUDE & SEASON.
3. RANK INDICATES COMBINED DAYLIGHTING, HEAT LOSS & SOLAR HEAT GAIN PERFORMANCE WITHOUT ADDITIONAL GLARE/SOLAR CONTROLS.
4. 'U' VALUE NOT IMPORTANT IF COOLING LOAD INTERNALLY GENERATED. 5. THIS SITUATION WILL ONLY OCCUR IN HOT CLIMATES.

Table X - Choice of glazing for daylit office buildings different transmittance, have been used on some large buildings[26].

ii. On the east, south and west sides, the glazing assembly must achieve low SC while maintaining high transmittance. That is, the percentage of visible solar to total solar energy must be higher than on the north side. This means using assemblies of clear or blue-green glass with shading devices, or heat mirror assemblies without shading devices. It must be re-emphasized that very low transmittance glazing assemblies are not an appropriate solution to daylighting: low shading coefficients are achieved only at the sacrifice of light transmittance.

Table X summarizes the criteria for glazing choice in daylit buildings, at the various orientations. The table has some limitations[27], and the solutions proposed must be understood as first approximations only.

2.3 Maintenance Factor

The accumulation of dirt on glazing produces scattering of the light impinging on it, with a loss in transmittance for heavily soiled glazing. In view windows of prestige office buildings, the soiling becomes objectionable aesthetically long before much drop in light transmittance can be detected[28,29]. On the other hand, daylighting apertures not normally in view, such as clerestoreys, skylights and roof monitors, can, with poor maintenance schedules, accumulate considerable dirt, leading to a substantial drop in the amount of light transmitted. Table XI [30] indicates suitable maintenance factors for daylighting apertures, for various atmospheric conditions and degrees of exposure.

LOCATION OF BUILDING	INCLINATION OF GLAZING	MAINT. FACTOR
NON-INDUSTRIAL OR CLEAN INDUSTRIAL AREA	VERTICAL	0.9
	SLOPING	0.8
	HORIZONTAL	0.7
DIRTY INDUSTRIAL AREA	VERTICAL	0.8
	SLOPING	0.7
	HORIZONTAL	0.6

Table XI - Maintenance factors for windows and rooflights in offices

In sizing daylighting apertures, a maintenance (or light depreciation) factor is used to compensate for this loss in transmittance. This factor (a fraction less than unity), is multiplied by the transmittance of clean glazing, to arrive at the approximate transmittance of soiled glazing in actual installations.

The maintenance factor may be used in one of two ways:

i. The area of glazing may be increased proportionally to the loss in transmittance indicated by the maintenance factor.

ii. The area of glazing is not increased, but allowance is made in calculating energy savings for a correspondingly larger proportion of light to be supplied by the electrical lighting.

In this context, Hopkinson[31] sounds a note of caution concerning the use of the maintenance factor. He suggests that even in situations when the expected dirt accumulation may reduce light penetration levels to less than 80% of the initial values, the maintenance factor allowed for should be no less than 0.9--and the glazed area increased only to that extent--with the deficit made up by electric lighting. Otherwise very large windows may result, with attendant increase in glare, heat loss and cost.

2.4 Net Glazing Area

Daylight penetration is obviously a function of the net transparent area, and allowance has to be made for the area taken up by the frame. The frame area for metal windows is around 15-25% of the gross window area[32,33]; while the frame area for wood windows can be 30-50% or more, of the gross window area[34,35].

Another, related point is that nominal sizes of windows may be considerably larger than the actual frame size. Figure 42 shows the various terms used in trade literature. For daylighting purposes, the 'glazed area' is the important figure; however, for windows whose frame and glazing bars have substantial depth, these will act as louvers to obscure part of the daylight at off-centre locations and appropriate correction

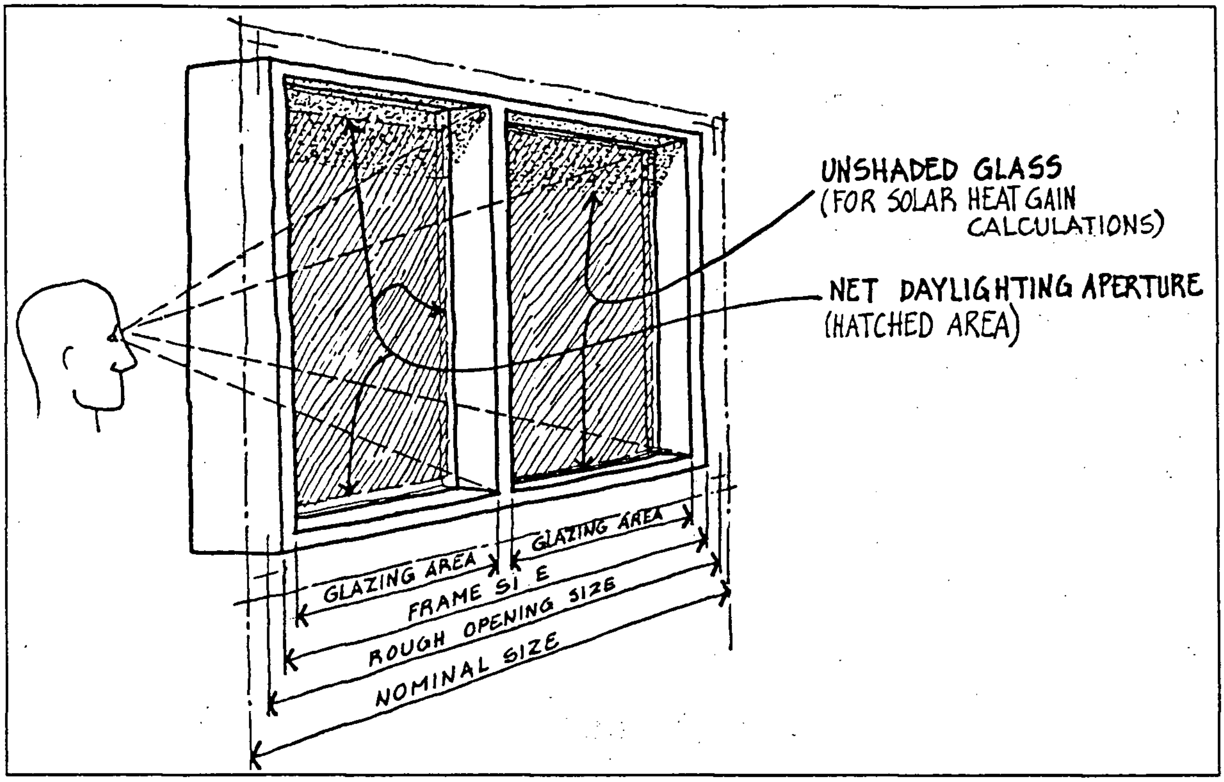


Figure 42 - Terms used in window trade literature

factors will have to be used with the 'glazed area' when deciding on the actual area of the exterior visible from a particular location.

2.5 Depth And Detailing Of Wall Around Daylighting Aperture

The wall thickness and detailing around the daylighting aperture can have a considerable effect on the daylight penetration into the interior. Deep walls, due to massive construction or thick insulation, or both, will reduce daylight penetration through an opening, if the edge detailing is kept the same as it would be for thin walls. In model tests done by Aschehoug[36], increasing wall thickness from 20 to 1000mm reduced daylight penetration at the back of rooms tested by 50%[37].

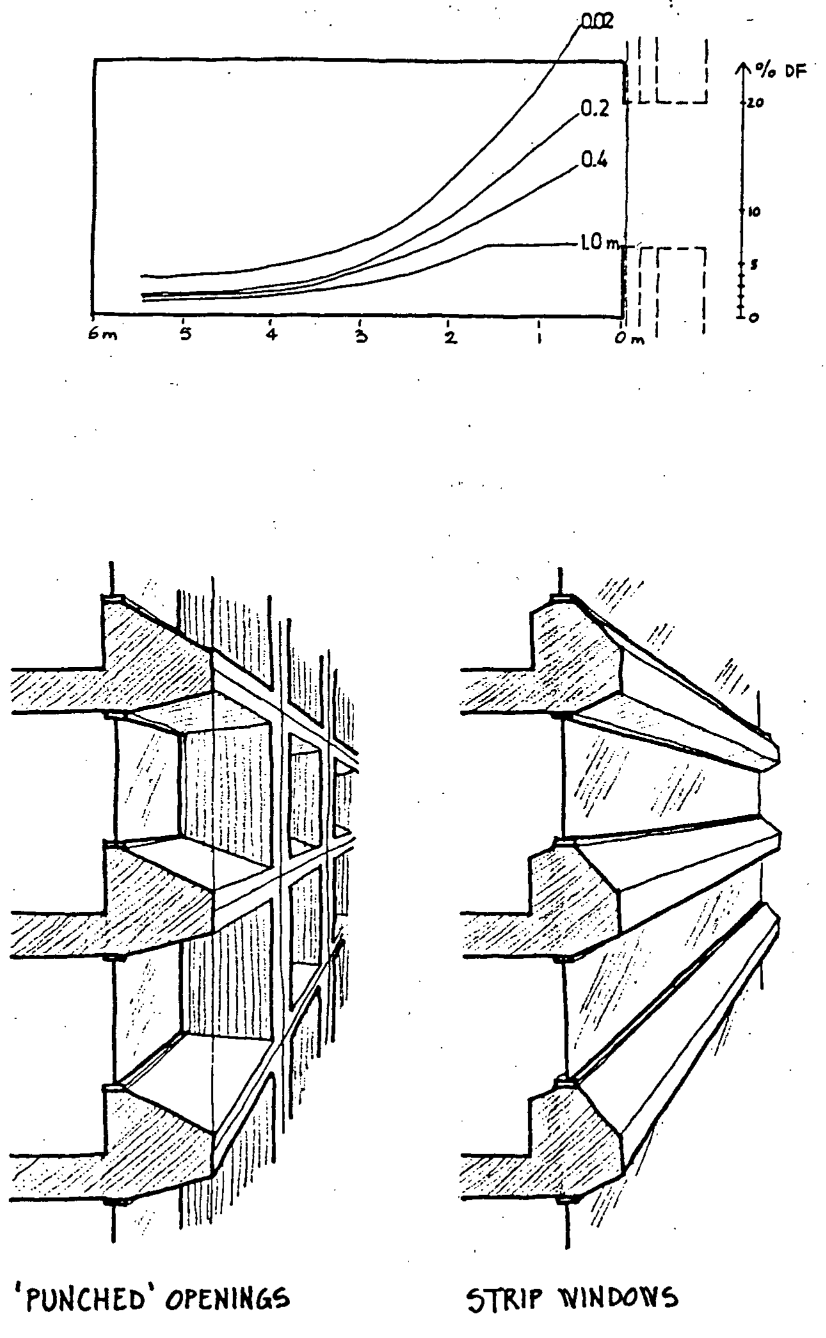


Figure 43 - Effect of wall thickness on daylight penetration and examples of thick walls

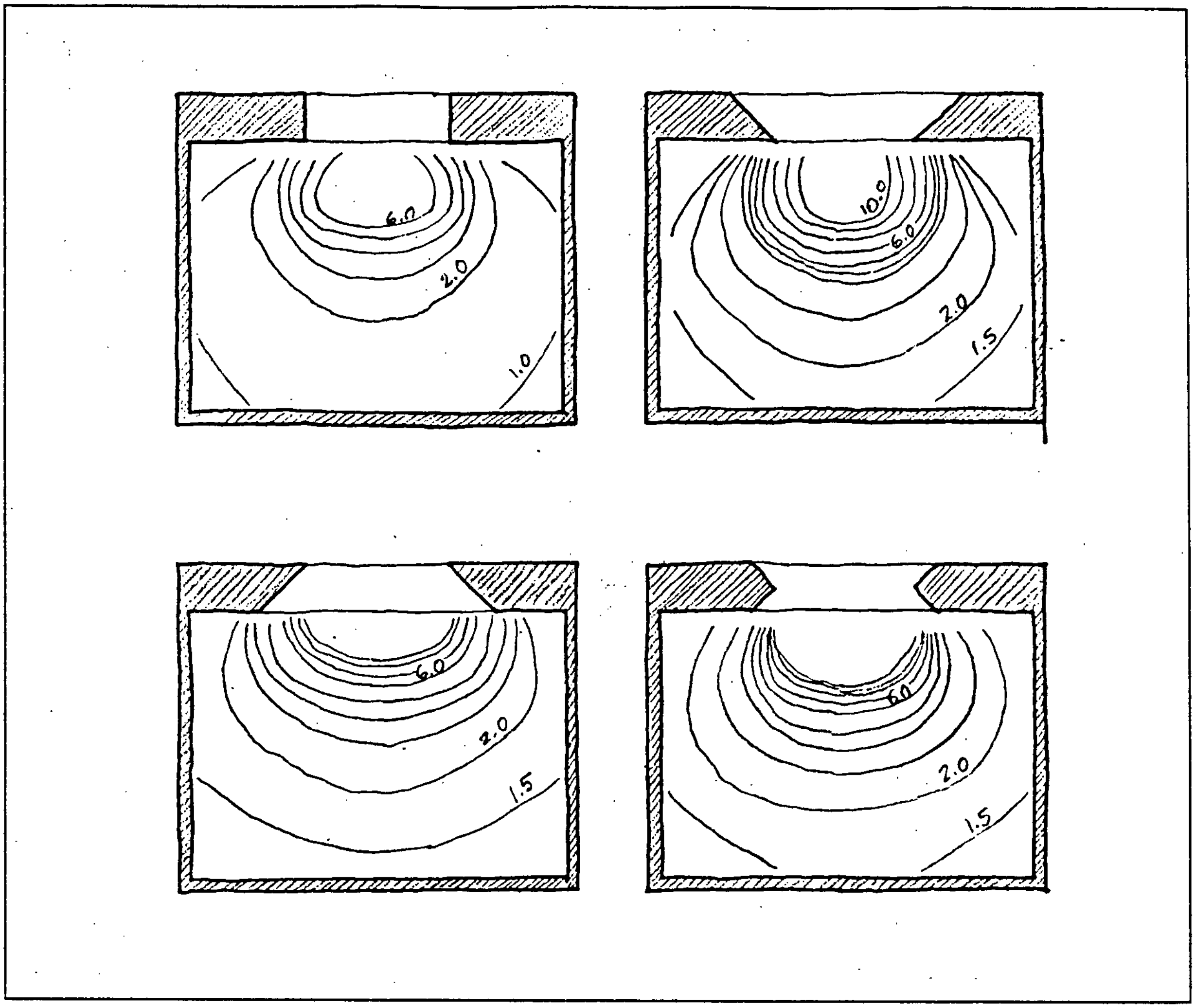


Figure 44 - Plan views of splayed jamb configurations

Figure 43 a. shows graphically the effect of increasing the thickness of the exterior wall. Figure 43 b. shows examples of thick exterior walls resulting from the use of precast or cast-in-place concrete.

If openings in a thick wall have splayed jambs with surfaces of high reflectance, the daylight penetration is essentially the same as that for the same size opening in a thin wall[38], with the additional advantage of contrast grading provided by the splayed jamb of the thick wall[39]. Figure 44 shows typical jamb configurations. In all cases, daylight penetration is greater for splayed jambs than for right angled ones.; inward sloping jambs (b.) give the best spread of light sideways (i. e. the widest effective window area) in a typical room, but daylight penetration for configuration (c.) and (d.) may be greater by about 15%[40] if jamb reflectances are high (approximately 60%).

2.6 Room Geometry

The following are results of parametric studies done by Aschehoug[41] and Evans[42]. In this series, summarized in figure 45 , the configuration and location of the daylighting aperture on the exterior wall were kept constant, while the geometry of the room was changed.

i. An increase in room width (and an accompanying increase in window width), produces no significant change in light penetration[43].

ii. With an increase in room depth, the DF is obviously lower at the back of the room. However, the deeper rooms have considerably lower daylight levels throughout their depth[44],[45]. This is summarized graphically in figure 45 a. The difference in daylight levels is due mostly to the reflected light from the back wall, which in the shallow room contributes a greater portion to the interior daylight than the back wall in the deeper room.

iii. An increase in ceiling height with window height remaining constant, reduced the light available at the back of the

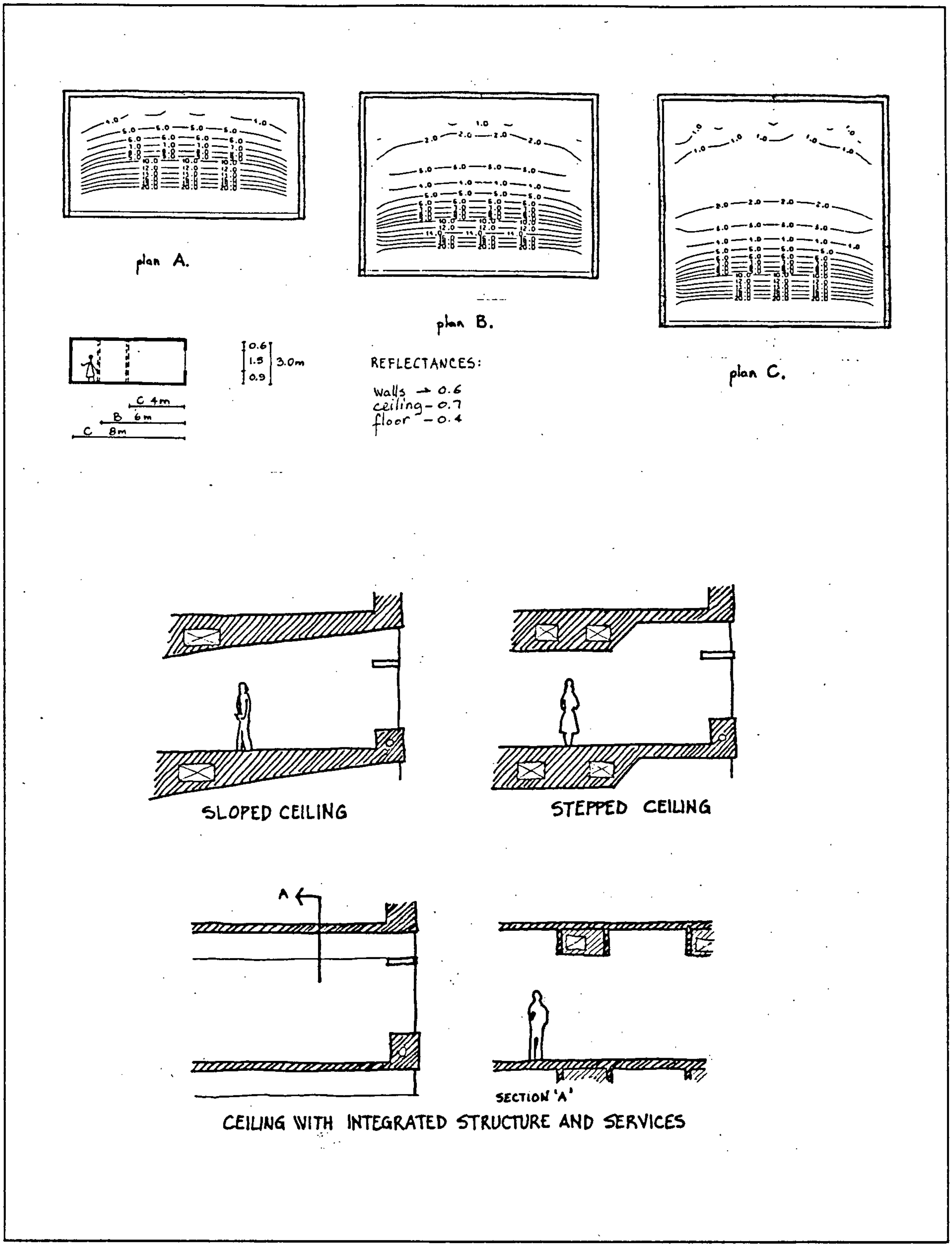


Figure 45 - Effect of room geometry on daylight penetration

rooms tested by about 15%[46]. The exact amount of reduction will depend on room geometry as well as on the reflectances of indoor and outdoor surfaces. The reduction in daylight levels is due to smaller amount of reflected light at the work plane in the room with the higher ceiling. If, however, advantage is taken of the greater ceiling height and the daylighting aperture is moved higher up, considerable improvement in daylight penetration may be obtained[47], as seen in a previous section. Figure 45 b. indicates how added ceiling height may be obtained, without adding to the floor to floor height.

iv. A variation in ceiling slope has, according to Evans[48], no effect on interior daylight levels.

2.6.1 Interior Reflectances

One of the more important parameters determining daylight penetration--and especially daylight quality--in a room is the reflectances of its various surfaces. This influence is most pronounced for unilaterally side-lit spaces, since the light reflectance from interior surfaces is the major contributor to illuminance levels at the back of the room, as shown in figure 46 [49].

A direct result of increased daylight penetration with interior surfaces of high reflectance is the considerable saving in energy. It has been estimated by Tamblyn[50], that a change from dark interior colours to light ones can result in a

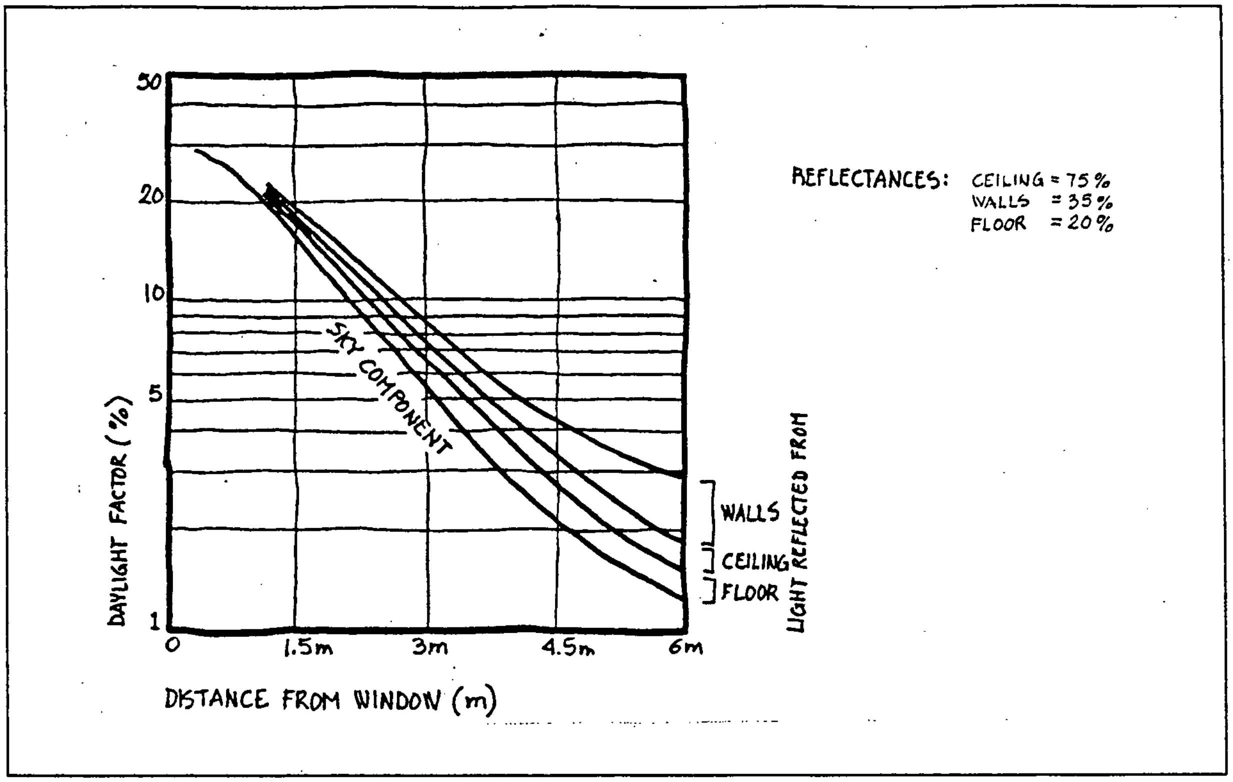


Figure 46 - The contribution of the IRC to the illuminance within a room

reduction of power of 10 watt per m², or between 20 and 40% of typical lighting load. Millet has reported even greater savings in energy when dark walls were replaced by light ones[51]. Figure 47 [52] shows the relative contribution of each of the room surfaces to the daylight levels in tests conducted by Evans. From these tests, and others done by Aschehoug[53], the following may be observed:

i. In the simple daylighting schemes tested, the ceiling was found to contribute more than all other room surfaces to the daylight illuminance levels in the room. Ceiling reflectance is found to be even more important in actual interiors (that include furnishings) than these tests indicate, since it is generally the least cluttered surface

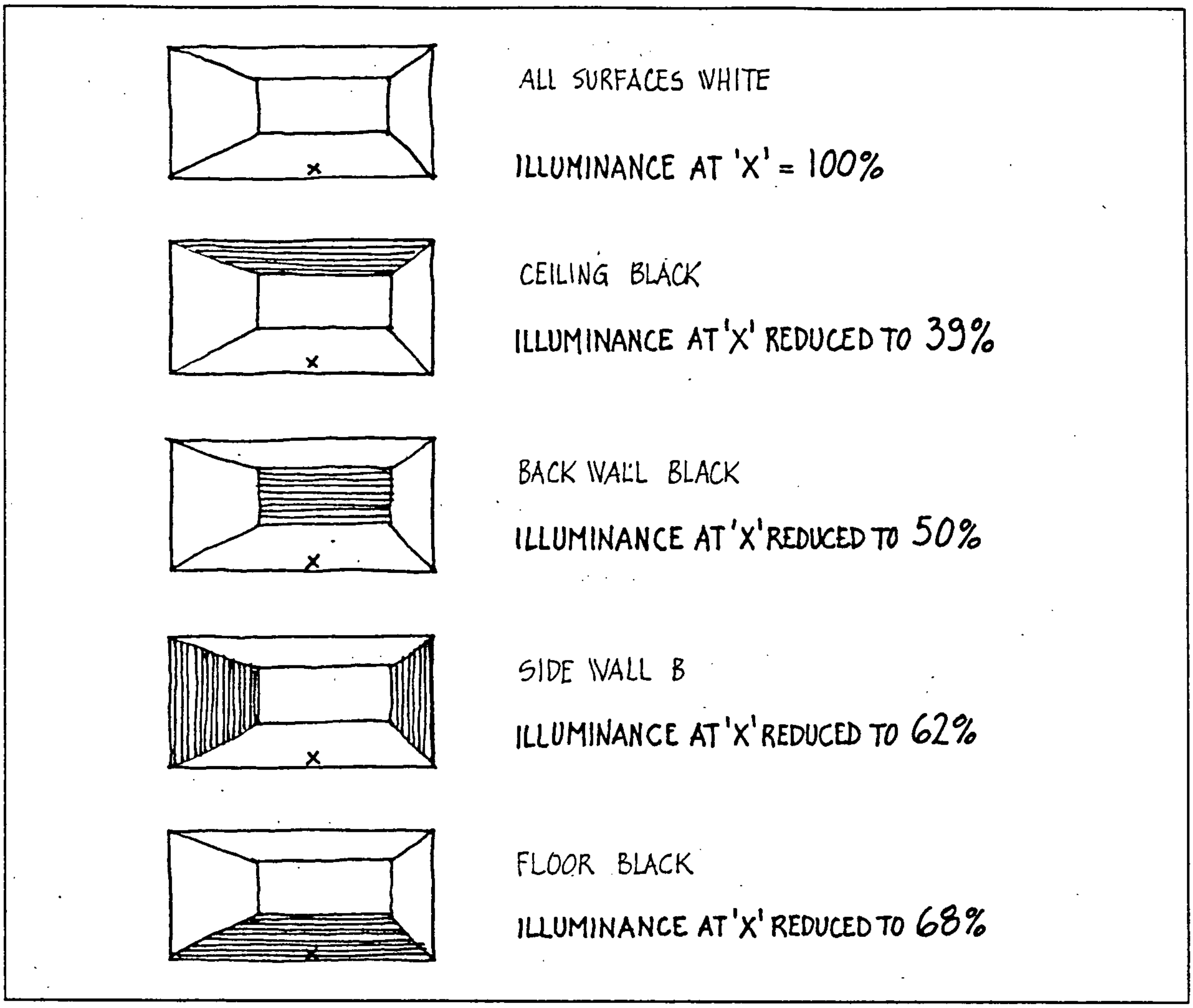


Figure 47 - The influence of room surface reflectances on daylight levels

in an office space, is usually of high reflectance, and therefore, can be relied upon to reflect daylight from the other surfaces onto the workplane.

ii. High reflectance for the floor is not as important as for the ceiling in achieving daylight penetration. The reason for this is that the floor, being below the reference (work) plane, contributes to the DF only by multiple reflections off walls d and ceiling. In actual installations, the floor is also cluttered with furnishings, and because of maintenance requirements, it generally has lower reflectance than other room surfaces. Its potential as a contributor to the DF is thus further decreased.

iii. High reflectance for side walls is considerably more important than high reflectance for back wall as far as the DF is concerned[54]. High reflectance for the back wall is important in establishing higher surface luminance at the back, and hence better balance of brightness in the room.

iv. High reflectance for the window wall is helpful in glare reduction, but assists little in daylight penetration, since it does not receive direct light from beyond the daylighting aperture.

v. A comparative analysis of parametric studies shows that the relative importance of the various interior surfaces in promoting daylight penetration is a function of the proportions and dimensions of the space. Therefore, in order to assess accurately daylight penetration for specific room configurations, computer simulations or model studies will be required.

vi. There is a qualitative difference between some schemes--a difference in the modelling quality of the lighting--that is not apparent from the DF plots. For example, schemes with very similar values of DF (horizontal illuminance), will, depending on the relative reflectances of adjacent surfaces, provide more or less light on the sides or the underside of three dimensional objects. These light quality differences may be modelled analytically[55,56], but must be studied with models to be fully appreciated.

3. INNOVATIVE DAYLIGHTING TECHNIQUES

Innovative daylighting techniques--sometimes termed beamed or deep daylighting techniques--involve the projection of daylight, and in some instances, of sunlight as well, deep into interior spaces. The idea of using refracting materials and reflecting surfaces to increase daylight penetration through view windows is not new. The use of high reflectance surfaces outside as well as inside, near the window, and the like, are methods that have long been used to bounce daylight deeper into interior spaces. However, innovative daylighting techniques incorporate components that are shaped and located--and indeed, whose main purpose is--to increase daylight penetration.

When properly designed, beamed daylighting techniques can perform substantially better for a given area of daylighting aperture than traditional systems. This improved performance has two aspects:

i. Innovative daylighting techniques provide increased daylight penetration over traditional daylighting techniques. With the latter, it is possible to daylight a room adequately, and with brightness ratios that are within comfortable levels, to a depth equivalent to 2 1/2 times the height of the daylighting aperture[57,58,59]. Assuming that the head of the daylighting aperture is at the ceiling, and the ceiling height is in the range of 2.5-3.0m found in contemporary offices, the maximum daylight penetration that can be achieved by traditional means is 6.0-7.5m.

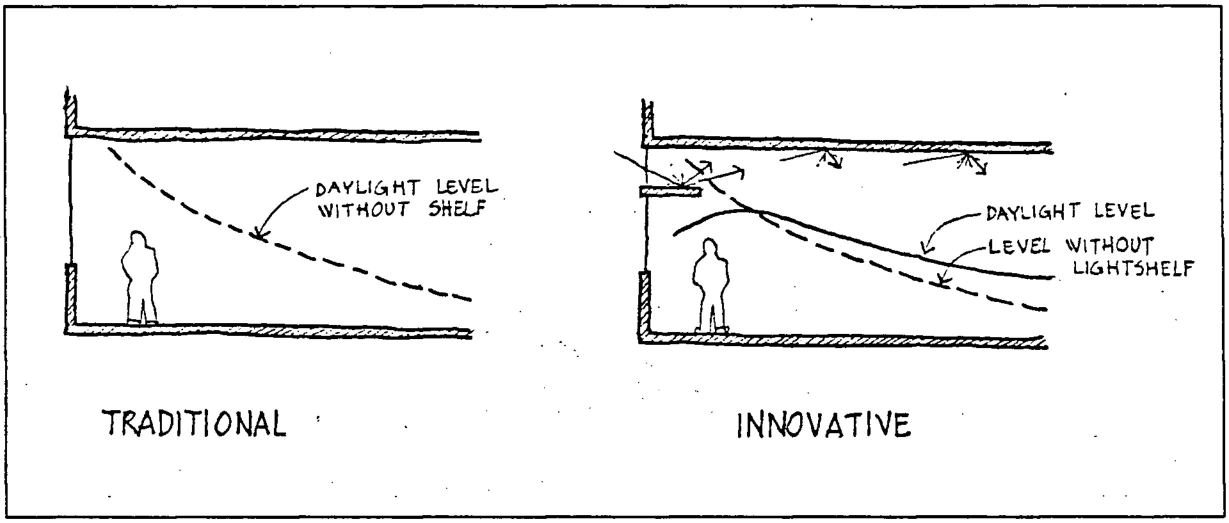


Figure 48 - Comparison of daylight penetration achieved by traditional and innovative techniques

Figure 48 shows comparative daylight penetration achieved by a typical traditional and an innovative technique. A survey by Eacret[60] has indicated that deep daylighting systems can provide at a room depth of 6m, for example, between 50% and 300% more daylight than a standard daylighting aperture of the same area and at the same location.

ii. Innovative daylighting techniques achieve better balance of brightness in interiors than traditional daylighting techniques. Figure 48 also shows that the deep daylighting scheme provides more even illuminance levels throughout the depth of the space (meeting both ambient and task lighting needs), whereas in the traditional system, there is a high maximum light level near the aperture, and a sharp drop towards the back of the room. If the room surfaces have high reflectance, then the DF curve is a good indicator of the general level of brightness across the room. By projecting a large part of the available light towards the back, surface luminances are increased at the back, and result in a balance of brightness throughout the room, less perceived glare (since the eye adaptation level is higher), and softer modelling characteristics (since the light from the window side is no longer as dominant). Hence, both quantitative and qualitative aspects of the daylighting scheme show improvement.

A summary of innovative daylighting techniques included in this chapter is shown in figure 49 .

3.1 Deep Daylighting Through View Windows

Where view windows are used for beamed daylighting, three types of solutions may be identified:

i. In the first type, the daylighting mechanism is incorporated in the window head and sill, or in the window sill alone. Figure 50 shows these responses. The first design response utilizes a reflecting sill and head, as exemplified by the IBM regional office building in Southfield, Michigan[61](a.), and by a design called "vision window" by Ashley et al.[62](b.) Another design response

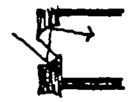
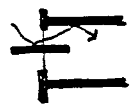
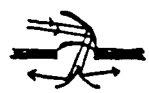
SCALE			
SITE PLANNING	BUILDING CONFIGURATION	BUILDING COMPONENT	BUILDING INTERIOR
		 DEEP DAYLIGHTING THROUGH VIEW WINDOW  DEEP DAYLIGHTING THROUGH APERTURES ABOVE EYE LEVEL  DEEP DAYLIGHTING THROUGH ROOF APERTURES	

Figure 49 - Summary of innovative techniques promoting daylight penetration

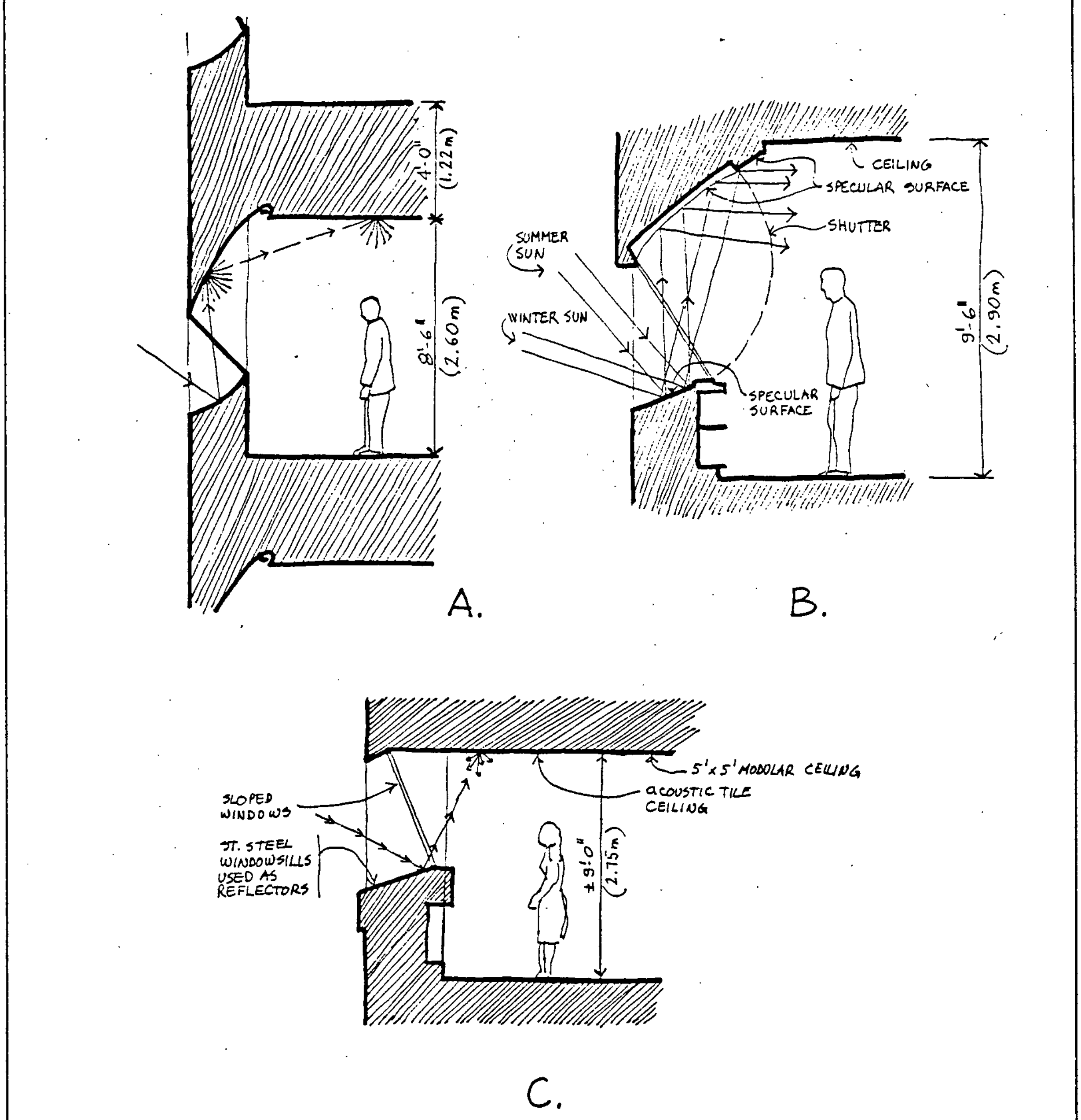


Figure 50 - Daylight beaming mechanisms integrated into the building envelope

utilizes an enlarged, reflective sill to bounce daylight onto the ceiling, as exemplified by the EG&G Willow Creek office building in Idaho Falls[63] (figure 50 c.) In this building, lighting from the windows provides all ambient lighting for the perimeter 9m. A follow-up study has also indicated that on a clear day, daylight reduces the energy used for mechanical services and electrical lighting by 20%, compared to a building with same-sized windows and no advantage taken of daylighting potential[64]. The double reflection at the window achieved in the first design types enables daylight to be reflected deeper into the interior than with the single reflection achieved in the previous scheme. However, the single reflective sill (with no reflective head) is a simpler concept, and is therefore more economical in first cost. In all these designs, glare control is achieved by sloping the glazing downward.

ii. In the second type of solution, the daylighting mechanism is an exterior accessory. This may consist of pivoting and retractable louvres, pivoting but non-retractable louvres, or small stationary lightshelves, as shown in figure 51 [65]. Operable louvres, when automatic, have the advantage of providing solar control as well as enhanced daylighting. The fixed louvres, on the other hand, cannot respond to changing sun angles and provide solar control at some sacrifice to daylight access.

iii. In the third type of solution, the daylighting mechanism is located between the glazing or on the interior. These

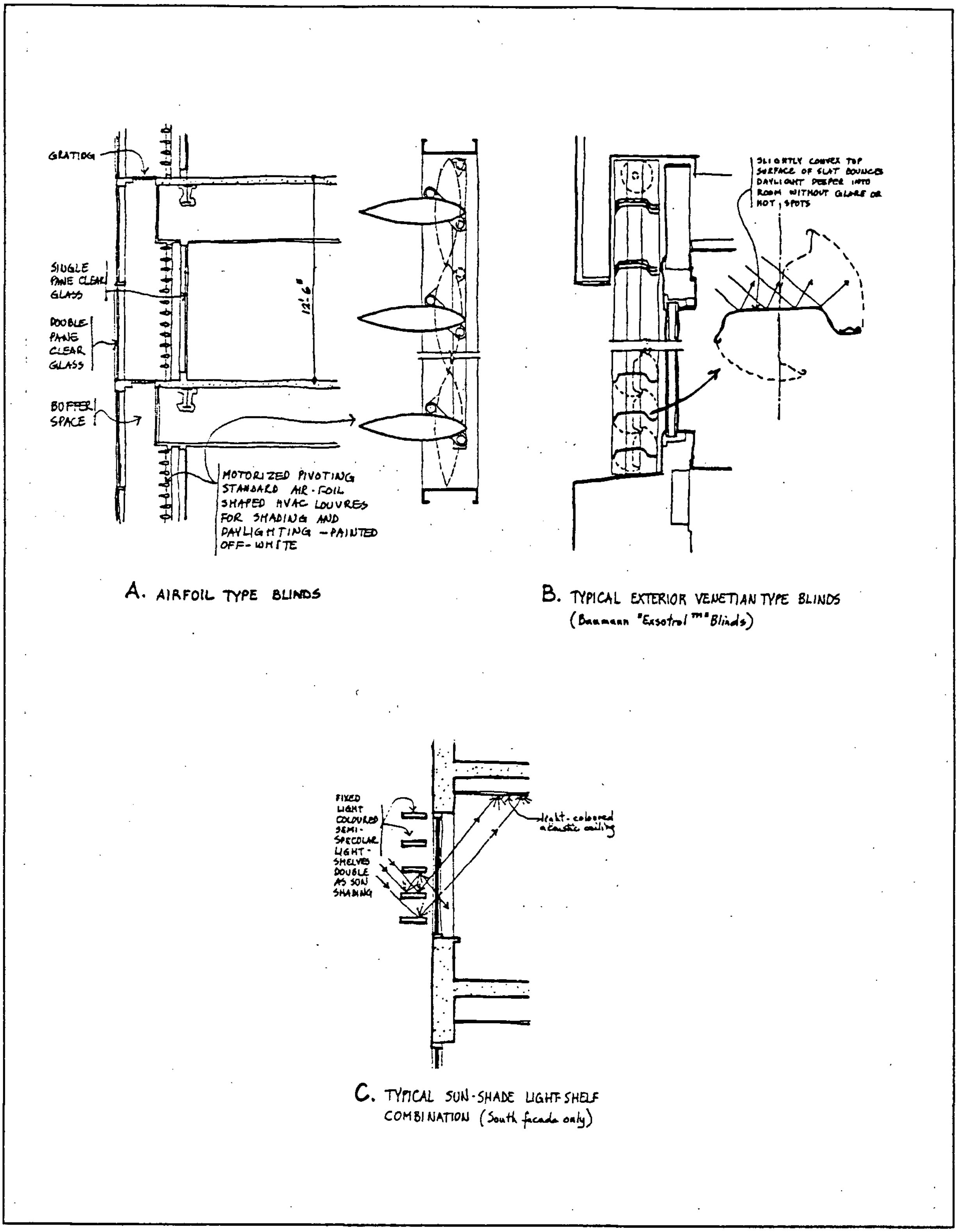


Figure 51 - Daylight beaming mechanism as an exterior accessory

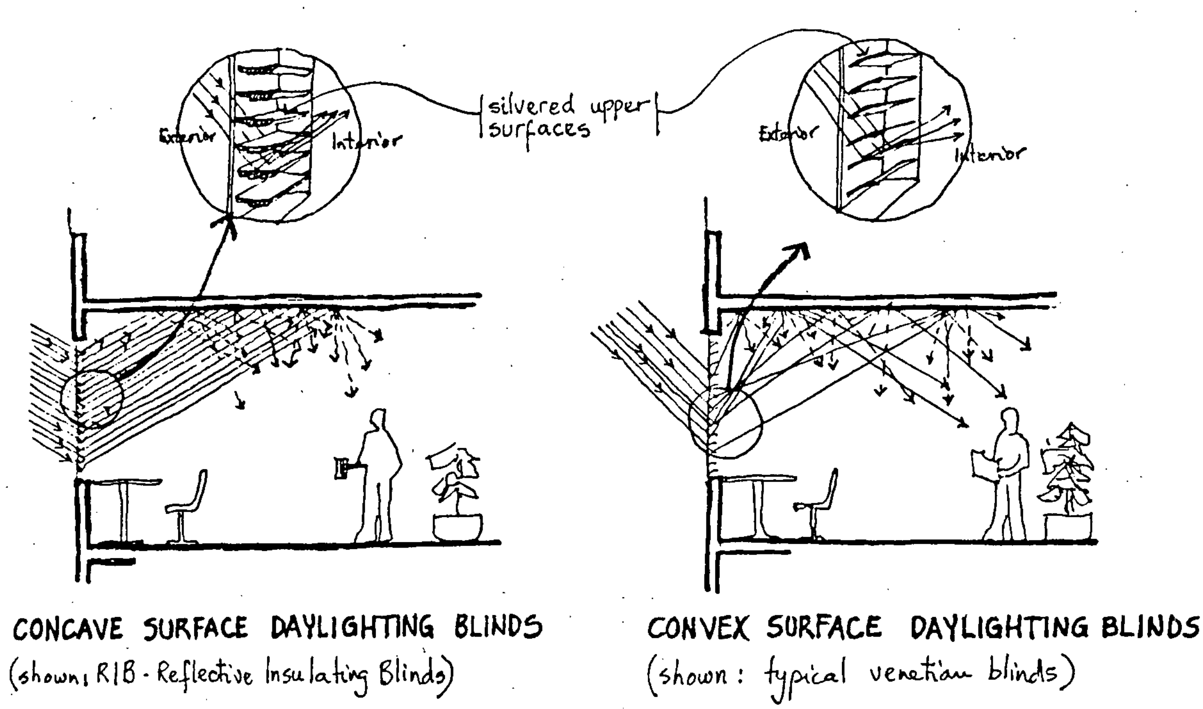


Figure 52 - Daylight beaming mechanism as an interior accessory

mechanisms consist of horizontal blinds of various profiles. Standard (1-1/2") or thin (1") venetian blinds, silvered on the convex side, are used, as shown in figure 52 (right). Some designs use blinds with the concave side up, as for example the Reflective Insulating Blinds (RIB) developed by the Oak Ridge National Laboratory, as shown in figure 52 (left)[66]. The original proposal by Selkowitz and Rubinstein[67], as well as the "Modulator" blinds used at the MIT solar building[68], also had concave reflective surfaces. The major disadvantage of the concave type blind seems to be the appearance of "hot spots" of light on the ceiling due to the slight focusing nature of the system.

In summary, the use of beamed daylighting techniques with view windows has the following advantages:

i. The use of the window for both view and daylighting eliminates the cost of extra, separate daylighting apertures.

ii. When compared to deep daylighting techniques through clerestoreys, the elevation is relatively simple, with no extra daylighting apertures to integrate into the elvation rhythm.

iii. For an equivalent daylight penetration, smaller daylighting apertures are feasible with the beamed daylighting mechanisms than would be without them. The mechanisms may be integrated into the building envelope, may be a part of the glazing system, or may be external or internal accessories--and their main function is to project daylight deeper into the interior.

3.2 Deep Daylighting--Through Wall Apertures Above Eye Level

3.2.1 Classification

When the function of daylighting is separated from the other functions of windows, it then becomes possible to locate and detail apertures so as to maximize daylight penetration. Deep daylighting schemes of the split function type may be classified by their height above floor level, with three locations distinguisheable:

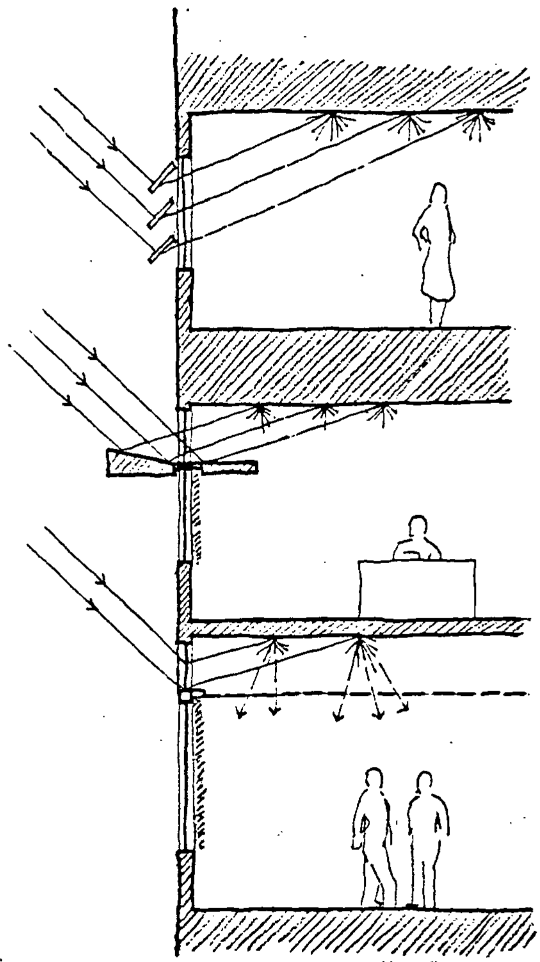


Figure 53 - Beamed daylighting designs at different locations in exterior walls

i. The daylighting aperture may be located below the 2m height above the floor level. A typical scheme, originating from Austria, is shown in figure 53 a[69]. It utilizes prismatic glass, and the daylighting apertures alternate with view windows. This location for daylighting apertures of the split function type is not common. Advantages are: the possibility of lower floor to ceiling height; feasibility of retrofit installation and the avoidance of a tiered window look on elevation. Disadvantages are: view windows are replaced by the daylighting mechanism, with a resultant loss of view; some systems may have a problem of glare (being more in the line of sight) and protruding daylighting mechanisms may create window washing problems for tall buildings.

ii. The daylighting aperture may also be located above the 2m height, and below the ceiling, as shown in figure 53 b. This is the most common location for split function beamed daylighting concepts. Advantages of this technique are: glare control is simpler than for openings that double as view apertures; little interference with the use of exterior wall below the daylighting aperture and potential for good daylight penetration increased due to height of opening above floor. Disadvantages are: more complex elevation, requiring careful proportioning and detailing and possible cleaning problem for the daylighting mechanism (for louvre and lightshelf systems).

iii. Beamed daylighting systems may also be located above the ceiling and below the slab of the floor above, as shown in figure 53 c. These systems are called plenum daylighting[70]. The design shown is based on a scheme for the Princeton Forrestal Center, a speculative office complex, in Plainsboro, N. J.[71] Advantages with this type of scheme are: since glare is not a problem, the daylighting aperture can be designed to maximize daylight penetration; the plenum space which is seldom fully utilized, can be put to use,saving in floor to floor height by a potential reduction of the floor to ceiling height. Disadvantages are: the ceiling needs to be able to transmit the daylight either through holes or by being transparent--and no readily available systems are on the market; surfaces in the plenum need to be spray-painted a light colour; piping and ducts have to be routed more carefully, so as not to block the daylight near the exterior walls.

Daylighting systems of the split function type can also be classed according to the type of daylighting mechanism, as follows:

i. lightshelf systems, consisting of a single large element or several smaller stationary louvre-like elements

ii. prismatic systems, consisting of refractive glass blocks, refractive glass or thin-film prismatics

iii. louvre systems, consisting of adjustable elments on the exterior, between window panes or on the interior

3.2.2 Lightshelves

Description

As Phillips[72] and Hopkinson[73] have documented, lightshelves have been used in hospitals and schools as early as the 1950s, and the concept has been known possibly 50 years earlier[74]. Phillips calls them "horizontal reflecting baffles"[75]--a descriptive term.

Figure 54 shows the components of a lightshelf system.

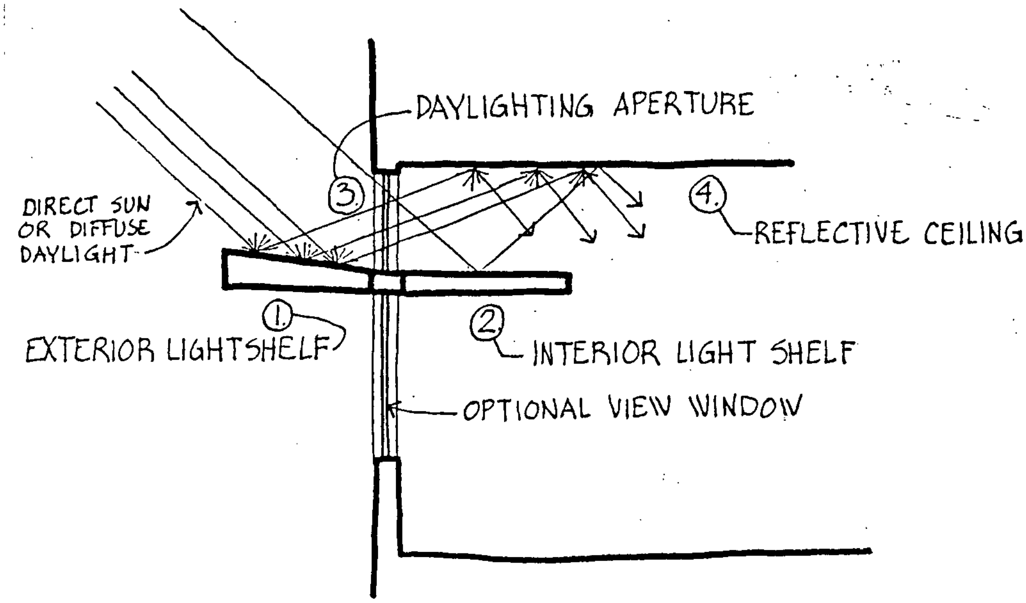


Figure 54 - The components of a lightshelf system

The major component is the exterior lightshelf (1). Its primary function is that of a large reflector, bouncing skylight and sunlight from the exterior onto the ceiling; it also acts as a shading device for any view window directly beneath. Horizontal projection of exterior lightshelves will vary with the geometry of the daylighting aperture above and the view window below, as well as with the orientation of the facade, the geographic latitude of the building, structural requirements, etc.

The reflectance of the upper surface is an important parameter, since it determines the amount of daylight the shelf will be able to "bounce" into the interior. This surface may be specular, semi-specular, or matte. Specular surfaces, such as aluminized mylar or polished stainless steel, have the highest reflectance (>80°). Their disadvantage is that directional reflectance may create "hot spots" of light on the ceiling and also suffer reduction in reflectance with time, even with good maintenance[76]. Semispecular reflecting surfaces (such as anodized aluminum, high gloss paint, etc.) have somewhat lower reflectances (peak at 70 to 80°) but their maintenance is easier. Nonspecular reflecting surfaces (such as matte paint, prefinished enamelled or porcelain panels) can have reflectances of up to 80°. Material and finish of the exterior lightshelf must be evaluated not only on the basis of daylighting performance, but also in terms of initial cost, maintenance, aesthetics, etc.

The tilt of the reflecting (top) surface will vary from design to design, depending on various parameters that determine its optical performance as well as requirements for good weathering, rain shedding, etc. Optimized solutions generally have a slight 5-10% upward tilt[77], (e.g. figure 55 a.[78]) but designs have been built having a tilt of 0° from horizontal (e.g. figure 55 b.[79]) to about 40° from horizontal (e.g. figure 55 c.[80]) It appears therefore that optimum tilt varies with the degree of specularity of the top surface, geographic latitude, structural solution and spatial characteristics of the interior.

The primary function of the interior lightshelf (2. on the diagram) is to reduce the brightness gradient between areas near the daylighting aperture and those further removed. It also

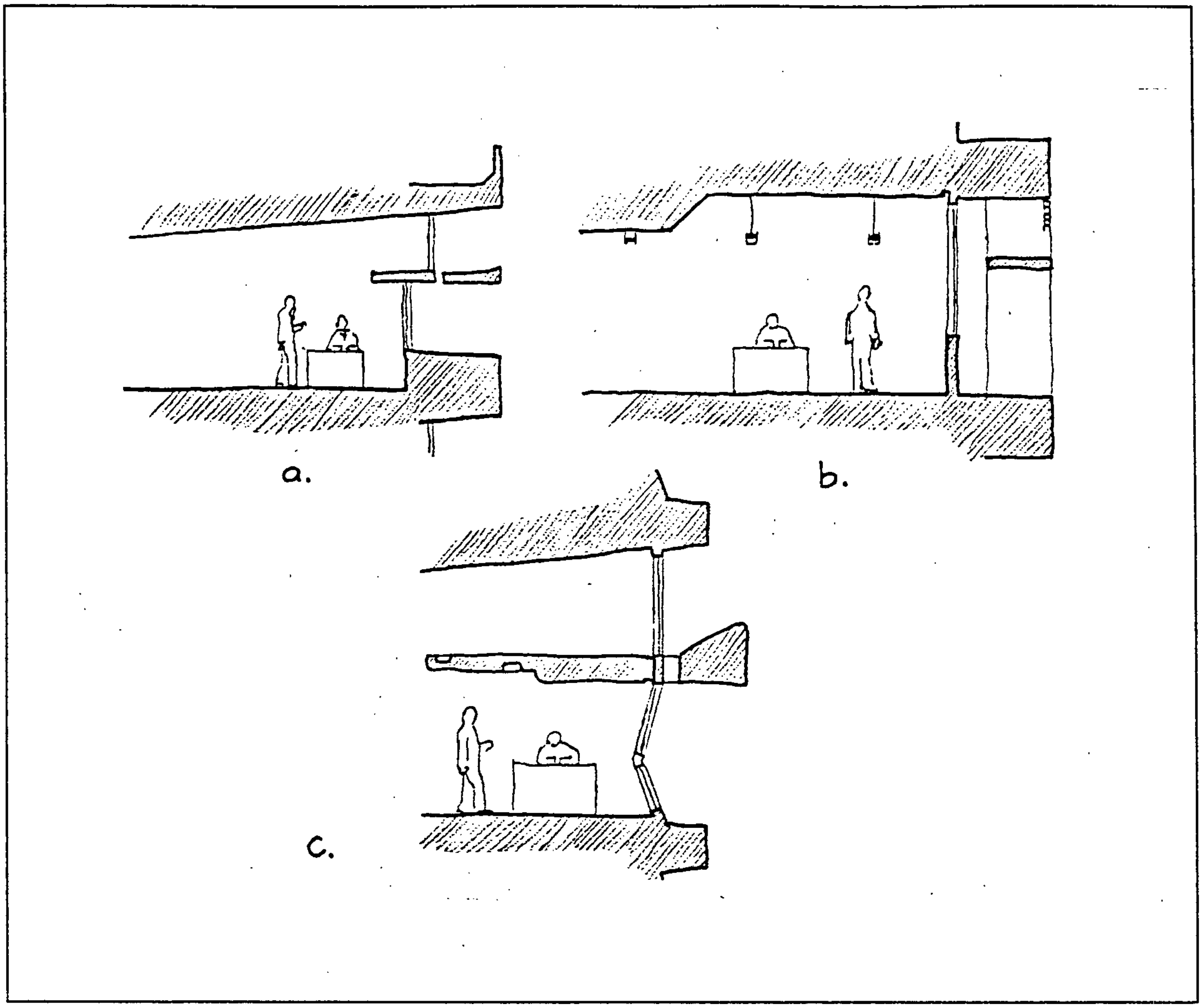


Figure 55 - Typical lightshelf configurations

increases daylight penetration somewhat, and acts as a baffle to reduce direct glare.

Aesthetics, performance and integration

Lightshelves are strong elevation design elements. Generally, they will impart a strong horizontality to the elevation. However, it is possible to reduce the horizontal emphasis of lightshelves by using the window surround as a frame for them. Lightshelves can be integrated into elevations of concrete buildings with relative ease, since concrete lends itself to massive, three-dimensional elevational treatment[81]. Some elevation solutions are shown in figure 56 [82].

Lightshelves (interior and exterior) can be massive structurally and, because of their area, exterior lightshelves can be exposed to substantial wind loads. They can pose maintenance problems and may interfere with window washing. These and other secondary effects need to be considered in their design and in assessing their cost effectiveness.

3.2.3 Prismatic Systems

Description

Prismatic systems for beaming daylight and sunlight were used in North American schools and offices in the 1950s[83] and many patents for beamed daylighting utilizing the principles of refraction have been traced back to the 1890s[84].

Figure 57 shows the components of a prismatic beamed daylighting system. The main component is the transparent or transluscent prismatic material (1) that "bends" the light rays and redirects them upward onto the highly reflective ceiling (2), whence the light is diffused in the interior. The refracting element may consist of prismatic glass blocks, prismatic sheet glass, linear fresnel lenses (similar to prismatic glass, but having focusing characteristics), or linear thin film prismatics. An enlargement of the prismatic element is also shown. Usually two parallel prismatic elements are

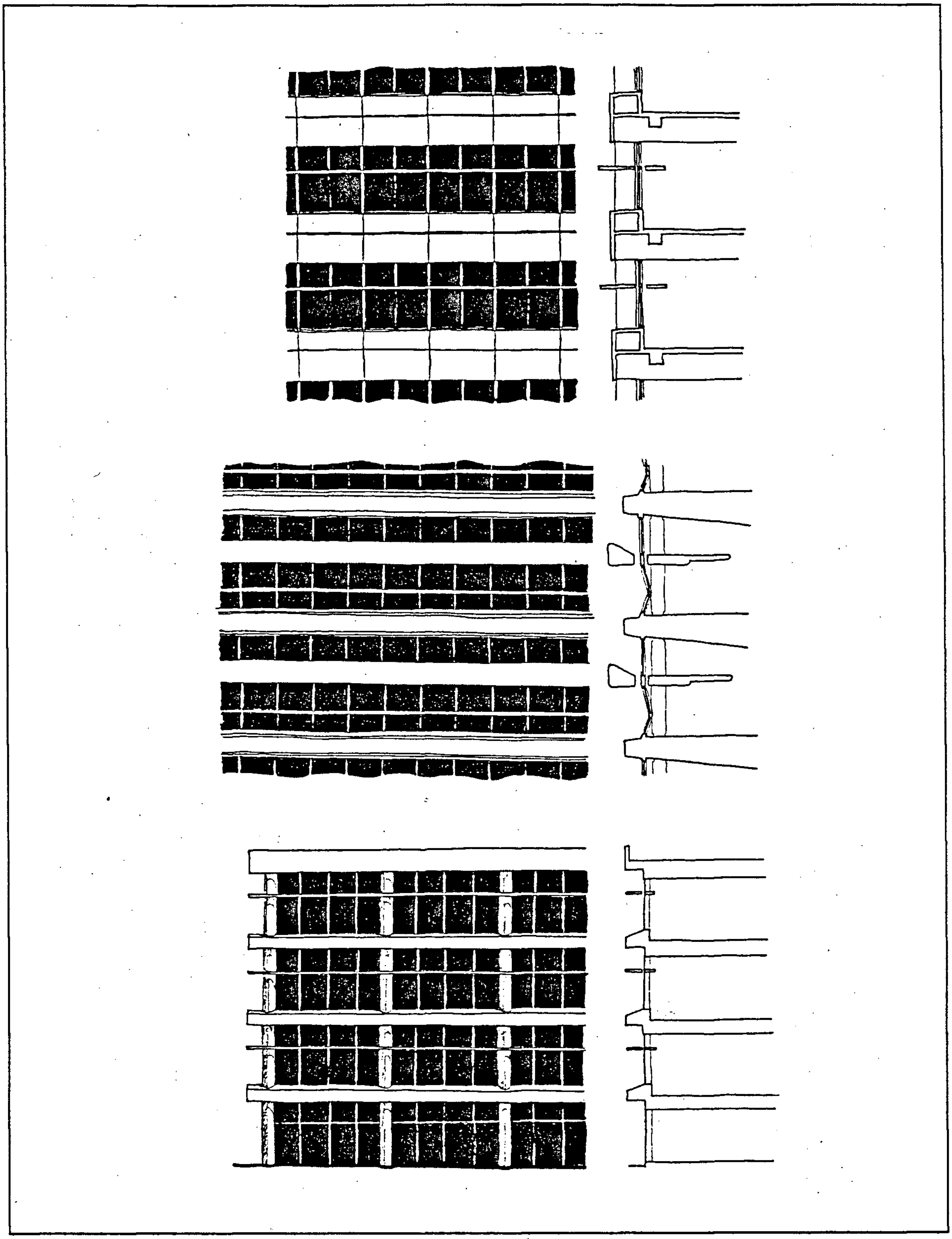


Figure 56 - Elevational treatments of lightshelves

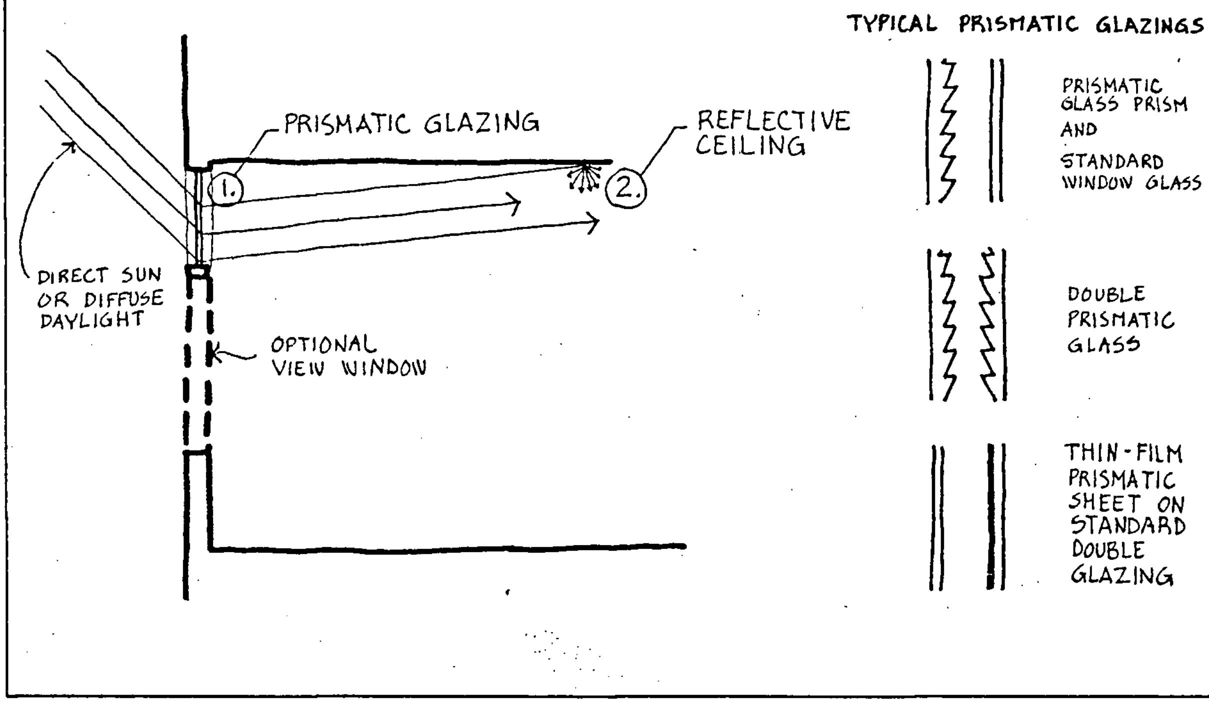


Figure 57 - The components of a prismatic beamed daylighting system

used, both to bend the light further than would be possible with a single element, as well as to ease maintenance by providing two flat outer surfaces. In an obstructed situation, the varying refracting properties of differently shaped prisms may be used to advantage, by locating prisms with the appropriate refraction characteristics on different floors of a building. Thus, as shown in figure 58 [85], prisms of highest refractance (no. 3 in the diagram) can be utilized on lower floors, while prisms of lower refractance can be used on intermediate and upper floors. The daylight penetration on each of these floors will be comparable, even though the lower floors are substantially more obstructed.

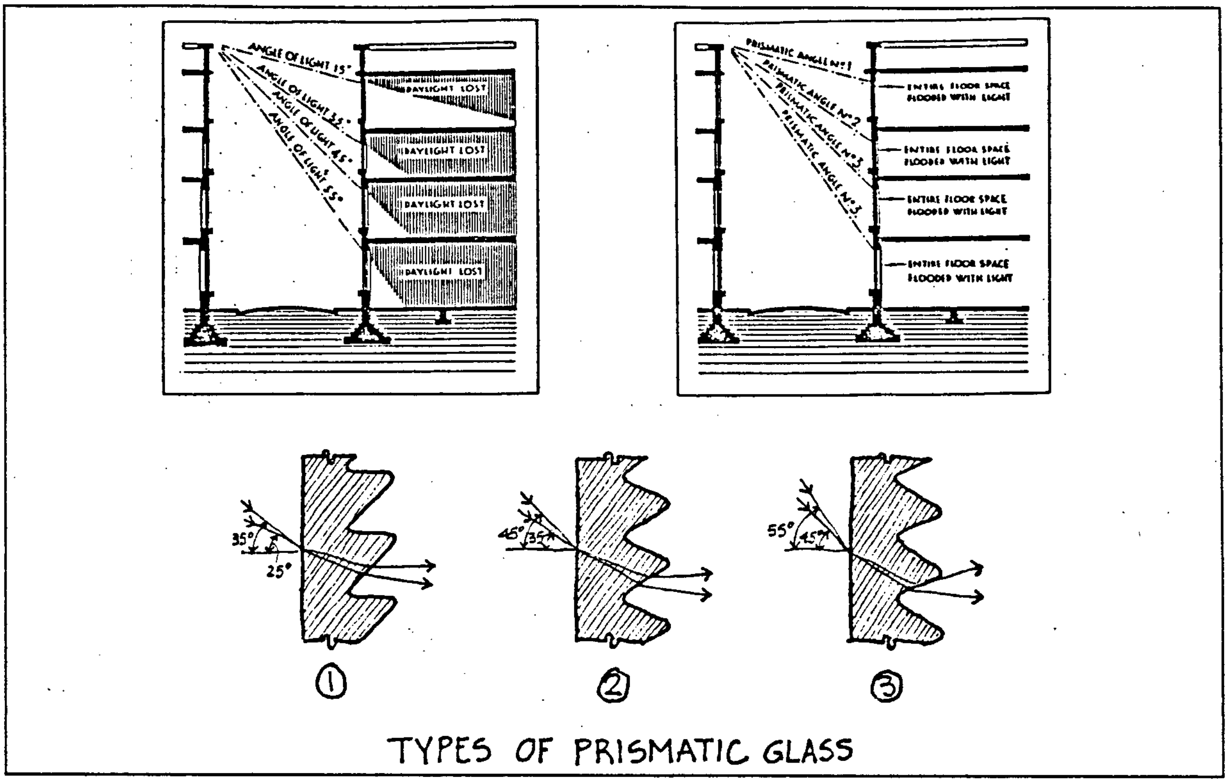


Figure 58 - Use of prismatic daylighting system in an obstructed situation

Aesthetics, performance and integration

Phillips[86], Bartenbach[87] and Eacret[88] have all published performance data on prismatic systems. Typical examples exhibit considerable improvement in daylight penetration over non-beamed daylighting solutions. This is true especially at the back of the daylit spaces. The relatively uniform distribution of light will also result in balanced brightness in the room.

Because prismatics redirect most of the light upward onto the ceiling, there is little light transmitted below the horizontal, and the glass surfaces appear of much lower brightness than the unobstructed sky would appear when viewed from task positions in the space[89]. Bartenbach[90] reports that the luminance of the prismatic glass is within the range of the luminance of surrounding surfaces, when seen from the interior. Thus the prismatic type of system can, by its inherent working characteristics, eliminate glare at the daylighting aperture.

The integration of prismatic systems in elevations is a simpler design exercise, than that involving lightshelf systems. Because in most instances the prisms will not protrude from the plane of the facade, they can be treated visually as clerestorey windows. Two possible elevational resolutions are shown in figure 59 [91].

The recent availability of thin-film prismatics eliminates the weight and bulk associated with prismatic glass. These new films may be glued to the interior faces of double glazing, thus eliminating maintenance and enabling standard glazing frames to be utilized. Most refracting systems have no diurnal or seasonal adjustment, but this may be provided if they are incorporated into operable windows or jalousie type elements[92], in which case seasonal adjustment or diurnal tracking can direct the refracted light accurately, for the best daylighting advantage.

In spite of their relative simplicity, inherent freedom from glare problems, low maintenance, and in some instances, of low first cost[93], prismatic beamed daylighting systems have not been extensively used in recent daylit buildings. There are several reasons for this:

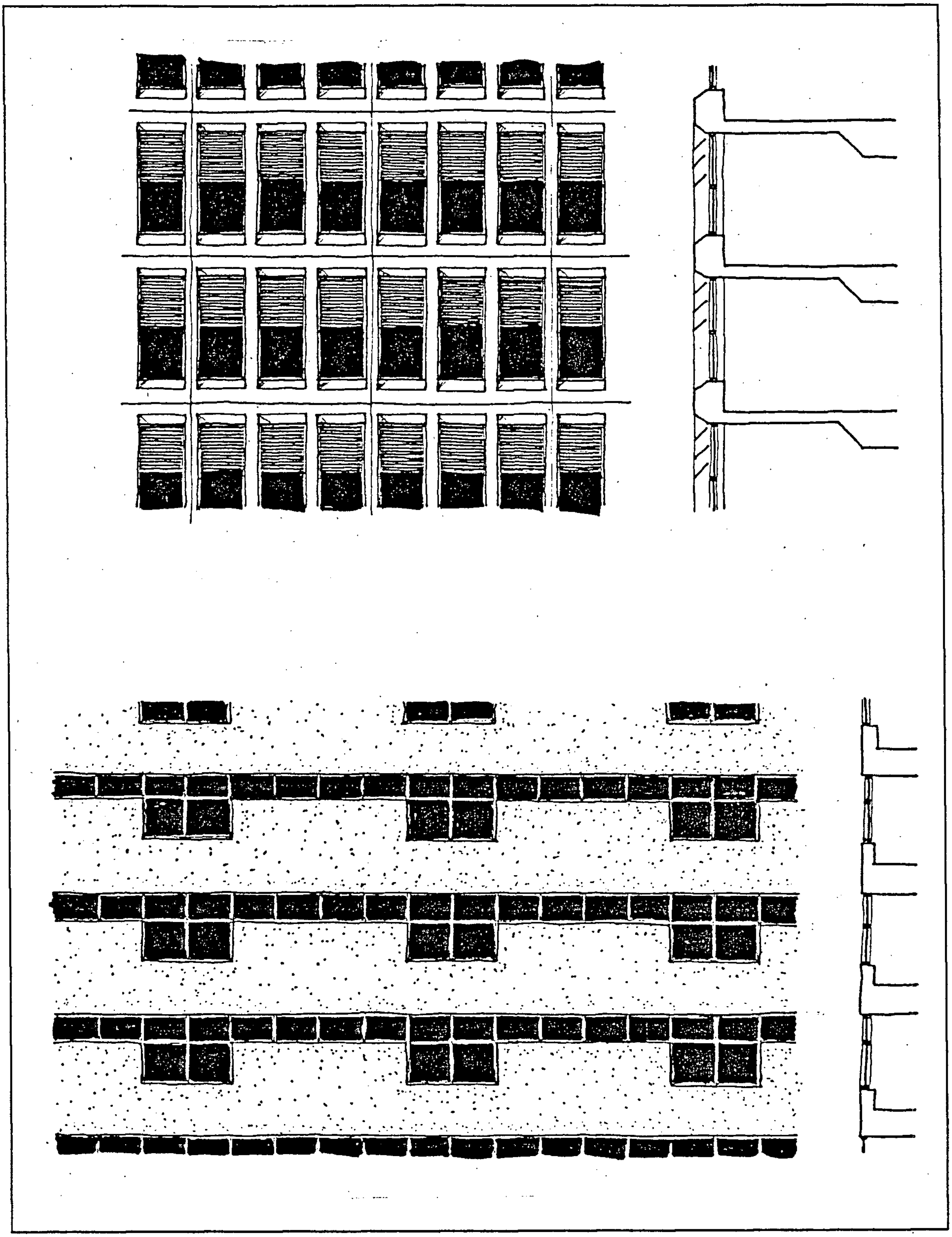


Figure 59 - Elevational treatments of prismatic systems

i. Architects are not familiar with the field of optics and the laws of refraction. Therefore, they are not able to custom design prismatic beamed daylighting systems for each project. What is needed is some step by step graphic method of designing with refracting materials. Because these design tools are unavailable to architects in a form they can readily use, there is a scarcity of recent examples using these methods, in spite of their great potential and simplicity.

ii. Prismatic glass block and sheet glass, though available in Europe and Japan, appear to have been discontinued by North American manufacturers, and literature describing their use[94] is no longer available. Recently, however, imported refractive glass blocks have become available[95].

iii. Linear thin film prismatics are available[96] but prototypes and technical literature describing their use is lacking[97]. These systems, however, have great potential in daylighting which will be realized when information describing and detailing their use will be available.

3.2.4 Louvre Systems

Description

Louvre systems utilize small scale, adjustable devices to reflect daylight deeper into the interior. The louvres pivot and, in many instances, retract as well. Louvres such as venetian blinds, have been used for decades to control glare and excessive solar heat gain. However, their purposeful use for daylighting is recent. Louvre devices for beaming daylight provide an integrated solution to four interrelated problems: two of thermal transfer--control of unwanted solar heat gain and of conductive heat losses; and two of daylighting--daylight penetration and control of glare.

The various techniques and products available were highlighted in the previous section describing beamed daylighting systems through view apertures.

Aesthetics, performance and integration

Exterior louvres provide the best thermal performance--both in blocking unwanted solar heat gain and reducing heat loss. They also provide security when closed. Their effect on the elevation is more pronounced than the effect of louvres on the interior. Because of the housing required when they are retracted, and because of the side tracks needed to stabilize most models, daylighting apertures designed with exterior louvres usually have articulated shapes, with aspect (height to length) ratio close to unity, as shown in figure 60 [98].

Louvres may also be located between the exterior and the interior glazing of double-glazed windows, and having widths of 1" or less. Their thermal performance, as indicated by the shading coefficient, is in this case somewhat poorer, but their initial cost and maintenance is less than that of exterior louvres. Louvres on the interior are the least expensive of the three possible locations. As described in the previous

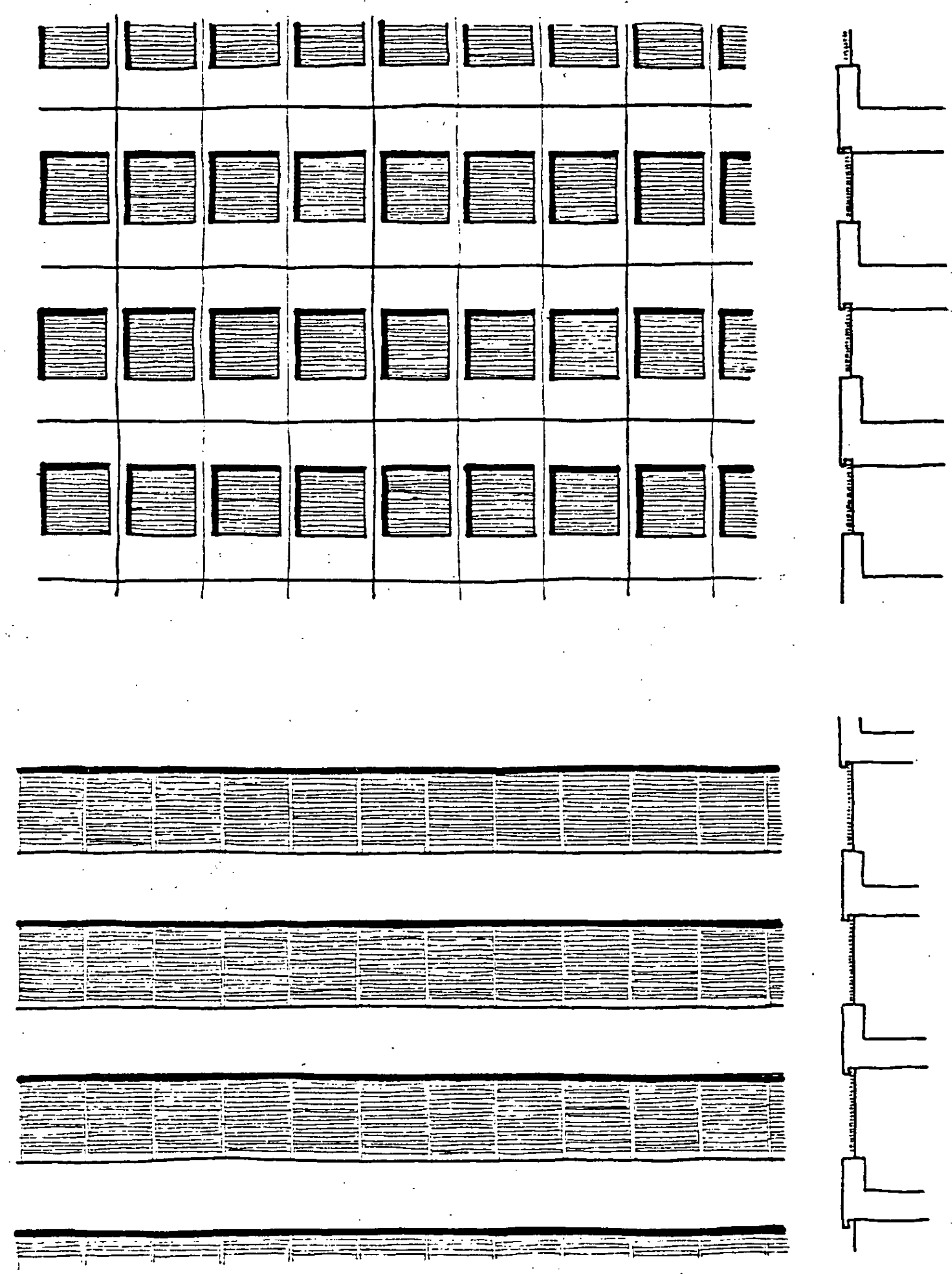


Figure 60 - Examples of elevational treatments with exterior louvres

section, many systems are available. Louvres on the interior or between the glazing have little influence on the elevational treatment since they they can adapt to the rhythm set up by the glazing mullions.

3.3 Deep Daylighting--through Roof Apertures

Daylight penetration through apertures on roofs may be increased by mechanisms similar to those available for wall apertures. The primary aims of beaming mechanisms are to increase illuminance levels in the areas away from daylighting apertures and to smooth out the brightness gradient in the interior. Usually, the secondary aim of glare reduction is simultaneously achieved. Figure 61 shows the technique employed in beaming light from the atrium into work spaces, in the TVA building, Chattanooga, Tennessee[99]. At a smaller scale, figure 62 shows a standard skylight, fitted with seasonally adjustable reflector/shade on the exterior, as well as a fabric reflector/diffuser on the interior[100]. This is an elegant solution, using mass-produced, and readily available components. Figure 63 shows two highly optimized, beamed daylighting systems developed by Ashley et al.[101] These utilize direct sunlight as well as diffuse daylight and, according to the designers, have uniform light distribution characteristics. The area of the glazing is reduced to a minimum, to cut down on heat loss and solar heat gain. These designs necessitate specially fabricated reflectors and light wells. Their cost effectiveness is not known.

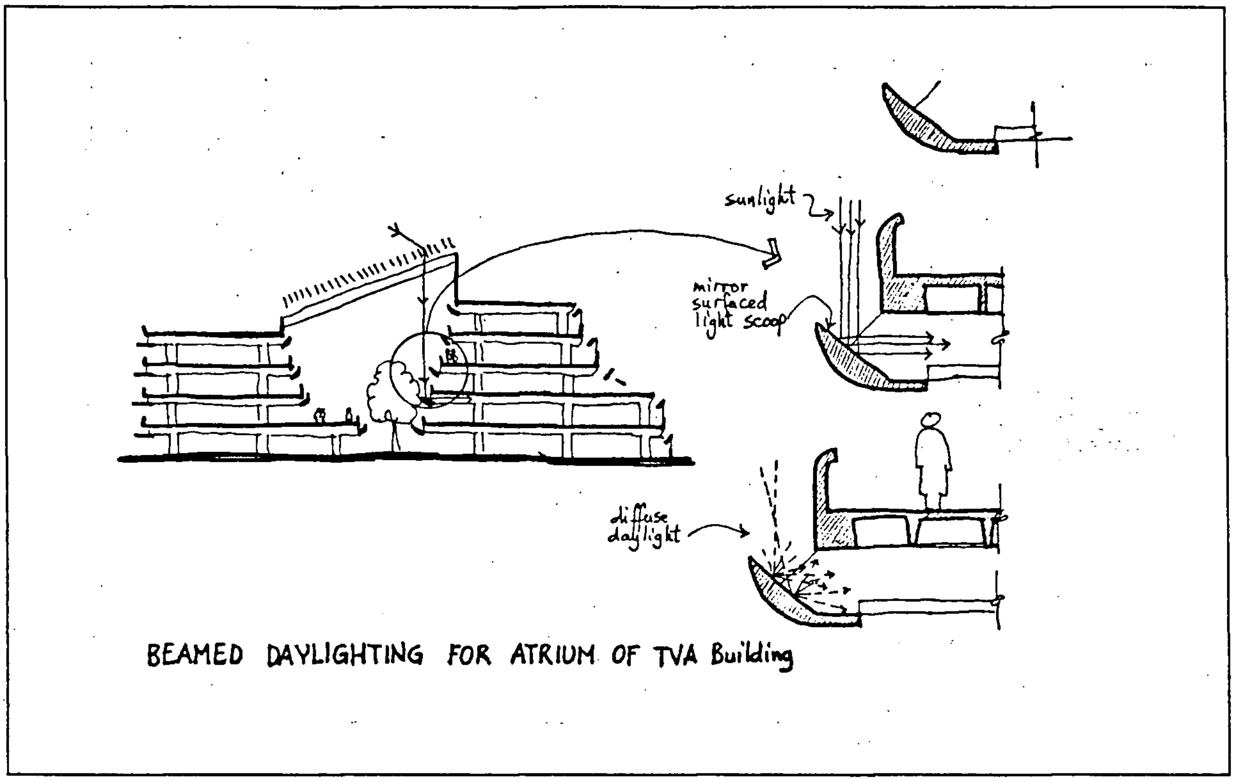


Figure 61 - Large-scale beamed daylighting from the top

The above examples utilize the principle of light reflection to increase daylight penetration and spread. However, the principle of refraction may also be used to achieve the same ends. Lemons[102] has made model studies with commercially available thin-film prismatics and fresnel lenses to achieve increased light penetration for skylights. He reports that linear lenses, both of the concave and the convex type, produce diffuse, large pools of light with overcast sky; and diffuse strips of light with a clear sky. Single and double linear prisms bend the light at predictable angles. Obvious applications appear to be corridor spaces, as well as wall washers, etc.[103] The use of light refraction principles, and especially of thin-film prismatics, to increase daylight

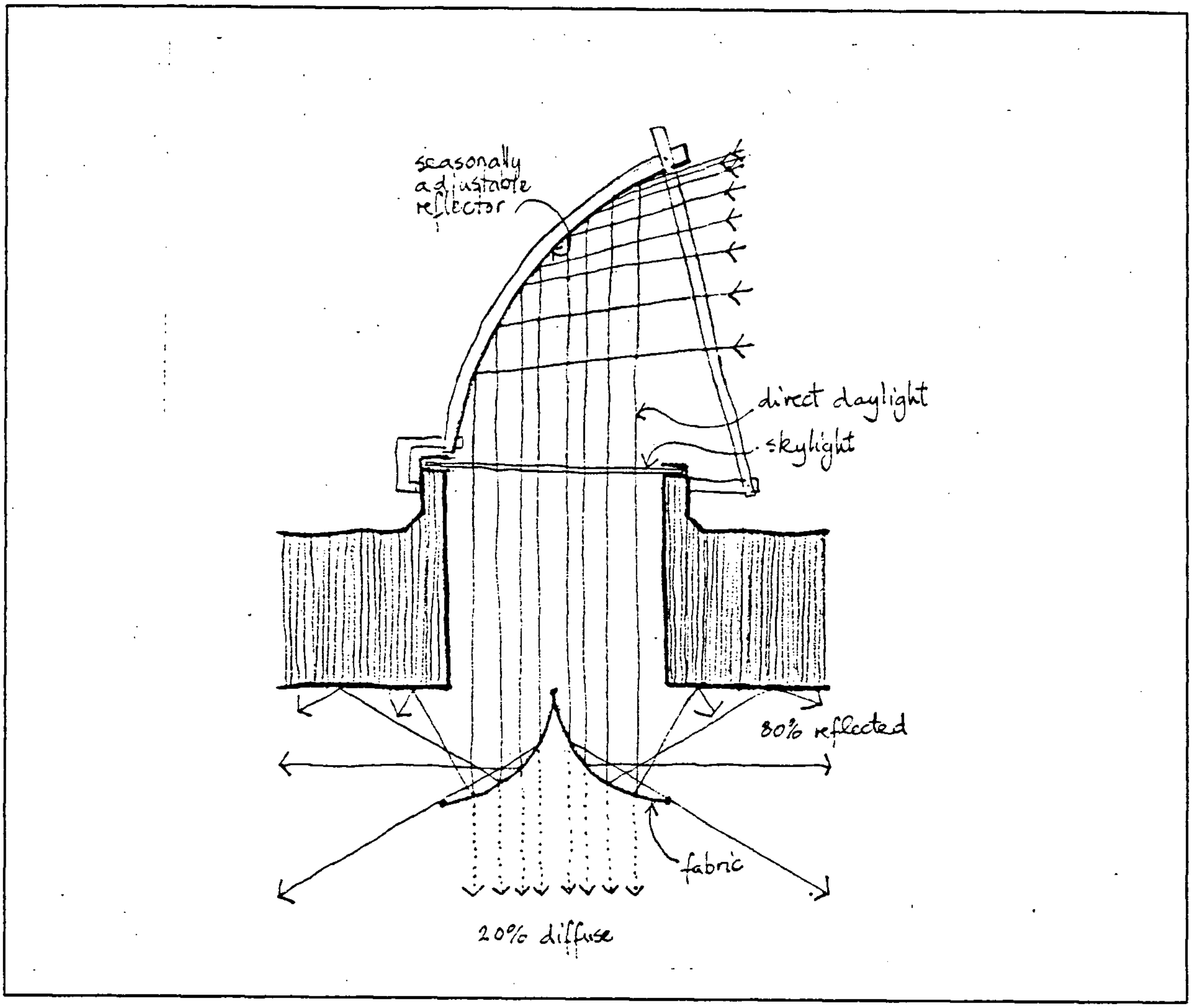


Figure 62 - Example of beaming mechanism added to standard skylight

penetration has much potential in beamed daylighting.

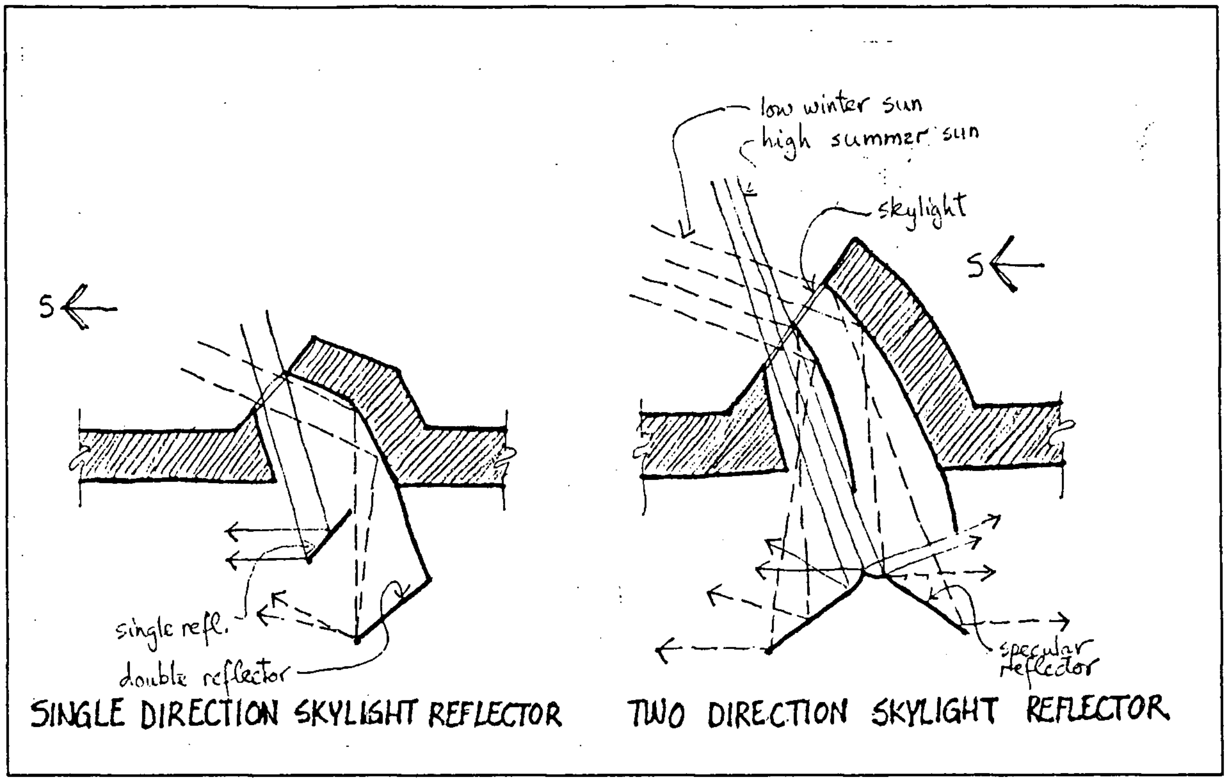


Figure 63 - Highly optimized skylight designs

4. NOTES

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82. Elevations and sections show, from top: CIGNA building, Bloomfield, Conn. (TAC, arch.) from Michael J. Crosbie, " Lighting Strategies: Case Study," Architecture, October 1984, pp. 62-63; GSIS building, Manila, Philippines (TAC, arch.) from Architectural Record, "Terraced Pods Invite

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91. Elevations adapted from: (top) Social security Administration , NE Program Service Centre building, Jamaica, N.Y. (Ehrenkrantz Group) as described in Magnusson, M, "Window Configuration: Designing for Daylighting and Productivity," Proceedings of the 1983 International Daylighting Conference, 16-18 February 1983 in Phoenix, Arizona. Washington, D. C.: 1983 International Daylighting Conference, 1983, pp. 155-57; (bottom) elevation adapted from prototype building described in Bartenbach (supra), insert pages.

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93. Eacret, p. 1177.

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95. N.E.G. Corporation, Japan, glass block products, distributed by Cerco Industries Ltd.

96. 3-M Corporation, for example, manufacture a range of thin-

film prismatics.

97. Personal communication by 3-M representative at the manufacturers' displays, The 1983 International Daylighting Conference, 16-18 February 1983 in Phoenix, Arizona .

98. Sources for elevations: (top) Office block, Hahnstrasse, and (bottom) South German Central Bank building, both in Frankfurt, W. Germany, shown in Faber "Maximatic" external blinds, trade literature.

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V.

INTERIOR SPACE PLANNING IN DAYLIT BUILDINGS

1. INTRODUCTION

The techniques included in this chapter comprise the third part in the overall objective of maximizing the potential for daylighting within a building: interior space planning.

The tenant of a daylit office building has to be sensitive to the daylighting implications of various office layouts and the lighting needs of various office activities, and must also work in harmony with the pattern of luminous zones naturally occuring in daylit buildings. Otherwise, the daylight penetration achieved in the design of the building may be impaired. This chapter outlines a range of techniques that can assist in achieving the main goal of daylighting: locating people and activities in such a way that advantage is taken of available interior daylight.

2. TECHNIQUES FOR SPACE PLANNING

The techniques included in this chapter are summarized in figure 64 .

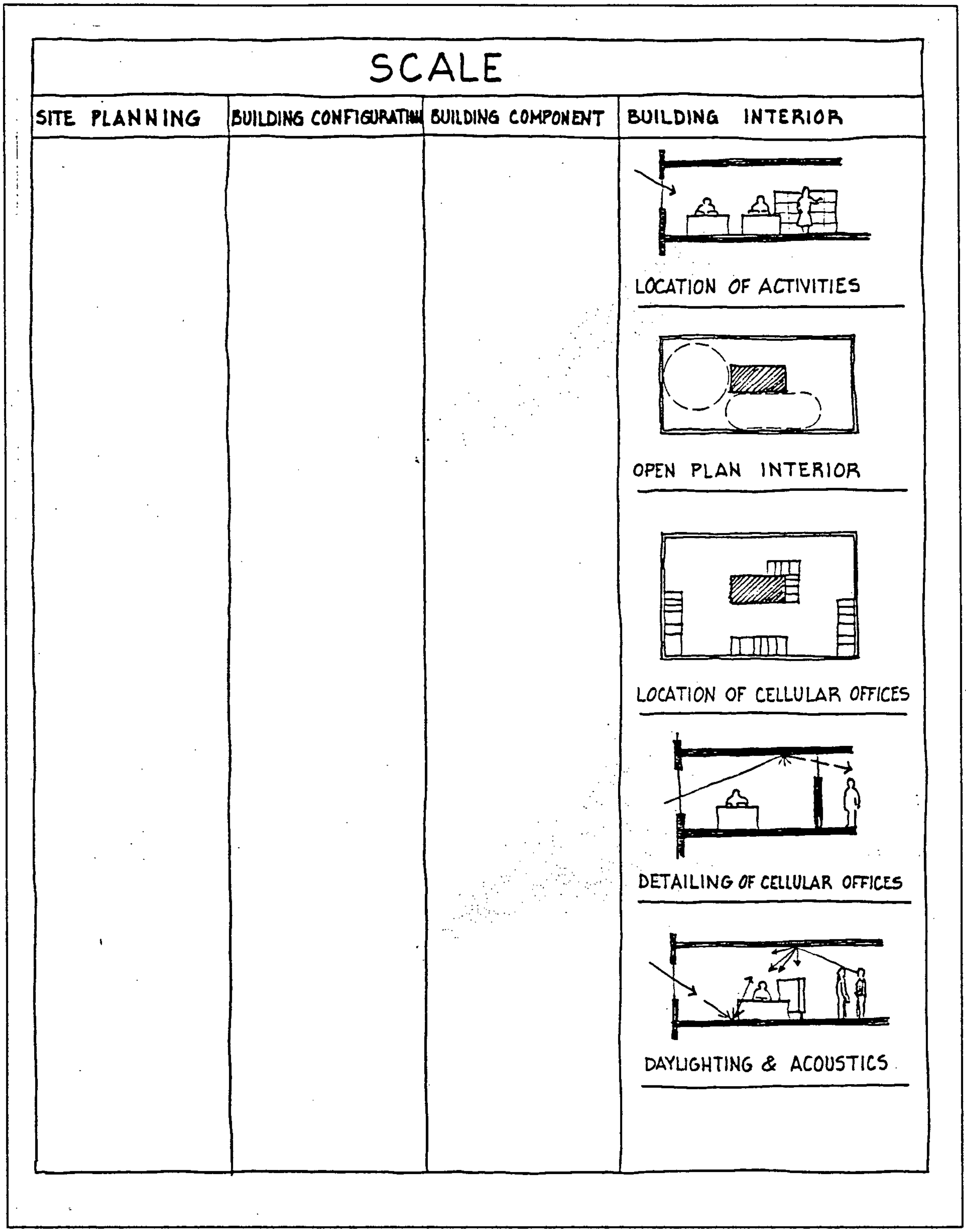

Figure 64 - Summary of techniques for interior space planning

2.1 Location Of Activities

In order to take advantage of available daylight, activities within a daylit building should be located according to their visual performance requirements.

In a typical sidelit office space, three zones of varying daylight penetration, shown in figure 65 , may be identified:

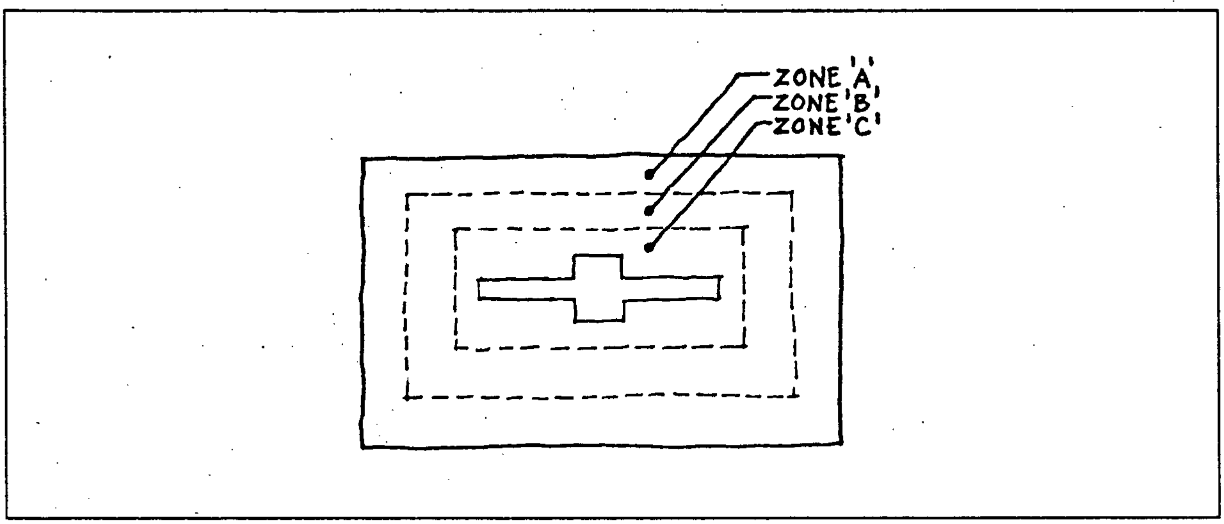

Figure 65 - The three zones of daylight penetration

i. Zone A, the perimeter zone, extends to about 3.5-4.5m from the daylighting aperture in traditional daylighting systems and to about 6-8m using deep daylighting systems. The actual distances will be greatly dependent on sky conditions, orientation of the daylighting aperture, and the extent of obstructions, as well as on the interior detailing[1]. This zone is characterized by the availability of view outdoors, an exposure to fluctuating climatic conditions and excellent daylighting potential. Daylighting in this zone has low veiling reflection for most positions[2], provides good illuminance on the vertical surfaces[3], well balanced spectral composition, good modelling characteristics[4] and generally, ESI values substantially higher than raw illumination measurements[5].

ii. Zone C, the core zone, is typically beyond 7m from the daylighting apertures in traditional daylighting systems and beyond 12m in designs utilizing deep daylighting techniques. This zone cannot benefit from daylight and is largely independent of the external climate. In offices, this zone is permanently lit by artificial lighting and requires cooling for much of the year[6]. Any daylighting that reaches this zone is more of psychological help than an aid to visual task performance[7].

iii. The intermediate area, Zone B, is characterized by daylighting adequate for ambient lighting, with task lighting supplementation. Its thermal behaviour, as its luminous characteristics, is somewhere between that of the core and the perimeter zone. This intermediate zone is found at 3.5-12m from the daylighting aperture. The actual location and extent of this zone will vary with the design.

Table XII shows a comprehensive list of office activities, with their approximate visibility requirements and preferred zone location. It is possible to capitalize on the characteristics of the luminous environment available in each of

ACTIVITY		COLOUR	ILLUMINANCE ON HORIZ SURF.	ILLUMINANCE ON VERT. SURF.	SCALAR ILLUMIN.	ZONE LOCATION
WRITING –	HANDWRITING PEN	0	1	0	0	A, B
	" PENCIL	0	2	0	0	A
	TYPEWRITING	0	2	2	0	A, B
	WORD PROCESSING	0	2	1	0	A, B, C *
DRAFTING –	LARGE SCALE WORK	0	2	2	1	A, B
	MEDIUM " "	0	2	1	1	A
	FINE " "	0	1	1	1	A
READING –	TYPEWRITTEN MTL. GOOD	0	1	0	0	A, B *
	" " POOR	0	2	1	0	A
	HANDWRITTEN MTL. GOOD	0	1	0	0	A, B *
	" " POOR	0	2	1	0	A
SORT/FILE –	SORTING (HORIZ.)	0	2	1	1	A, B
	FILING (VERT.)	0	1	2	1	B
	STORAGE ACTIVE	1	1	1	1	B
	" DEAD	0	1	1	0	C
INSPECTION –	COLOUR MATCHING	2	1	1	1	A
	TEXTURE MATCHING	1	1	1	2	A
	INSPECT 3D MAT'L.	1-2	1	1	2	A
	PHOTOCOPYING	0	2	1	0	A, B, C *
DISCUSSION –	TELEPHONE	0	0	0	1	B, C
	INTERVIEW	1	1	0	2	A, B
	CONFERENCE SMALL	1	1	0	2	A, B
	" LARGE	2	1	1	2	A
A/V PRESENTATION –	GRAPHICS	1	0	1	0	A, B
	SLIDES	x	x	x	x	C
	TV	x	x	x	x	C
	V.D.T.	x	1	x	x	A, B, C *
SECONDARY ACTIVITES –	LUNCH	1	1	1	1-2	A, B
	BREAK	1	1	1	1	B
	WASHROOM	1	1	1	1	C
	BULLETIN B	0	0	2	0	B, C

LEGEND: * ADDITIONAL TASK LIGHTING MAY BE NEEDED; 2 – VERY IMPORTANT; 1 – IMPORTANT; 0 – NOT IMPORTANT; X – NOT APPLICABLE

Table XII - Illumination requirements and preferred zone location of various office activities these three zones, by giving consideration to locating the various activities in the appropriate zone, according to their visual performance requirements. Thus, activities such as texture and colour matching, drafting, and other similar, visually demanding activities, will benefit from being located in Zone A. Activities such as graphic presentations to a group, interviews and conferences,vertical filing and other work requiring good modelling and vertical illumination, will benefit from being located in Zones A or B.

Circulation, storage and other low use and visually non-critical spaces, as well as equipment rooms, washrooms and similar spaces that require compartmentation, access to mechanical services, or special lighting needs, are best located, from the point of view of daylighting, in the core zone. Locating these secondary spaces in the core zone liberates floor area near the perimeter zone for primary office activities and increases the chances that daylighting will be used for these primary activities. In low rise office buildings, skylights or lightwells can effectively bring daylight into some secondary spaces--such as corridors or washrooms--to provide a sense of focus, and assist in orientation.

In many deep space office buildings, it will not be possible to locate activities in their preferred locations on the perimeter, due to insufficient space in these zones. Furthermore, there are other criteria, overlaid on daylighting considerations, that may override the above guidelines.

Nevertheless, it is important to understand the daylight requirements of different tasks and attempt to locate these in the appropriate luminous environment: this is an important aspect of efficient resource allocation.

2.2 Open Plan Interior

Where the type of office work and the management style permits, the use of an open plan interior will facilitate daylight penetration. It is now technically and economically feasible to provide workspace definition, environmental comfort conditions and acoustical privacy for the requirements of most office activities, in open plan, "landscaped offices"[8].

When opaque, full-height partitions are used to define shallow depth offices along the perimeter, resulting in open areas on the interior, view and daylight are totally blocked and the open area must rely entirely on electric lighting for its illumination. Without such partitions, daylight in the interior zones might otherwise be sufficient to save electric energy, but in any case would provide improved modelling and a feeling of increased spaciousness. Evans[9] has argued that ideally "the whole structure of the interior must allow for and complement ... [the] horizontal flow of daylight from windows for best effect".

2.3 Location Of Cellular Offices

In current North American practice, cellular offices, when required, are located at the perimeter. Such space allocation

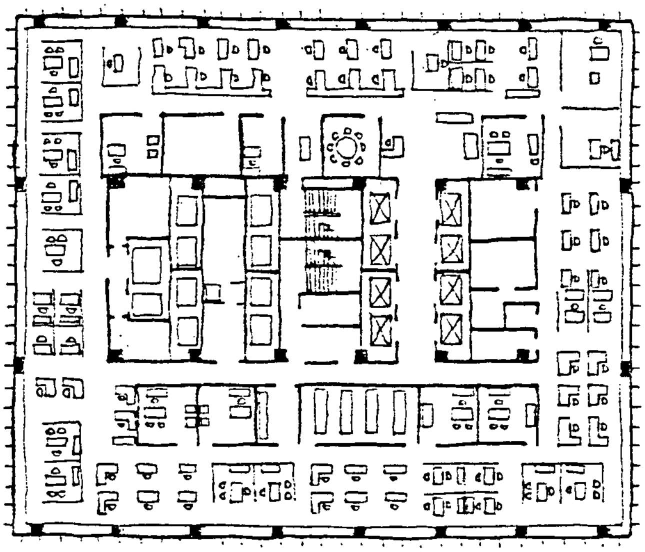

Figure 66 - A recent example of office floor plan having cellular offices on the interior

decisions are the result not of functional requirements, but a reflection of the social value system held by the organization and the larger social structure. This fact can be appreciated when it is realized that cellular offices in European practice of today, and even in North American practice of three decades ago, have not necessarily been located along the perimeter of the building. For example, in the 1950's the concept of "executive core plan" was popular in the USA[10]. In this layout, executives were located in the centre of the space, in individual offices, with staff along the perimeter of the building, in an open plan arrangement. From a functional point of view, this is still considered superior[11]. A recent daylit building in the U. S. A., has defied social convention and provides cellular offices for management personnel at the interior, leaving, as shown in figure 66 [12], perimeter areas open.

To give interior cellular offices amenities and prestige, glazed or partly glazed partitions with curtains may be used; greater amount of plant material can also be introduced. Interior offices on lower floors may be daylit through light wells and, on the upper floor, through skylights[13].

If the interior placement of cellular offices within a larger open plan is not acceptable, intermittent breaks in the line of cellular offices at the perimeter may be considered, so that the open areas have views to the exterior and some access to daylight. This is shown in figure 67 . Intermittent breaks in a line of cellular offices are of added importance in deep plans, because the subjective sense of enclosure in deep layouts greatly increases if more than two exterior walls are blocked by cellular offices[14]. If cellular offices are located along three exterior walls of a deep space office floor, as many as 90% of the people working on the floor will be in open areas behind these cellular offices and most of them will have negligible daylight illuminance at their workstations[15].

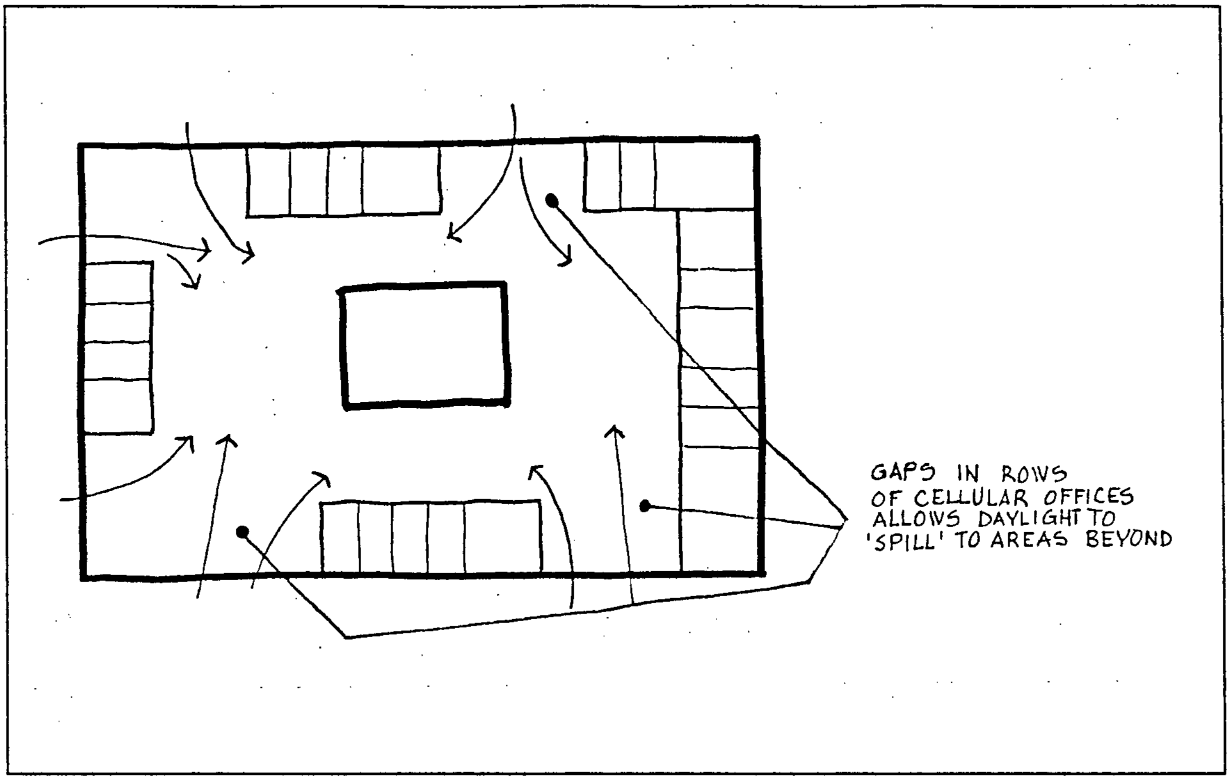

Figure 67 - Layout of cellular offices at building perimeter to enable some daylight penetration

There are functionally and technically workable alternatives to cellular offices. The "landscaped office" concept is one alternative, but there are other feasible concepts, such as the flexible, semi-private office compartmentation, based on work group units, proposed by Alexander et al.[16]

2.4 Detailing Of Cellular Offices

Full height, opaque partitions, enclosing cellular offices at the perimeter of a deep office space, block all access to view and daylight for the open plan areas beyond. Alternate detailing of these partitions will enable daylight penetration:

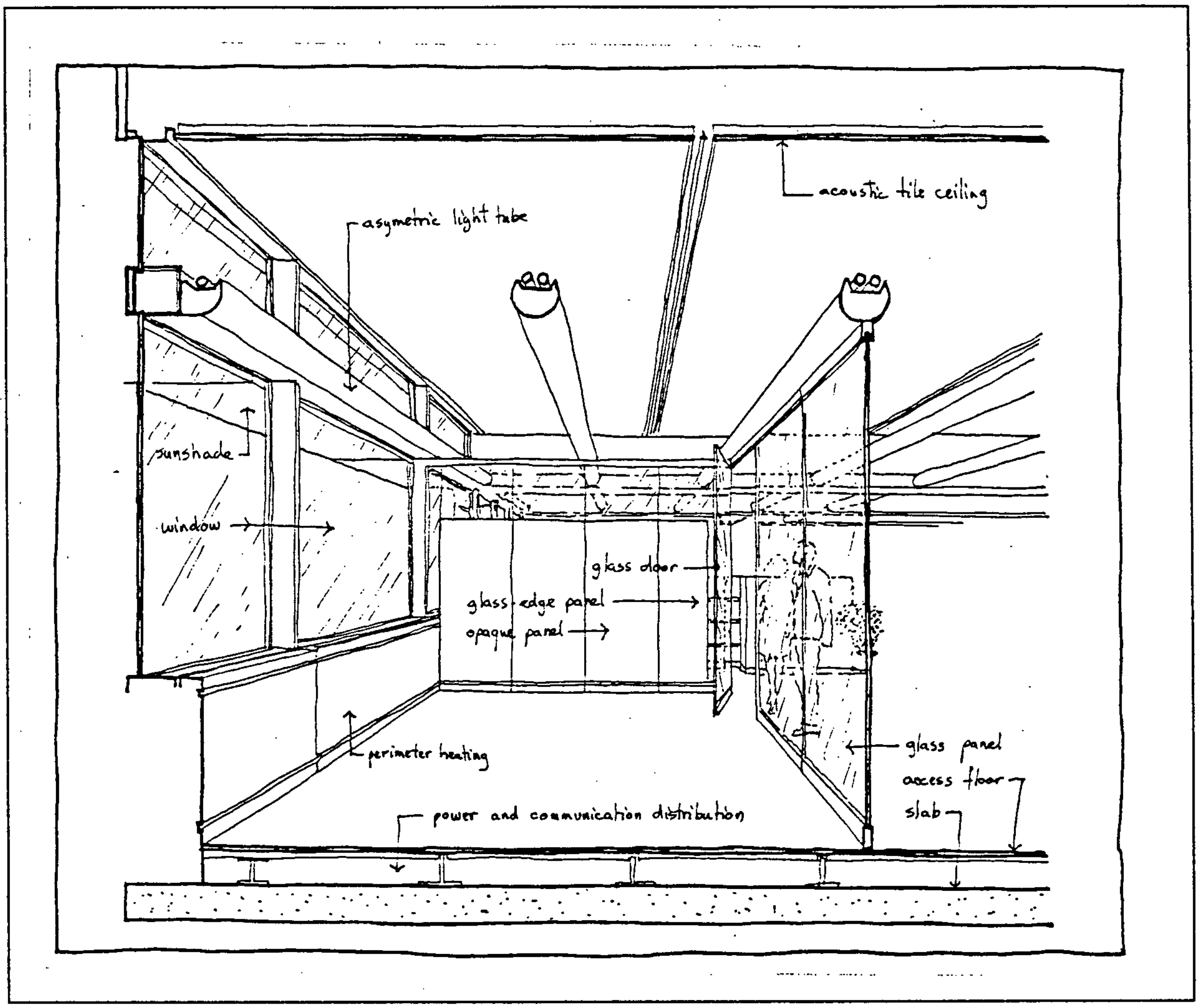

Figure 68 - Detailing of glazed partitions for cellular offices at building perimeter

i. Use fully glazed partitions. Patterned glass or clear glass with curtains may be used below door head height; above this height clear glass may be used (see for example the Connecticut General Life Insurance Company building, in Bloomfield, Connecticut, by SOM Architects[17]). Alternately, clear glass may be used in some cases without a curtain. An elegantly detailed example is shown in figure 68 , which is a recently (1983) completed building for the same clients as the previously mentioned building (re-named CIGNA Corp., Architects Collaborative Architects[18]). The owners were pleased with the spaciousness of the earlier building and requested to have the daylighting concept retained--or improved--in their newer building[19].

Attention to detailing and close co-ordination between architect, lighting consultant and acoustical consultant especially are necessary for this type of work to succeed[20].

ii. Use partitions with opaque lower portion and glazed upper portion to allow reflected light to spill into the interior zones, beyond the cellular offices at the perimeter, and thus provide ambient daylighting[21],[22]. Besides their function in "borrowing" light--both electric and daylight--there is an increase in the sense of spaciousness[23]. In offices, this glazed portion is usually above the door head height. Examples of this type of partitions are commonplace[24]. While the quantity and quality of daylight on the interior is inferior with this lesser amount of glazing, the acoustical performance of the partition (in both absorbtion and transmission) is improved and flexibility in location of furniture and filing/storage is greater.

iii. Even with fully opaque partitions for perimeter cellular offices, it may be possible to bring in daylight to interiors beyond. This may be done by bringing daylight through light wells, skylights or through the ceiling, where plenum lighting is used, as in figure 69 .

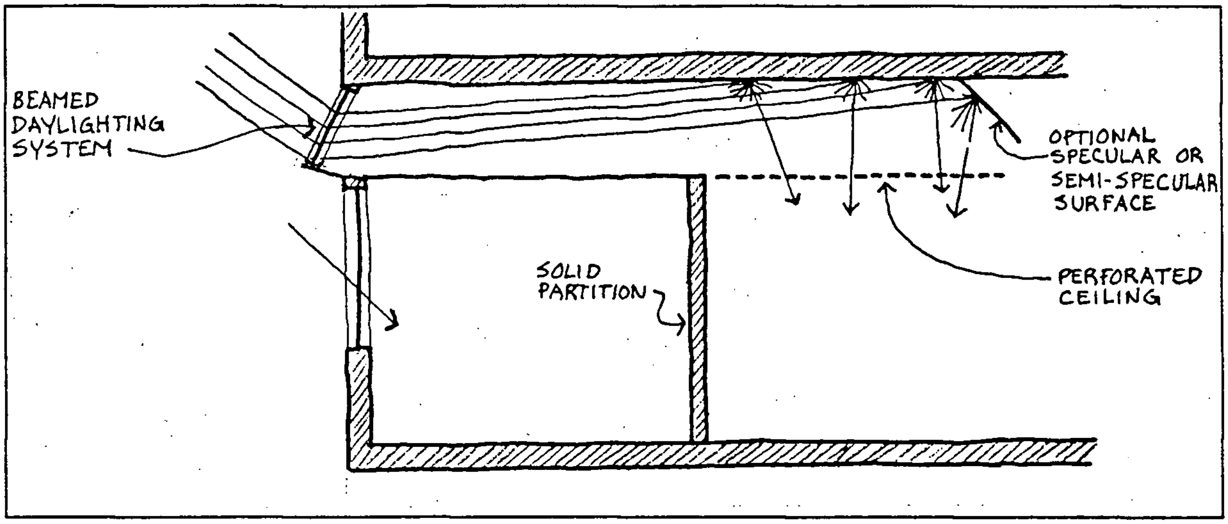

Figure 69 - A technique for indirectly daylighting interior areas obstructed from daylighting apertures by solid partitions

2.5 Daylighting And Acoustics

Both acoustical and daylighting solutions involve choices regarding interior building surfaces, interior geometry and compartmentation. As such, solutions to one can influence the effectiveness of the other. This section outlines how daylighting details may affect acoustics and vice versa and figure 70 provides a summary of typical details which integrate requirements of acoustics and daylighting.

Daylighting solutions affecting acoustics

The requirement for relatively large exterior glazing areas, for either daylighting or view, can adversely affect

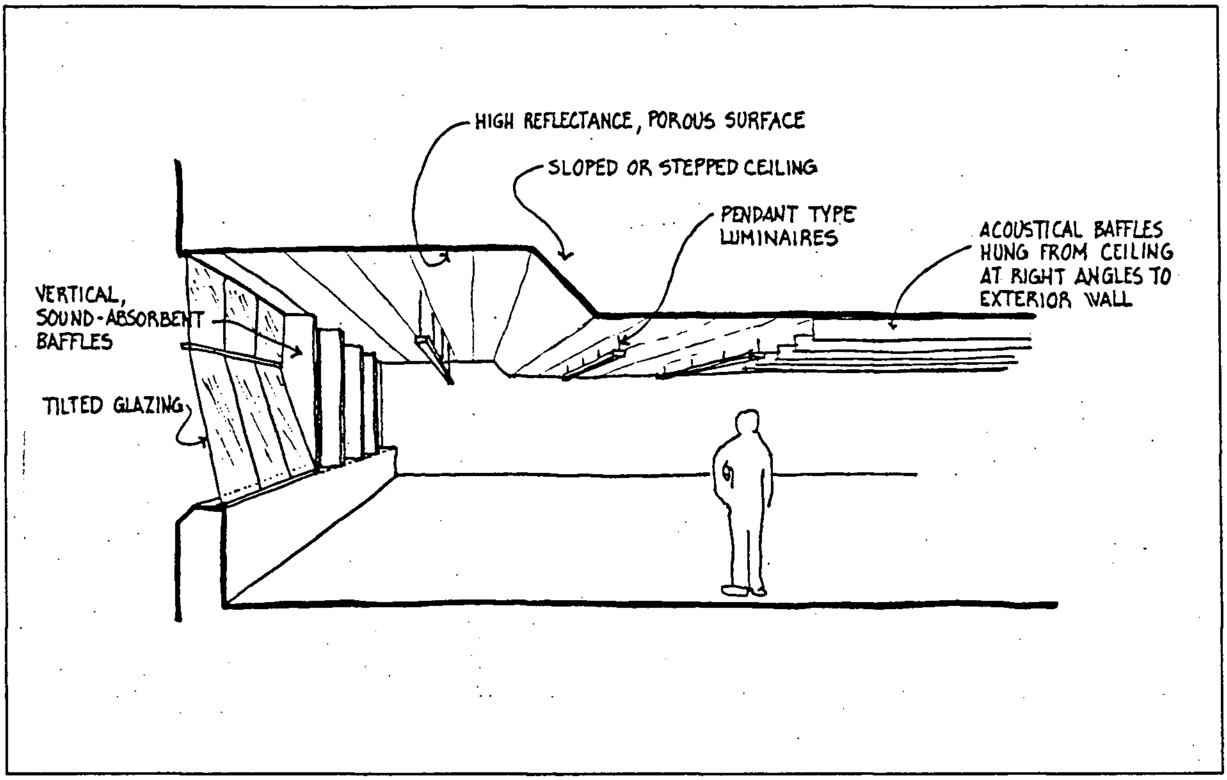

Figure 70 - Details that integrate acoustical and daylighting requirements

acoustical performance of office interiors. The glass acts as a sound-reflecting surface, which is undesirable in open plan offices. This may be resolved by tilting the glazing to deflect sound onto either the floor or the ceiling[25], or by the use of light-coloured, vertical sound-absorbent baffles, at right angles to the windows, to absorb some of the sound before it strikes the glass[26]. A fortuitous effect of both these solutions is a reduction in perceived glare from the window.

Another acoustical problem may arise when fully glazed partitions are used to enable daylight to penetrate beyond compartmented areas at the building perimeter. To reduce unwanted sound reflectance, semi-glazed partitions, or a combination of fully glazed and semi-glazed, acoustically absorbent partitions[27], may be used instead.

Daylighting solutions may also affect acoustics advantageously. Pendant type ceiling lamps[28], indirect lighting, and furniture mounted task lighting, leave the ceiling free of luminaires, thus eliminating the sound-reflective surfaces created by the lenses of recessed fluorescent fixtures, and improving acoustics in open plan offices. The stepped[29] or sloped ceilings[30] in some daylit buildings are also advantageous to acoustics, as they reduce multiple reflections of sound between the floor and ceiling.

Acoustical solutions affecting daylighting

A detail which may adversely affect daylighting is the use of a grid of vertical, sound-absorbent baffles, hung from the ceiling, to increase sound absorption in open plan offices. One solution which may not compromise daylighting involves the use of baffles having high light reflectance, arranged only in one direction, perpendicular to the exterior wall.

Some acoustical details may enhance daylighting. Soft, porous ceiling surfaces, for example, are ideal for acoustical absorption and these same surfaces, if of high light reflectance, are helpful in reducing glare[31].

3. NOTES

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2. James W. Griffith, "Benefits of Daylighting: Energy and Cost Savings," ASHRAE Journal 20, January 1978, p. 55.

3. Ernest Wotton, "Some Considerations Affecting the Inclusion of Windows in Office Facades," Lighting Design and Applications, February 1976, p. 34.

4. J. A. Lynes, Principles of Natural Lighting (Amsterdam: Elsevier, 1968), p. 48-50.

5. Eric Thrun and Robert Jennings, "Levels of Performance Related Illumination Available from Daylight in Typical Office School Interiors," Journal of IES, October 1981, p. 14.

6. Leu, pp. 119-20.

7. Wotton, p. 33.

8. David A. Harris et al., Planning and Desiging the Office Environment (Toronto: Van Nostrand Reinhold, 1981).

9. Benjamin H. Evans, Daylight in Architecture (New York: McGraw-Hill, 1981), p. 40.

10. Harris et al., p. xi.

11. Frank DeSerio, in Architectural Record, "Round Table: A Realistic Look at The Passive Approach--Using Natural Means to Conserve Energy," Architectural Record, Mid-August 1983, p. 98.

12. Manufacturers' Hanover Trust World Headquarters (SOM), after S. Daryanani, "Design Considerations for the Daylighting of New Commercial Buildings," Energy and Buildings, 6(1984):115, figure 10.

13. DeSerio, p. 98.

14. Frank Duffy et al., editors, Planning Office Space (London: Architectural Press, 1976), p. 43.

15. Ibid.

16. Christopher Alexander et al., A Pattern Language (New York: Oxford, 1977), pattern no. 146, "flexible Office Space", pp. 690-95.

17. Juergen Joedicke, Office Buildings (New York: Praeger, 1962), p. 21.

18. Architectural Record, "Partitions and Lights Work as a Modular Pair to Create Luminous Space," Architectural Record, April 1983, pp. 160-67.

19. Ibid., p. 160.

20. Ibid.

21. Marietta S. Millet, "Daylighting Design Guidelines for Pacific Northwest Buildings," Proceedings of 'Solar 79 Northwest' Conference, August 10-12, 1979 in Seattle. Seattle: Pacific Northwest Solar Energy Association, 1979, p. 53.

22. J. Longmore, "The Engineering of Daylight," in Developments in Lighting--Part 1, edited by J. A. Lynes (London: Applied Science, 1978), p. 178.

23. Alexander et al., pattern no. 194, "Interior Windows", pp. 897-99.

24. See for example, MacMillan Bloedel building, in Vancouver, B. C. and the CIGNA building (supra).

25. DeSerio, p. 98.

26. Harris et al., p. 57. Actually, these baffles would have to be larger, or closely spaced, to be effective acoustically--personal communication, Professor Charles Tiers, UBC School of Architecture.

27. As for example, in the CIGNA building, Architectural Record, supra, pp. 160-67.

28. As in the Water Resources Control Board building (Site 1-C), Sacramento, Calif. Harvey Bryan, slide presentation at the Daylighting Design Tools Workshop, The 1983 International Daylighting Conference, 16-18 February 1983 in Phoenix, Arizona .

29. As for example, in the Water Resources Control Board building, Sacramento, Calif. See Bryan, supra.

30. As for example, in the Ventura Coastal Corporation building,Ventura, Calif. See Architecture, "Ingeniously Daylit Seaside Offices," Architecture, January 1984,

pp. 64-67.

31. DeSerio, p. 98.

VI.

CONTROL OF BRIGHTNESS EXTREMES

1. INTRODUCTION

The control of brightness extremes in a building interior may be accomplished by two means:

i. increasing the brightness level of surfaces away from daylighting apertures

ii. decrease the perceived brightness of the daylighting aperture.

The methods used to accomplish these are different for traditional daylighting techniques and for innovative daylighting techniques.

i. In traditional techniques, the two brightness control strategies--increasing brightness of surfaces away from the daylighting apertures and decreasing perceived brightness of daylighting apertures--are conceived in isolation, and are designed to achieve either the one goal, or the other. Because of this, a reduction in glare at the daylighting aperture, achieved with traditional techniques, always entails a proportionate reduction in daylight penetration.

ii. By contrast, innovative daylighting techniques may accomplish simultaneously several goals: increasing daylight penetration, reducing perceived brightness of the daylighting aperture, increasing the brightness of surfaces remote from daylighting apertures.

Figure 71 illustrates examples of these two approaches.

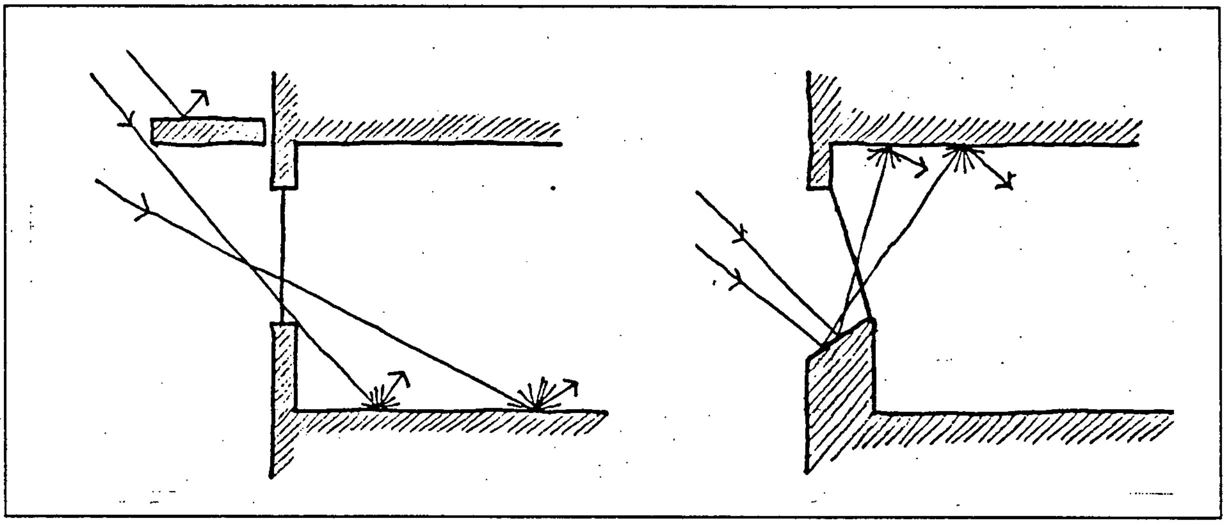

Figure 71 - Reducing brightness extremes using traditional and innovative daylighting techniques

Figure 71 a. shows a traditional response to control of brightness extremes. The sun/glare control device reduces the perceived brightness of the daylighting aperture, but inevitably also reduces daylight penetration to some extent, the amount depending on the configuration of the shading device. High reflectance values for interior surfaces tends somewhat to offset this loss by increasing the IRC. Design trade-offs are involved between these competing requirements. The innovative daylighting technique in figure 71 b. shows: the perceived brightness of the daylighting aperture is reduced by tilting of the glass to reduce the transmittance of light from higher angles; reflective surfaces away from view are used to bounce

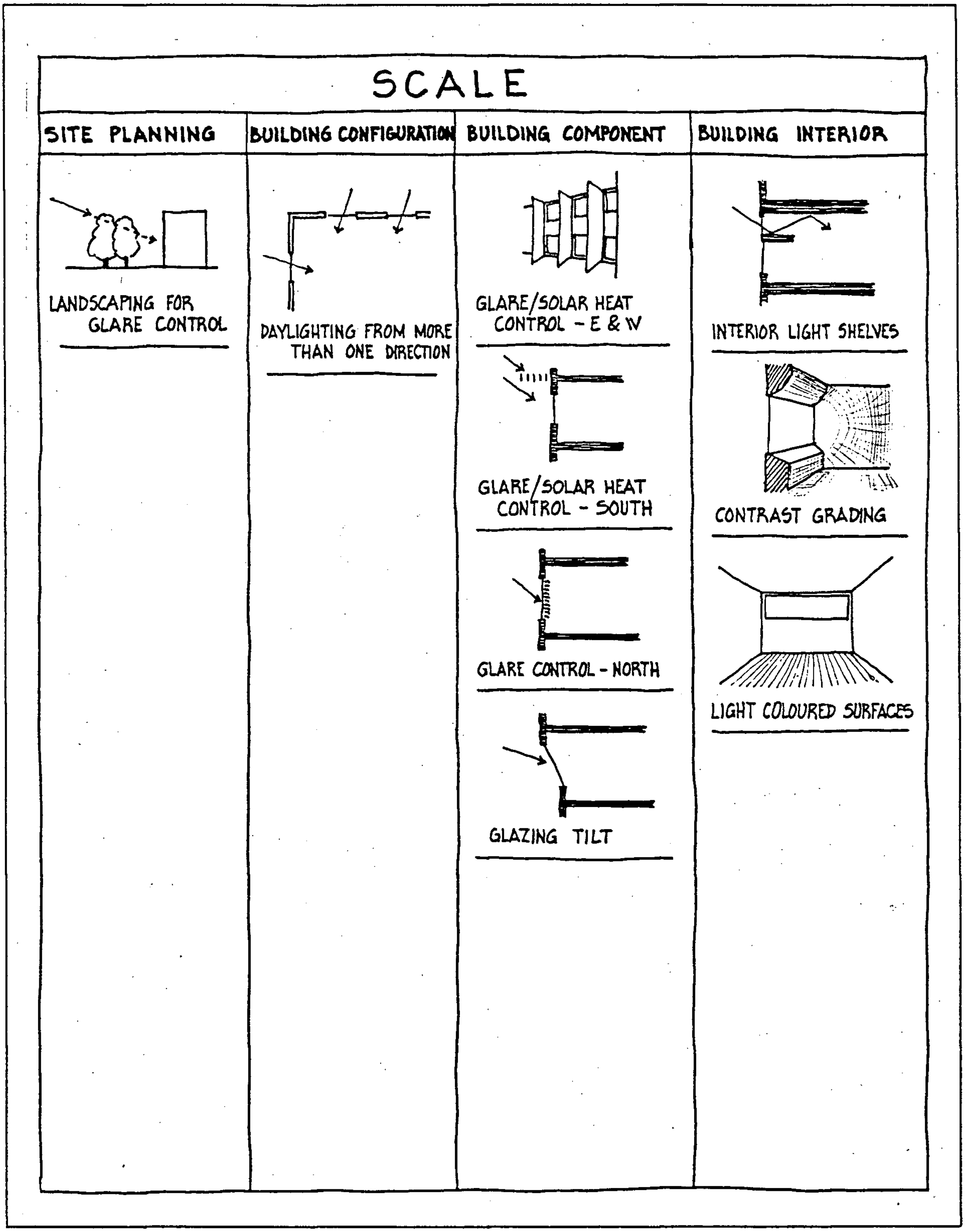

Figure 72 - Summary of techniques for controlling brightness extremes

sun/sky-light deeper into the interior, thereby enabling a smaller daylighting aperture for a given daylight penetration; the use of high reflectance ceiling to increase luminance of surfaces away from the daylighting aperture. The same characteristics of innovative daylighting techniques that enable them to distribute, rather than reject, excess sun/daylight, also provide the means of controlling brightness extremes.

2. TECHNIQUES FOR BRIGHTNESS CONTROL

Figure 72 gives a summary of the techniques examined in this chapter.

2.1 Landscaping For Glare Control

Landscaping--planting in particular--may be designed with a view to its architectural and engineering uses[1]; saving energy in buildings[2],[3]; providing a generally more comfortable thermal environment[4]; and with the aim of promoting daylight penetration and control of glare[5]. However, beyond the strictly functional, the use of plants in and around our buildings satisfies symbolic, aesthetic and emotional needs[6],[7]. This means that, more than any other aspect in the built environment, the use of plants cannot be considered solely from a narrowly functional viewpoint: the less tangible benefits must also be considered.

Part of the purpose of a daylit building is to establish a sensitive relationship between itself and its surroundings.

Plants, when used as elements of the daylighting scheme, naturally tend to strengthen that relationship, as well as the awareness of that relationship.

The control of glare from daylight and sunlight by the use of land forms, structures, or vegetation may be accomplished either by filtering or by reducing reflection.

Glare control by filtering

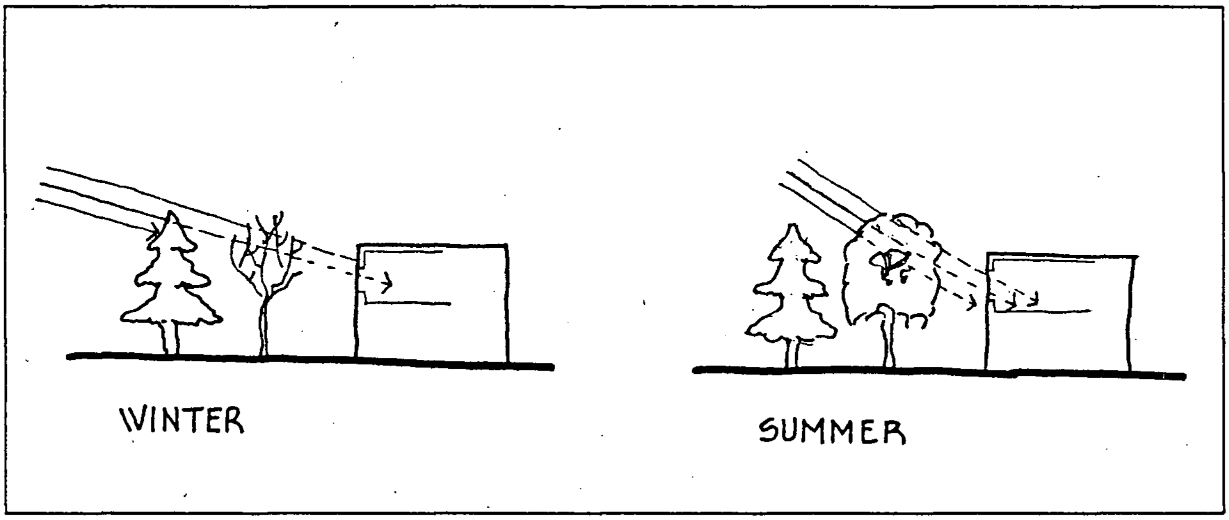

Figure 73 - Glare reduction by filtering during summer and winter

Trees may be used in low-rise office buildings, or on the lower floors of high-rise buildings, to control glare by filtering of sun/daylight. A problem arises with deciduous trees that, if they filter sufficient amount of light in the summer, then they will allow too much glare in the winter, when they are leafless. One solution is shown in figure 73 : the lower, winter sun is blocked by low conifers and the higher, summer sun by higher deciduous trees. The use of trees and shrubs on the west/east sides for heat and glare control is especially advantageous because the low angle sun can be blocked relatively easily by younger, or lower mature trees and by trees at varying distances from a building. By contrast, filtering of sunlight on south facades cannot be accomplished beyond the second or third floor, unless mature trees are already present on the site or other glare control devices are used for many years until newly planted trees mature. On the north side, the task is that of reducing sky glare and, since there is little problem with sun shading, the requirements are not as stringent as on the south side.

Trellises of climbing plants are appropriate for west walls, where they can be quite dense. One such solution is shown in figure 74 . On the south side trellises must be horizontal in order to keep the sun out; and therefore, both the trellis structure and the trimming of the plants may require additional maintenance on this facade. Plants climbing directly on building faces create a softened, "old country" appeal[8], but in office buildings--especially daylit ones, requiring constant view and unobstructed windows--they may present maintenance problems.

As material for glare control, plants of open, loose foliage are most useful; they filter the light, whereas denser plants obstruct it[9]. Table XIII [10] indicates light intensities found under mature stands of various trees.

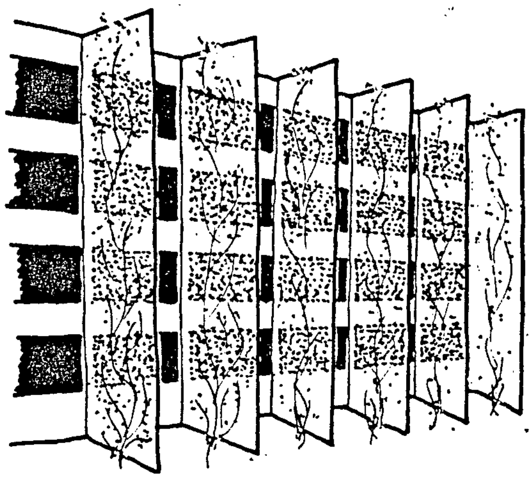

Figure 74 - Glare control at west or east walls with trellises

TYPE OF TREE (OLD STAND)		NO FOLIAGE	FOLIAGE
DECIDUOUS	RED BEECH	23-66	2-40
	OAK	43-69	3-35
	ASH	39-80	8-60
	BIRCH		20-30
EVERGREEN	SILVER FIR		2-20
	SPRUCE		4-40
	PINE		22-40

Table XIII - Light intensities (% of that outside) under mature stands of various trees

Glare control by reflection

As is the case with other light sources, the ground as a secondary light source may require brightness control[11]. Potential glare problems may be reduced by studying the angular relationship between the occupant, the window and the reflective surfaces (specular and non-specular), and in locating these surfaces out of direct line of sight as much as possible.

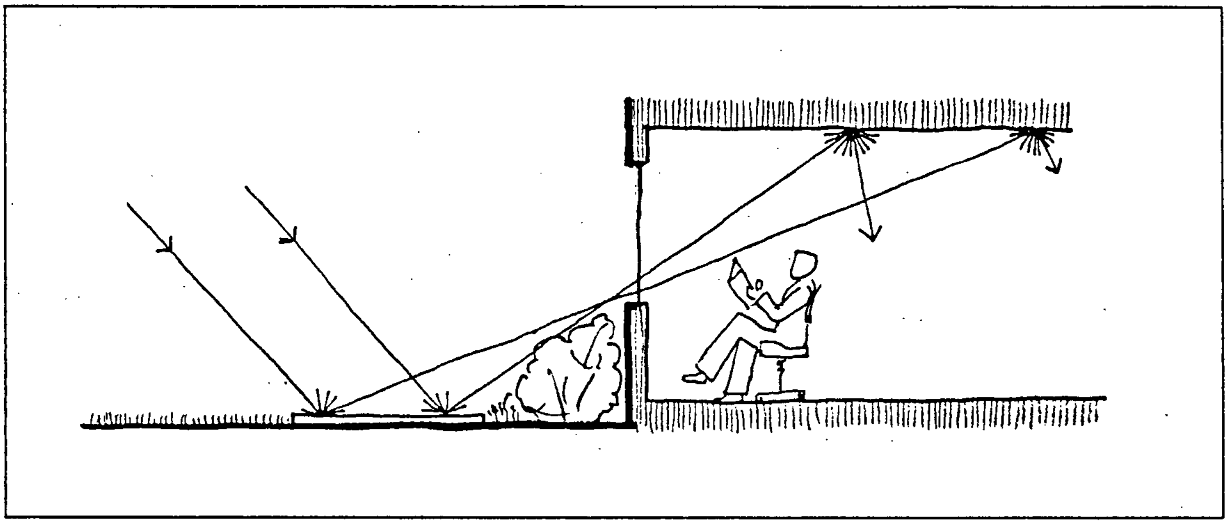

Figure 75 - Optimum positioning of planting and of the exterior reflecting surface

Figure 75 shows that generally, for locations at or near the ground floor, reflective sources closer to the fenestration (i.e. seen from workstations at a steeper angle below the horizontal) are less likely to cause glare than sources far away. There is a range of angles from the horizontal (between 15° and 45°) that causes least glare and still assists with daylight penetration. The use of specularly reflective surfaces must be studied carefully since these may cause glare and/or solar heat gain at certain sun angles[12]. Surfaces which are non-specular reflectors are preferrable, since they make luminous and thermal control easier. It can also be seen in figure 75 that it is better, from the point of view of summer heat gain, to locate asphalt driveways, or concrete surfaces some distance away from the building. Instead, low growing plants and shrubs should be used immediately adjacent to it, since they do not heat up as high density, man-made materials do.

The reduction of ground-reflected glare can also be accomplished by trees. To this end, dark plants with a smaller leaf surface, are most effective in reducing reflection[13].

2.2 Daylight From More Than One Direction

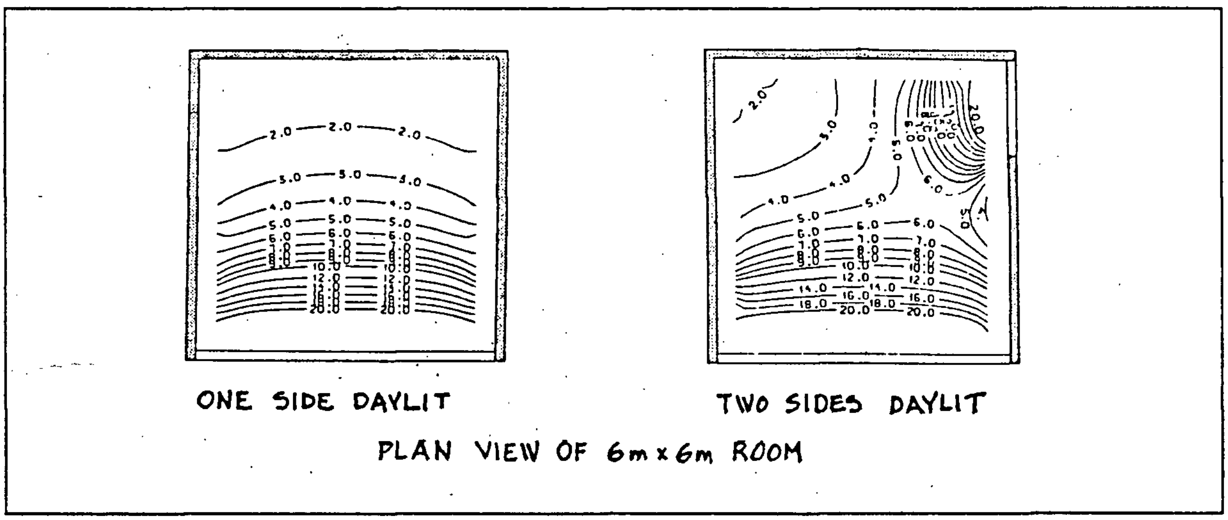

Figure 76 - Daylighting apertures on more than one side reduces brightness gradients

The provision of daylighting apertures on more than one side of a space reduces brightness extremes, improves modelling and raises illuminance. Whenever the configuration of the building allows, it is therefore advantageous to provide daylight from more than one direction. In practice, however, unilateral lighting will prevail for office buildings due to economic and organizational forces that require deep office space. In the latter type of spaces, any techniques used to increase illuminance levels by secondary daylighting apertures (such as atria, lightwells, skylights, etc.) will serve to balance the interior brightness.

Even relatively small daylight apertures in walls adjacent to the main source of daylight can provide a softening of the harsh modelling of unidirectional light[14], and by reflecting light back onto the interior surface of the window wall, can lessen the contrast between the window and its surrounds[15]. Windows from two opposite sides will also reduce glare, but the lighting quality is somewhat poorer because of cross shading[16] (figure 76).

2.3 Glare And Solar Heat Control -- East And West

There are three design responses to the conflict between sun-shading and daylighting on the east and west orientations:

i. a reduction in the size of windows, or their total elimination on these elevations

ii. the incorporation, in plan, of zig-zag east and west exterior walls, with the openings in these facing south and/or north

iii. provision of shading and glare control devices for east and west facing daylighting apertures

In situations in which considerations other than daylighting require windows facing east or west, the following responses for glare/shading control are appropriate for daylit buildings:

i. Use reflective or heat absorbing glass in specific locations to reduce glare and solar heat gain without undermining daylighting. The prevalent way of using these glasses uniformly in all windows of a building, impairs daylight penetration since these glazings substantially reduce the amount of light transmitted to the interior for a given window area[17].

Reflective or heat absorbing glass may, however, be utilized without penalty in terms of daylighting in two instances. First, in designs which utilize separate apertures for daylighting and view, the view window can have tinted glass for glare and solar heat control. Many daylit buildings employ this solution[18]. A second type of glare/shading control utilizes heat absorbing glass as a sun shade, as shown in figure 77 . The heat absorbing glass is held in a frame above and in front of clear glass windows, allowing a free circulation of air between it and the window, dissipating the heat gain. Depending on the relative location of the shade with respect to the window, this concept may be used on the east/west or southeast/southwest facades. In figure 77 (left)[19], this accessory is used together with slatted horizontal, opaque shading slats (a configuration that will serve south,

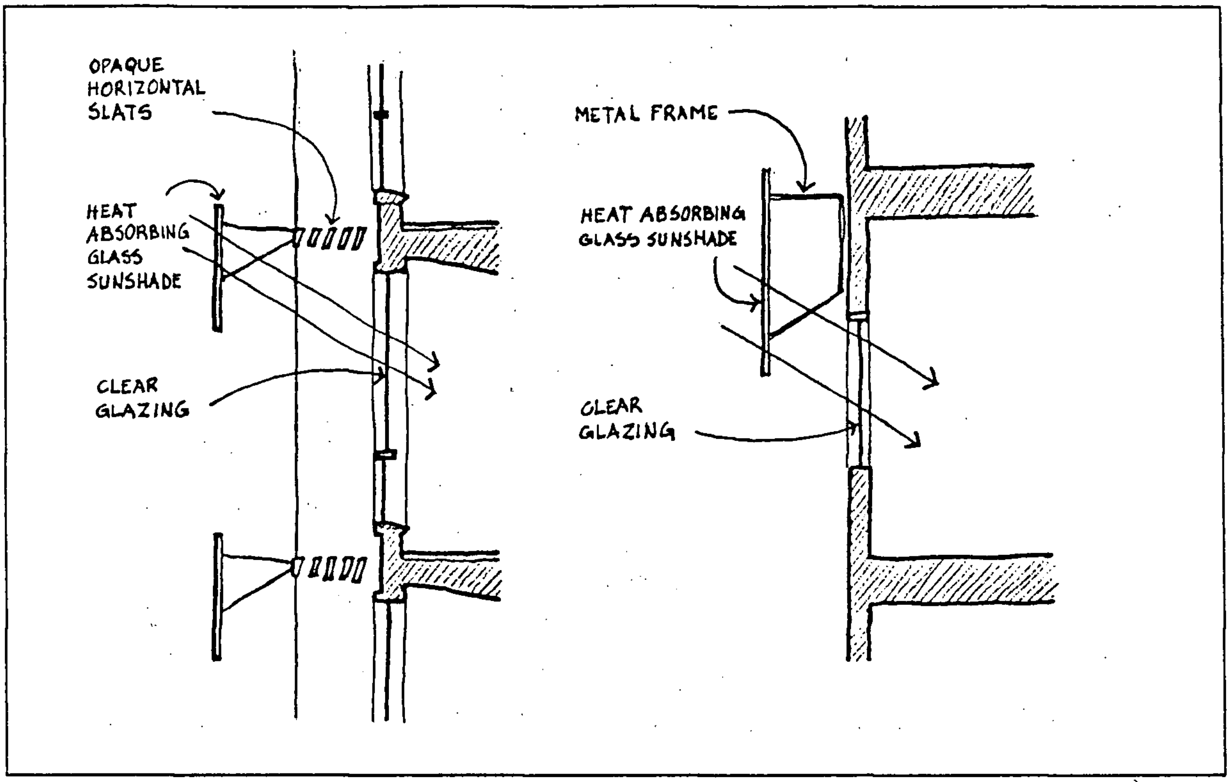

Figure 77 - Heat absorbing glass as a sunshade

southeast and southwest orientations). Figure 77 (right)[20] shows a shade designed for east and west orientations. Here, the glass shade is utilized alone, without the slats.

ii. Use opaque, fixed, vertical projections suitably proportioned to screen the sun out at the low angles encountered on east and west facades. According to Walsh[21] and Millet et al.[22], different configurations of shading devices having the same thermal performance (i.e. derived from the same shading mask[23], and therefore equally effective in blocking out the sun), do not necessarily have the same luminous efficacy. Millet et al. have studied the luminous effectiveness of the vertical sun control devices shown in figure 78 [24]. All four devices shown are of equivalent thermal effectiveness. Figure 78 shows the results of experiments on both sunny and overcast days. Under both conditions, the multiple solid vertical louvres offered the highest luminous performance.

For isolated windows on the east or west facades, as shown in figure 79 [25], a return wall some distance from the window can provide screening from unwanted sunlight, without seriously affecting daylighting.

iii. Vertical, operable louvres avoid some of the drawbacks of fixed sun control devices, since their orientation may be adjusted to maximize solar shading at some hours of the day, while at other times they may be set to maximize daylighting. Figure 80 [26] shows such an installation.

Like all shading devices, operable louvres are most effective thermally when they are located on the building exterior. However, interior vertical blinds may also be used: they are less effective in blocking solar heat, but serve well in reducing glare from sun and sky. They require less mechanical maintenance, have much lower initial cost and, since they are available in a wide range of colours and textures, they can also contribute to the interior decoration concept. Vertical interior blinds retract as well as pivot, thus providing a clear view. By contradistinction, exterior louvres of the vertical type can usually only pivot, without retracting.

A combination of fixed architectural projections for sun

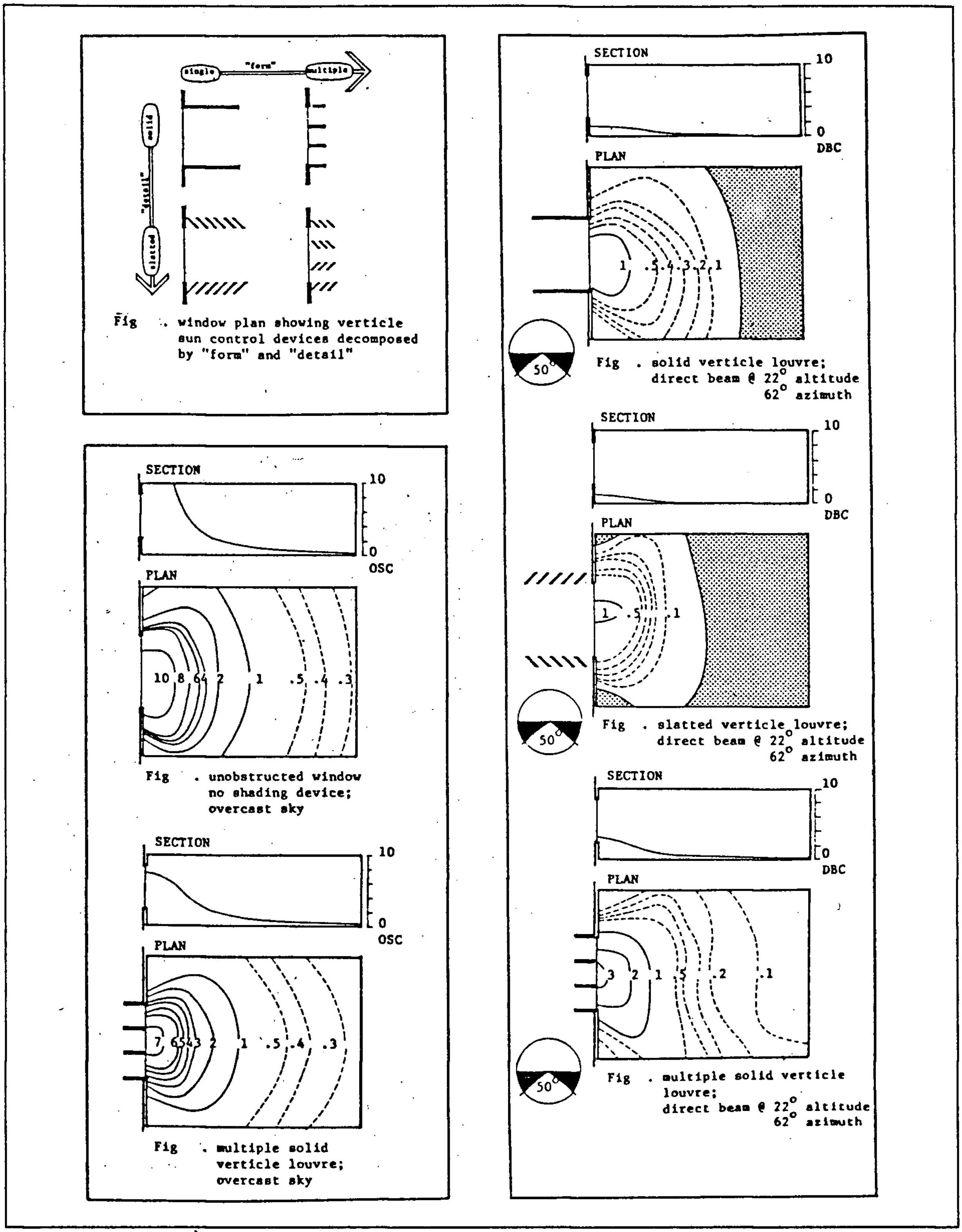

Figure 78 - Luminous performance of various vertical shading devices having equivalent thermal performance

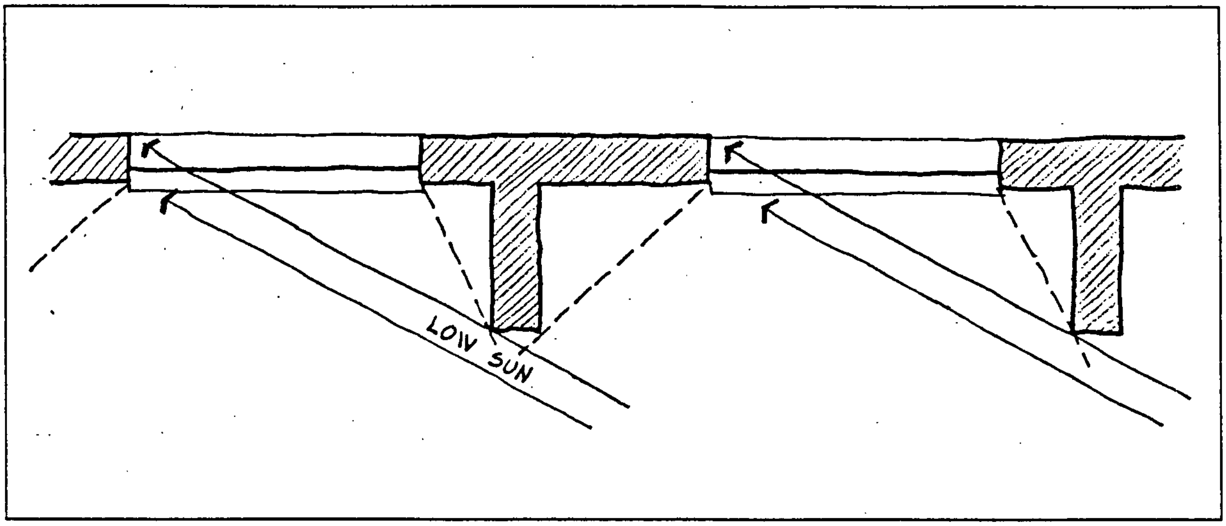

Figure 79 - Return walls on east or west facades can provide sunscreening while allowing daylight in

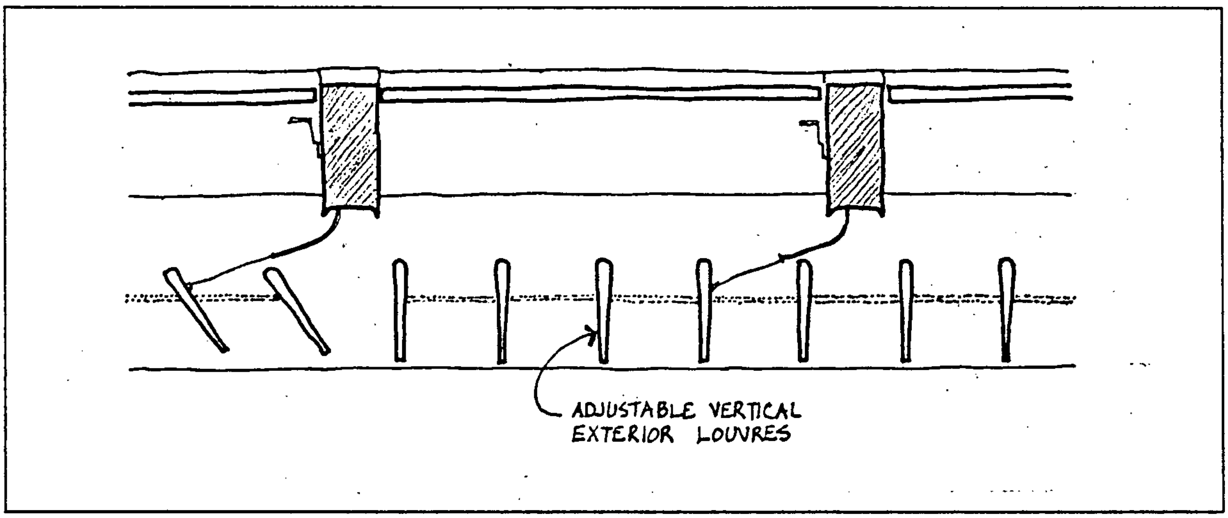

Figure 80 - Example of vertical adjustable louvres on west facade

shading and interior vertical blinds--vertical or horizontal--for additional glare control may be an economically appropriate response.

iv. Where building facades orient towards southeast and southwest, neither vertical, nor horizontal shading devices alone can provide sufficient solar shading. Eggcrate type louvres (a combination of vertical and horizontal shading elements) are appropriate in these cases. Evans has given an example of this solution, used in a speculative high rise office building in Southwestern U.S.A. As shown in figure 81 [27], eggcrate-type louvres between the glazing screen out direct sun, but reflect daylight into the space, simultaneously blocking the view of a bright sky. The lower, view window, utilizes reflective glazing to reduce the brightness of the exterior.

v. Horizontal blinds or louvres may also be used on east and west facing windows. They can be manually--and preferably automatically--closed to block direct sun when this can penetrate into the work space. The Hooker Chemical Building in Niagara Falls, N.Y., is an example of this response: all four elevations have horizontal louvres that are controlled by sensors independently on each facade[28]. While these louvres do not retract, they do respond to the different luminous and thermal conditions at each facade. Venetian-type blinds, that retract as well as pivot, are other examples of horizontal glare/sun control devices. These may be on the exterior or interior and be either of the manual or the automatic type. The use of fabric shades--the Gregory Bateson building in Sacramento, California, is an example of this--is also an appropriate

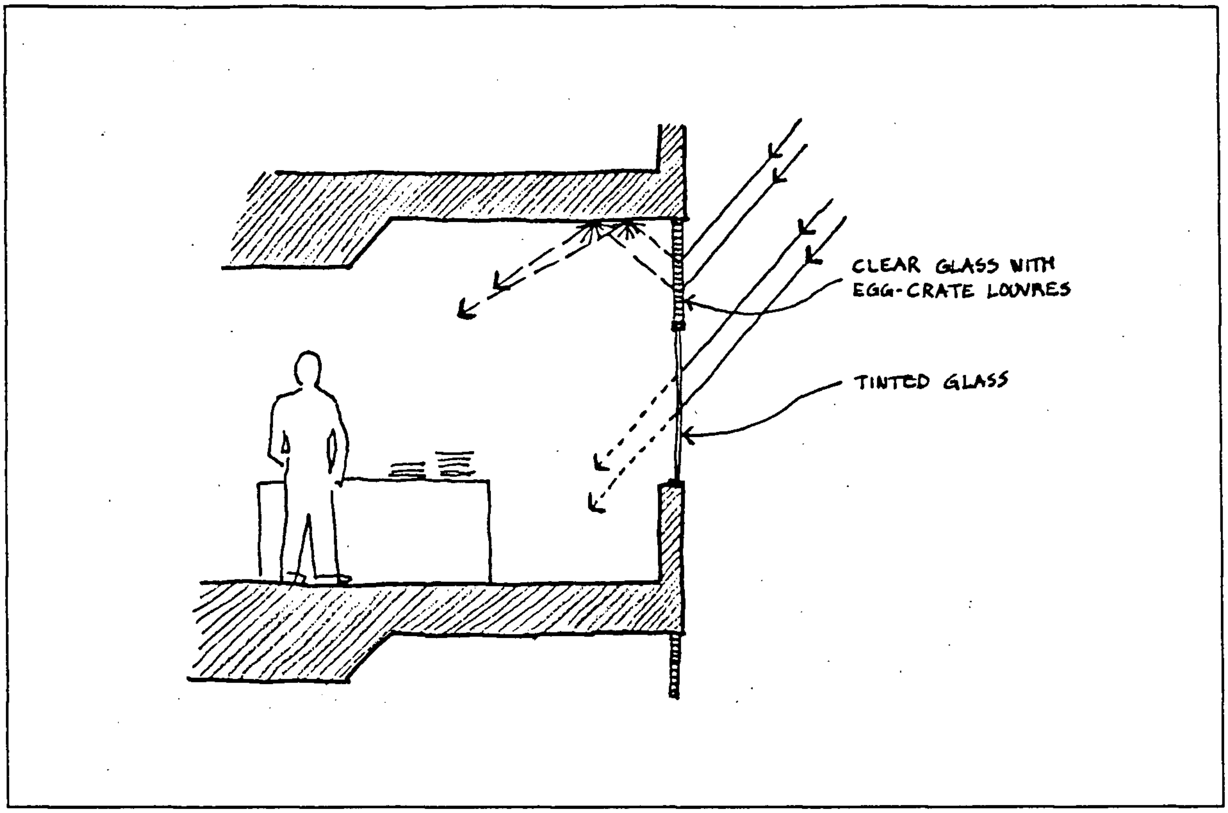

Figure 81 - Eggcrate louvres being used on southeast facing windows

response for various orientations, including the east and west[29].

One advantage of automatic horizontal devices is their ability to close over the daylighting aperture, thereby reducing heat loss when daylight is unavailable. A disadvantage in their use on east or west facing apertures is that, since they must cover most or all of the aperture when the sun is in offending position, they will restrict, and in some cases eliminate, the availability of daylight at these times.

2.4 Glare And Solar Heat Control -- South

Solar shading of south facing daylighting apertures is a relatively simple matter, when compared to the intricacies of simultaneous solar shading and daylighting on east and west facing apertures. Although the configurations for shading/glare control devices on south facing apertures are different from those facing east/west, the categories of responses are the same as outlined in the previous section:

i. Use heat absorbing or reflective glass in specific locations to reduce glare and solar heat gain without impairing daylighting. These glasses are only appropriate--as mentioned in the previous section--when used in windows which serve only for view (in designs where daylighting is provided by other apertures) and when they are used as sunshades in front of daylighting apertures.

ii. Use opaque, fixed, horizontal projections configured to block unwanted solar penetration through the daylighting aperture. As noted previously, solar shading devices having identical thermal performance but different configuration, will differ in their luminous performance. Millet et al.[30] have studied the effect of the horizontal sun control devices shown in figure 82 . The three devices tested are of equivalent thermal effectiveness but of very different luminous performance. The multiple solid vertical louvres offered the best luminous performance[31]. Walsh[32] also suggests this "tiered

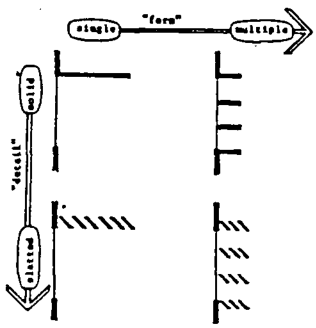

Fig 3A. wall section showing horizontal sun control devices decomposed by "form" and "detail"

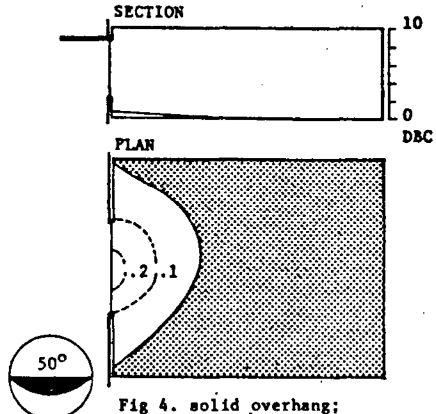

Fig 4. solid overhang; direct beam @ 50° altitude 4° azimuth

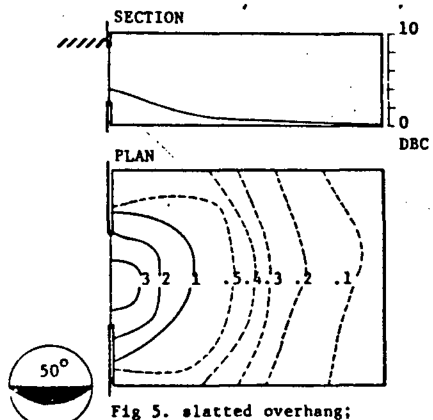

Fig 5. slatted overhang; direct beam @ 50° altitude 4° azimuth

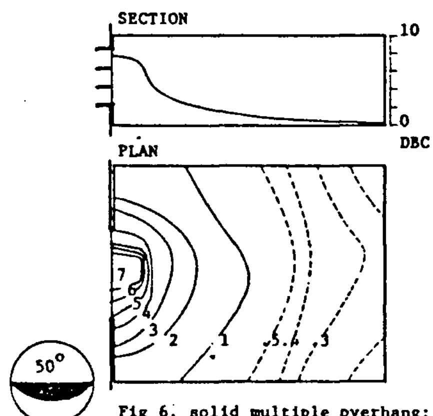

Fig 6. solid multiple overhang; direct beam @ 50° altitude 4° azimuth

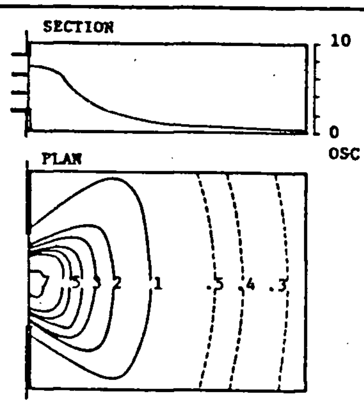

Fig 10. multiple solid overhang; overcast sky

Figure 82 - Luminous performance of various horizontal shading devices having equivalent thermal performance

sunbreak" as a solution to the sun shading/daylighting conflict--especially for tall windows, for which a single, large overhang, high above the opening is not feasible. Of two shading devices having identical thermal performance, the one higher above the window head has greater luminous effectiveness (i.e. allows in more daylight). Its projection from the building must, however, be correspondingly greater and thus a trade-off is involved between the cost due to the extra depth of the shading device and savings due to daylighting[33].

iii. Horizontal operable louvres, blinds and shades avoid some of the drawbacks of fixed sun control devices, since they can, if properly controlled, maximize solar shading when needed and maximize daylighting at other times. Horizontal louvres on south facades can potentially provide glare/solar heat gain control at all sun angles and simultaneously provide daylighting. If the operating mechanism is automatic, then such devices can predictably provide energy savings.

iv. Automatic, sensor activated fabric shades--on the exterior or interior--are another solution to the glare/solar heat gain problem encountered at south facing daylighting apertures. Fabrics come in many colours, providing an opportunity for colour highlights on elevations[34]. Fabrics also come in several densities, providing a choice of shading coefficient most appropriate for the particular building and orientation. Even when drawn, fabric shades, especially the less dense weaves, can provide some view outside and limited daylight penetration[35].

2.5 Glare Control -- North

Glare control on north elevations can be more easily accomplished than for other orientations because solar control is not necessary. Thus the luminous conditions on the north side are relatively static, with luminance distribution of both the clear and the overcast sky relatively constant, only absolute luminance being changeable. Because of this, the amount of potential glare can be readily predicted and simple design responses, that reduce sky luminance to acceptable levels, can be developed. Light curtains, loose weave interior fabric shades (of appropriate light transmittance) or interior venetian blinds, can be utilized as simple solutions to the glare problem at this orientation.

2.6 Glazing Tilt

Requirements for sun shading and glare control on the south elevations, and to a lesser extent on the east and west as well, may be resolved by increasing the angle of incidence[36] of the sunlight on the glazing at a given time, i.e. by tilting the glass downward. A downward tilt for the glazing reduces solar heat gain without obstructing view out and automatically reduces glare by allowing less daylight in, primarily because of increased reflection at greater angles of incidence. Figure 83

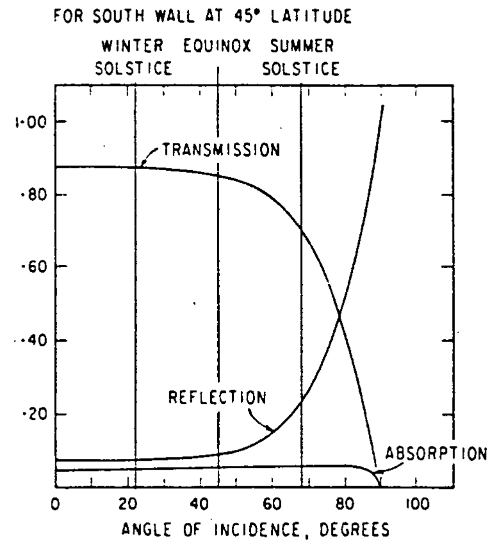

Figure 83 - Reflectance values through glass at various angles of incidence

a.[37] shows the relatioship between reflectance and angle of incidence. It can be seen that reflectance values rise sharply above incident angles of 57 degrees[38].

Solar heat gain and glare are further reduced, because the outward projection of the tilt reduces the area of glass exposed to the sun. The geometry is equivalent to a comparable vertical overhang shading vertical glass[39]. Figure 84 shows a typical solution to solar shading involving tilted fenestration. The energy falling on this window is the same as if the window were vertical and had a 1'-4" projecting shade along the lintel[40]. The energy transmitted is, however, less than for the comparable vertical window with overhang, because of the glass tilt which reduces transmission by a further 22%[41].

Since the trajectory of the sun in winter is lower, the angle of incidence of sunlight is lower and the effectiveness of tilt as a shading device in winter is much reduced. In the morning and late afternoon the resulting solar heat gain may be acceptable in office workspaces, but at other times of the day, additional shading mechanisms, such as architectural projections or adjustable devices, will need to be used. Figure 85 [42] shows a solution using a combination of tilted glass and overhang.

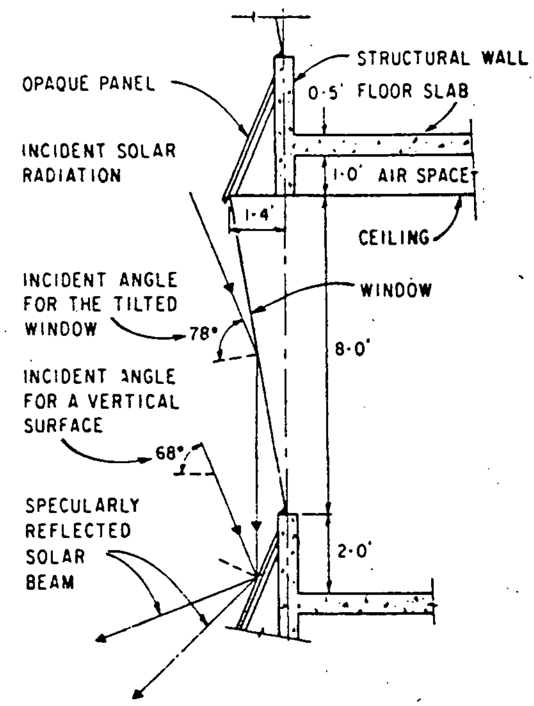

Figure 84 - Tilted glazing as means of glare and solar heat gain control

The effectiveness of a given tilt also diminishes with

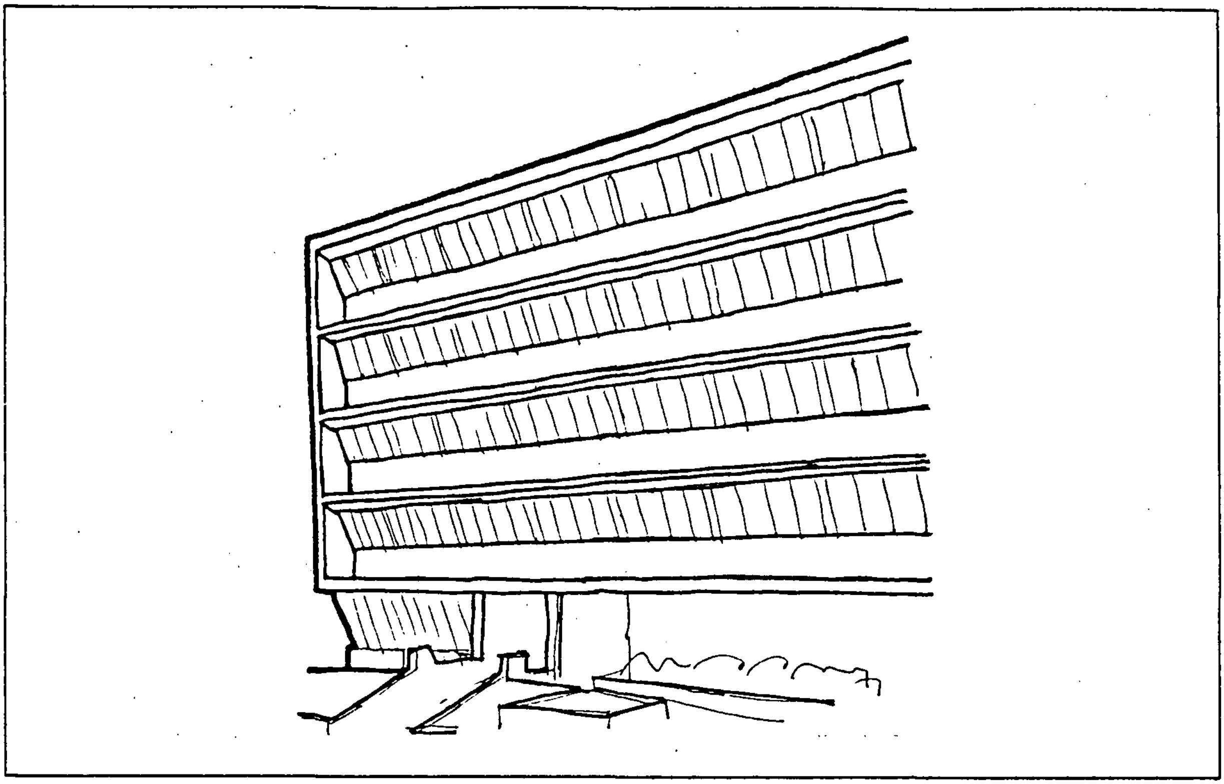

Figure 85 - A building facade with sloped glass and overhang

increasing latitude and thus more tilt will need to be provided at say, Vancouver, B.C. than in San Francisco, California, for a given percentage of solar heat reflection at the same time of year and day.

In a similar manner, lower sun angles on east and west facades means that window tilt at the east and west orientations, as a primary shading mechanism at Canadian latitudes is not feasible because of the excessive tilt required to exclude the sun during overheated periods. As can be seen in figure 86 , window tilt can be incorporated either at the massing scale--whereby the whole of the envelope tilts inward, or at the element scale--in which the window tilts in an essentially vertical wall.

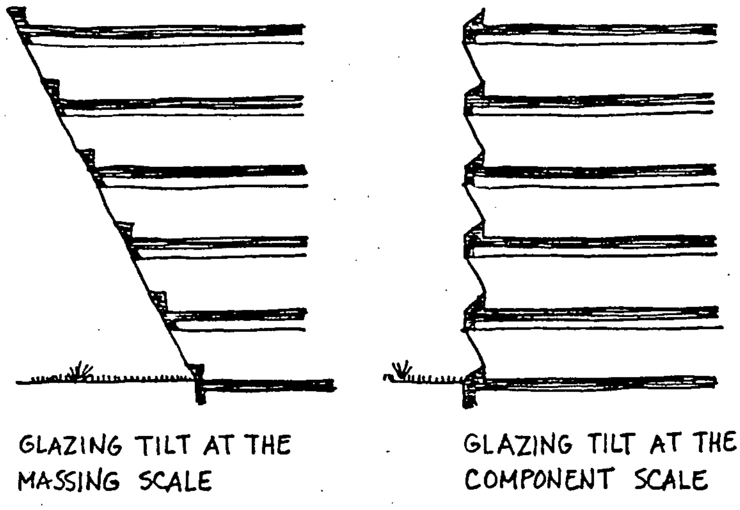

Figure 86 - Incorporating window tilt at massing or component scale

Window tilt adversely affects daylight penetration. In some innovative daylighting solutions, this has been recognized and reflective window sills (and in some instances, window heads as well), have been incorporated to reflect diffuse daylight through tilted windows[43]. However, in traditional daylighting schemes, the trade-off between control of glare and daylight penetration must be recognized, and and the appropriate balance between them analytically and/or experimentally established.

A fortuitous advantage of tilted fenestration is that it helps the acoustics within open space interiors, by deflecting sound onto sound-absorbent ceilings[44]. Where windows use tinted glass and are for view only, such as the lower glazing in the Lockheed Building no.157--the glass is, in fact, tilted primarily for acoustical reasons[45].

Like other shading/glare reduction devices, tilted glazing has aesthetic and functional advantages and disadvantages[46] that must be studied on a project by project basis.

2.7 Interior Lightshelves

The primary function of interior lightshelves (with or without exterior lightshelves) is to modulate brightness gradients and improve illuminance levels within a room. Secondarily, they can also act as an integrating element for environmental services, alter the spatial characteristics of the area below them and assist in the visual organization of the window wall.

The effect of interior lightshelves on illuminance levels varies with sky condition. Selkowitz et al.[47], have shown that under clear sky conditions without direct sunlight, and under overcast conditions, their use results in illuminance levels lower than levels obtained through the bare window. The reductions are, however, greater near the window[48]. When direct sunlight is present, they perform as a shading device. In this case they will provide improved performance over the base opening[49,50].

The main benefit of interior lightshelves, is a reduction in perceived glare and in the brightness gradient across the room. Figure 87 shows the mechanism of glare reduction. The interior lightshelf reduces the area of sky visible to occupants

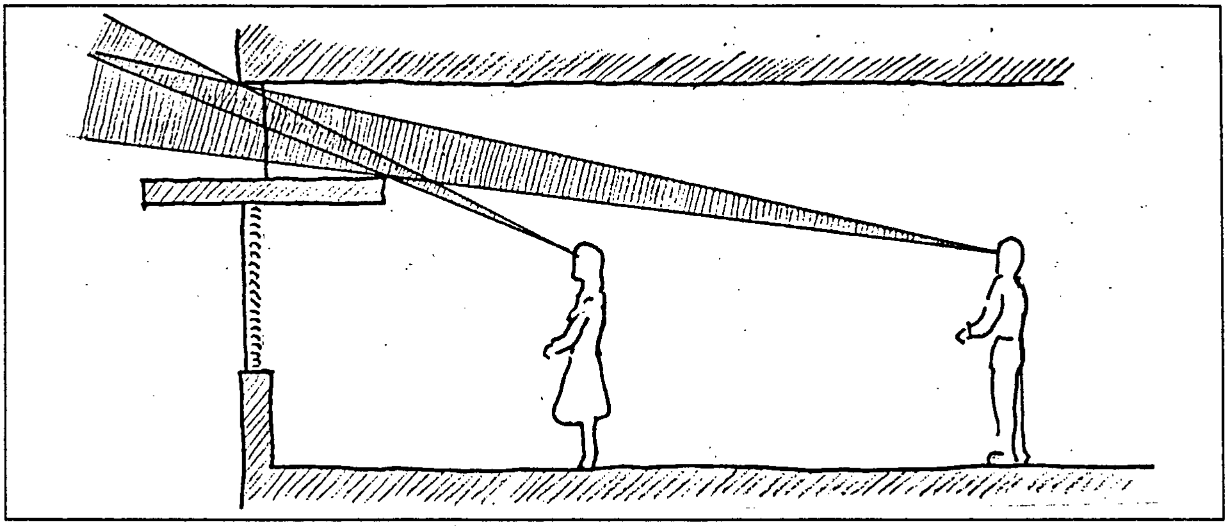

Figure 87 - The mechanism of glare reduction by an interior lightshelf

nearer to the daylighting aperture and this leads to a substantial reduction in direct glare. The loss in illuminance levels is not significant near the daylighting aperture. At points further away, the lightshelf screens out much less of the sky component and hence the reduction in illuminance is not pronounced[51]. However, the perceived brightness gradient across the space is reduced and as a result, the perception of glare is lessened even at the locations further removed from the daylighting aperture[52]. Whereas exterior lightshelves have been used primarily on southern exposures to "scoop" reflected sunlight into a space, interior lightshelves have been used alone on other elevations as well, primarily on north elevations. The Lockheed Missiles building shown in figure 88 , has exterior and interior lightshelves on the south side, as well as smaller lightshelves along the perimeter of the atrium[53]. The north side has interior lightshelves alone.

Interior lightshelves can serve the secondary roles of

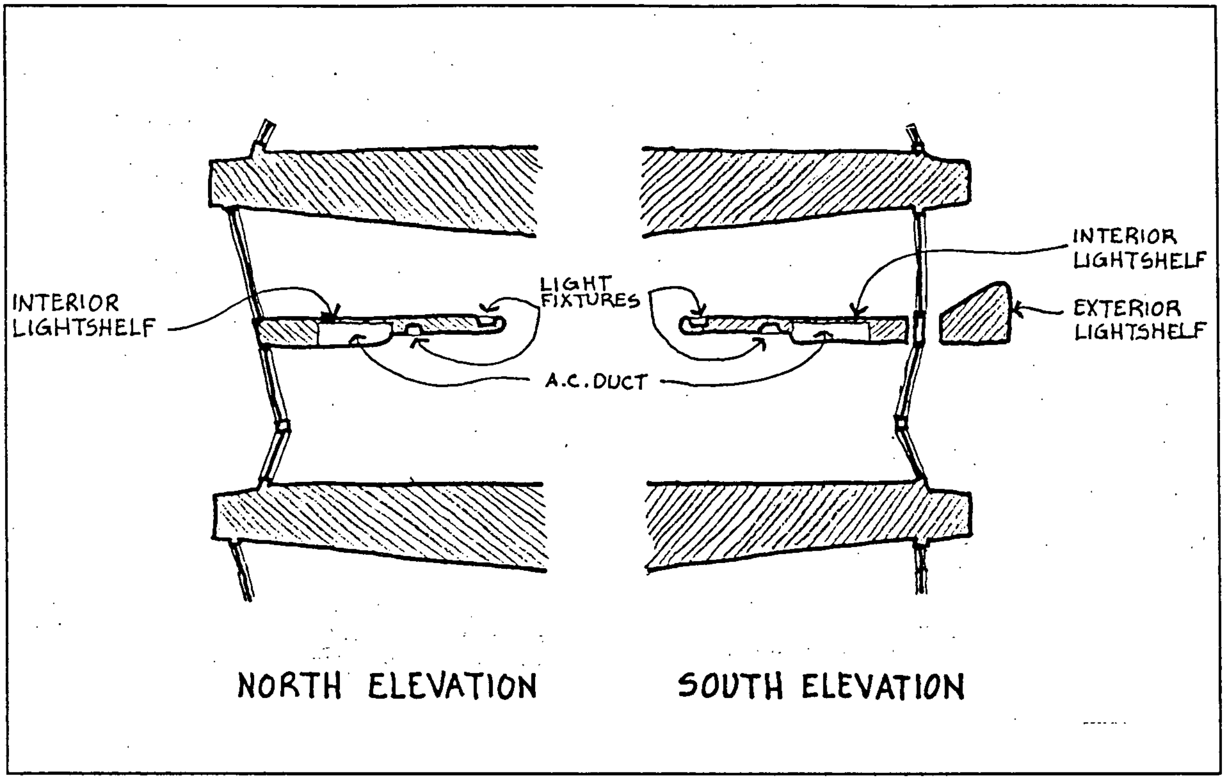

Figure 88 - Interior lightshelves in the Lockheed Missiles no. 157 building

containing equipment for other environmental needs. In the Lockheed building, for example, the scale of the building and of the lightshelf enables it to house electric lighting, HVAC ducts, sprinklers, photocells and sound masking speakers[54].

Interior lightshelves will alter the characteristics of the space under them and Lam considers their ability to impart an intimate scale to the perimeter area, an asset which can be readily utilized[55]. Activities such as small conferences, reading areas, etc. can be advantageously be located in this area, to benefit from the improved modelling and colour rendering available near the daylighting aperture, as well as from the scale of the space.

Interior lightshelves also assist in the visual organization of the window wall: they allow the establishment of a dominant horizontal line and facilitate different treatment for the upper and lower fenestration, a need arising from their different functions and location[56].

2.8 Contrast Grading

Contrast grading is the detailing of surfaces immediately surrounding daylighting apertures to reduce the brightness contrast between the two. The geometry and surface reflectance of the immediate surround are manipulated so that some of the luminous flux entering through the daylighting aperture strikes and is reflected from these surfaces, greatly increasing their luminosity.

This gradation in luminosity from the daylighting aperture, through the immediate surround, to the general surround, reduces the perception of glare. This is partly because of a reduction in harsh contrasts, but also because the adaptation level of the eye is raised. While the effect of the immediate surround on the perception of discomfort glare is complex[57], the following points have been established experimentally:

i. The larger the area of the immediate surround, the greater is its influence in the perception of glare. For daylighting apertures, the immediate surround may be deep, splayed jambs, about 300mm wide, with an optimum angle from the window plane of 50°-60° [58,59].

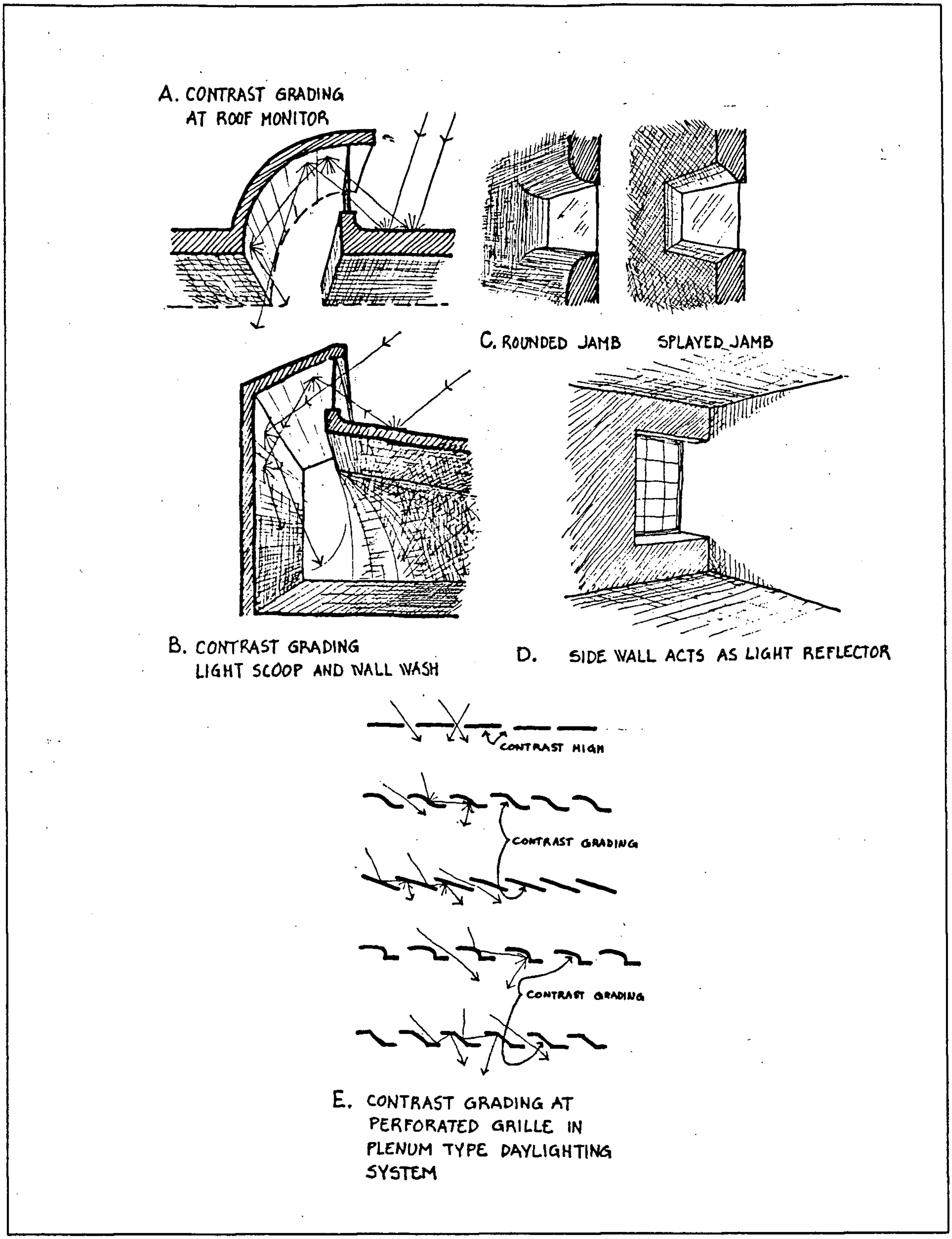

Figure 89 - Examples of contrast grading

ii. As the brightness of the immediate surround is increased beyond that of the general surround, glare is progressively reduced. The degree of improvement of the glare conditions is a function of the width of the surround, the brightness of the glare source and on the amount of glare that is considered acceptable for the occupancy.

iii. For sources of high brightness (above 5000 asb), the effect of contrast grading--raising the brightness of the surround--is uncertain[60].

iv. For sources of low brightness (less than 5000 asb), the effect of raising the brighthtness of the immediate surround is definitely beneficial in glare reduction; this is especially so if the surround has an area of about 4-10 times that of the source[61].

Figure 89 [62] shows practical examples of contrast grading: at windows, overhead daylighting apertures, and at perforated ceilings.

2.9 Light-coloured Surfaces

Light-coloured surfaces in interiors can assist in balancing brightness levels. This technique can be considered under two aspects: high reflectance and colour.

High reflectance

High reflectance of room surfaces near the daylighting apertures assist substantially in daylight penetration, raising illuminance within a space. Simultaneously, high reflectance room surfaces will assist in balancing the brightness across a room, by raising the luminosity of the surfaces being seen, and reducing the contrast between the daylighting aperture and these surfaces. This, in turn, raises the level of adaptation for the eyes, leading to reduction in the sensation of glare.

The following are general guidelines concerning this technique:

i. At all surfaces immediately adjacent to the daylighting aperture, a high reflectance, as well as appropriate detailing, will lead to successful contrast grading.

ii. At the window wall, a high reflectance will reduce the contrast between the daylighting aperture and the adjoining surfaces, thus reducing glare.

iii. Towards the back of the room, high reflectances are of considerable assistance in maintaining high brightness levels[63], and in reducing the impression of gloom that may occur if the brightness levels in this area fall substantially below the general level of adaptation of the eyes. In this regard, glazed partitions, while they allow light penetration beyond them, act as if they had reflectance approaching 0%, and therefore contribute little or nothing towards raising the level of brightness in their vicinity.

iv. The desirability of having surfaces of high reflectance is also applicable to carpeting, draperies and office furniture. While very high reflectances (over 80%) may tend to produce diffuse reflected glare and veiling reflections, reflectances in the mid to high range (40-80%), will provide good contrast grading between the task, the immediate surround, and the general surround[64]. High reflectance for the work plane and nearby furniture surfaces, will be a factor in raising the level of adaptation for the eyes and hence in reducing the potential for perceived glare.

MATERIAL (CLEAN)	REFLECTANCE	
POLISHED ALUMINUM	75 - 95%	(1)
POLISHED STAINLESS STEEL	60 - 80%	(1)
PLASTER (MATT WHITE)	70%	
DRYWALL (UNPAINTED)	60%	
WHITE PINE	61%	
POPLAR	47%	
CONCRETE (UNPAINTED)	45%	
YELLOW BRICK	35%	
RED OAK	32%	
DARK BRICK	23-48%	(1)
GALVANIZED STEEL (UNPAINTED)	16%	
SLATE, DARK CLAY	7+%	(1)

Table XIV - Reflectances of common building materials

Table XIV [65] and table XV [66] respectively, indicate reflectances of common building materials and reflectances of various colours used in interiors. Reflectances of colours may be determined by matching with a standard system ("Munsell colours"), and converting these to reflectivity values by using the mathematical relationship between the two[67], by using graphs[68] and tables[69] of this relationship, or by using colour samples of known reflectance[70].

COLOUR	REFLECTANCE	
WHITE	80 - 90%	(1)
PALE YELLOW OR ROSE	80%	(1)
PALE CREAM	76%	
PALE BLUE, GREEN	70 - 75%	(1)
DEEP CREAM	70%	
LEMON	69%	
LIGHT BUFF	61%	
GOLDEN YELLOW	60%	
ORANGE	42%	
MUSTARD YELLOW	35%	(1)
DEEP BUFF	31%	
LIGHT BATTLESHIP GRAY	31%	
SKY BLUE	30%	
TURQUISE BLUE	27%	
MEDIUM BROWN	25%	(1)
GRASS GREEN	18%	
DARK BATTLESHIP GRAY ...	11%	
CRIMSON	6%	
"BLACK"	<10%	(1)

Table XV - Reflectance values for typical colours

Colour

The "value"[71] dimension of colour--another term for reflectance--has been dealt with above. The two other dimensions of colour--"hue" and "chroma"[72]--can also be utilized to enhance the visual quality of daylit spaces.

The superior colour rendering of daylight is an important point in favour of its use. Whereas electrical light sources exagerate some colours and dull others[73], sometimes to a great degree[74], daylight can render the whole range of visible colours successfully. Colours under daylit conditions have a vibrancy and subtlety which cannot easily be simulated by electrical lighting. The following are some guidelines concerning the use of colour to enhance the daylighting scheme:

i. Use colours of high value and medium to low chroma as background colours.

ii. Use colours of high to medium value and high chroma as accent colours on trim, dadoes and on vertical surfaces located towards the back of daylit spaces. The relatively high vertical illuminance component at the back of side-lit rooms, will highlight these surfaces and help in overcoming the impression of gloom in the surrounding area.

iii. Colours and their various combinations ellicit distinct emotional and mental states. Therefore, colour combinations, especially in work areas, must be chosen with care, to maintain a pleasant and productive environment. Much has been written about this psychological effect of colours[75],[76]. This branch of colour science is vast and is beyond the scope of this work.

iv. The use of a well co-ordinated colour scheme can do much to enhance the daylighting concept. Light, lacy curtains, for example, of high value and medium chroma will filter daylight and provide a subtle and rich texture. Certain colour combinations create impressions of elegance and restrained good taste, as exemplified by the CIGNA Building, in Bloomfield, Connecticut[77].

v. In the visual environment, the dimension of colour, along with those of light intensity, distribution, directionality, etc. may be utilized to enhance the total Gestalt experience--to create positive foci and sparkle, provide orientation, etc.[78]

3. NOTES

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2. Gary O. Robinette and C. McLenon, eds, Landscape Planning for Energy Conservation (Reston, Virginia: Environmental Design, 1977), .

3. Donald Watson, Climatic Design (New York: McGraw-Hill Book Company, 1983), .

4. Robinette, pp. 95-101.

5. Benjamin H. Evans, Daylight in Architecture (New York: McGraw-Hill, 1981), p. 55.

6. Robinette, pp. 2;103-125.

7. Christopher Alexander, Sara Ishikawa, and Murray Silverstein, A Pattern Language (New York: Oxford, 1977), pp.794-821;1105-07;1132-37.

8. Ibid., pp. 1135-37.

9. Robinette, p. 71.

10. Ibid., p. 72.

11. IES Daylighting Committee, Recommended Practice of Daylighting (New York: Illuminating Engineering Society, 1962), p. 9.

12. Watson, p. 83.

13. Robinette, p. 72.

14. Alexander et al., pp. 746-51.

15. Marietta S. Millet, "Daylighting Design Guidelines for Pacific Northwest Buildings," Proceedings of 'Solar 79 Northwest' Conference, August 10-12, 1979 in Seattle. Seattle: Pacific Northwest Solar Energy Association, 1979, p. 52.

16. Walsh, J. W. T, The Science of Daylight (New York: Pitman, 1961), p. 90.

17. Evans, p. 23.

18. See, for example, the Shell Oil Co. Exploration and Production Offices, Houston, Texas, and the Lockheed Missiles #157 building, Sunnyvale, California.

19. Sunshades in UNESCO building, Paris, after Kurt Hoffman and Alex Pagenstecher , Buro-und Verwaltungsgebaude (Stuttgart: J. Hoffman, 1956), p. 126.

20. From a design for an industrial building, after Thomas A. Markus, Daylight with Insulation (St. Helens, Great Britain: Pilkington, 1960), p. 25. See also D. G. Stephenson, "Principles of Solar Shading," Division of Building Research, National Research Council of Canada, Canadian Building Digest 59, November 1964, p. 3.

21. Walsh, pp. 167-68.

22. Marietta S. Millet, Joel E. Lakin, and Jeffrey Moore, "Rainy Day Shading: The Effect of Shading Devices on Daylighting and Thermal Performance," Proceedings of the 6th National Passive Solar Conference, September 8-12, 1981 in Portland, Oregon, Newark, Delaware: American Section of the International Solar Energy Society, 1972, pp. 845-49.

23. For constructing solar shading masks, reference may be made to Baruch Givoni, Man, Climate and Architecture, 2nd edition (London: Applied Science, 1976,. and to Victor Olgyay, Design with Climate (Princeton, N.J.: Princeton University Press, 1964).

24. Millet et al., pp. 847-49.

25. After Walsh, p. 167.

26. Operable vertical louvres at the Olivetti building in Milan, Italy--after Hoffmann, p. 95.

27. After Evans, p. 83.

28. Jim Murphy, "Rainbow's End," Progressive Architecture,

April 1980, pp. 103-04.

29. Scott Matthews, "Proving the Benefits of Daylighting," Architectural Record, Mid-August, 1981, pp. 46-51. And Dave McNary, "Ship of State on a Solar Course," Solar Age, October, 1981, pp. 48-51.

30. Millet et al., pp. 845-49; and Millet, Daylighting Design Guidelines, p. 52.

31. Ibid., pp. 848-49.

32. Walsh, p. 167.

33. Ibid., p. 166.

34. For examples, see Mecho Shade and Helioscreen trade literature, and the Gregory Bateson building, Sacramento, Calif.

35. See, for example, Mecho Shade Corp. trade literature.

36. The angle of incidence is the angle formed between the light ray and a line perpendicular to the glass surface. Robert S. Hastings and Richard W. Crenshaw, Window Design Strategies to Conserve Energy (NBS Building Science Series 104, Washington D.C.: Department of Commerce, 1977), p. 3.23.

37. D. G. Stephenson, "Solar Heat Gain through Glass Walls," Division of Building Research, National Research Council of Canada, Canadian Building Digest 39, March 1963, pp. 2 and 3.

38. Hastings and Crenshaw, p. 3.24.

39. Ibid., p. 3.26.

40. Stephenson, CBD #39, p. 3.

41. Ibid., p. 2.

42. IES Daylighting Committee, Recommended Practice of Daylighting (New York: Illuminating Engineering Society, 1962), p. 4.

43. See Section 3.1.

44. Ernest Wotton, "Some Considerations Affecting the Inclusion of Windows in Office Facades," Lighting Design and Applications, February 1976, p. 39.

45. M. D. Shanus, "Deep Daylighting: Innovative and Lighting Concepts for a Large Office Building," 1982 IES Combined

Pacific Northwest and South Pacific Coastal Regional Conference,Santa Barbara, California, 1982, p. 9.

46. Some advantages not already mentioned are: a reduction of exposure to cold winter night sky; no window management required; less proneness to soiling by birds; protection of opened sash section from daylight penetration; increased sense of spaciousness due to greater ceiling area on each floor. Some disadvantages are: greater heat loss due to increased envelope area; reduced effectiveness of tilt as a glare control measure when ground surfaces have high reflectance; dust more prone to collecting on the inside surfaces of glass; washing tilted windows may be more difficult than washing vertical windows; stronger roll blinds or special venetian blinds may be required they are mounted off vertical; when window tilt is achieved at the massing scale, projection of the building outward may create a sense of dominance during the day (at night, with the glass appearing transparent, this effect will be minimal); some occupants may feel a sense of discomfort, due to a perception of insufficient protection, when tilted glazing reaches below the work plane. See Hastings and Crenshaw, pp. 3.27-3.32.

47. S. Selkowitz; S. Navvab; and S. Matthews, "Design and Performance of Light Shelves," Proceedings of the 1983 International Daylighting Conference, 16-18 February 1983 in Phoenix, Arizona. Washington, D. C.: 1983 International Daylighting Conference, 1983, p. 267.

48. Ibid.

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VII.

INTEGRATION OF DAYLIGHTING WITH ELECTRICAL LIGHTING

1. INTRODUCTION

The depth of most office spaces and the design illuminance level prevalent in today's office buildings, makes it impossible to satisfy illumination requirements throughout interiors solely with daylighting. Some electric lighting will need to be used during part of the work day in all zones; in interior zones, electric lighting may be used at all times. Therefore, a key element in the success of a daylighting scheme is the integration of daylighting with the electrical system--luminaire layout, lamps, ballasts and controls. This will result in reduced electrical lighting consumption, without adversely affecting the quality of space and user satisfaction[1,2].

Integration of electrical lighting with daylighting, can be understood as having three aspects:

i. decision on lighting philosophy--system, delivery method and light source

ii. fixture circuiting and layout

iii. selection of automatic controls

The daylighting concept and the electrical lighting concept influence one another and need therefore to be developed concurrently.

2. TECHNIQUES OF INTEGRATING DAYLIGHT AND ELECTRICAL LIGHT

Figure 90 lists the techniques for integrating daylight and electric light that will be examined in this chapter.

2.1 Lighting Design Philosophy

The electrical lighting philosophy must be compatible with daylighting. When designing office lighting, three basic issues must be considered:

i. concept (system type)--task/ambient or ambient

ii. delivery (type of fixtures)--direct or indirect

iii. source (kind of light source)--fluorescent or HID[3]

Figure 91 [4] shows these parameters arranged in a decision tree format, which allows for progressively more specific decisions in the design of lighting--and this, prior to selection of hardware or detailed architectural considerations[5].

Table XVI [6] summarizes the characteristics of each System concept, Delivery method and Source type. It is beyond the scope of this thesis to describe the process of electrical lighting selection for offices. Only the connection between daylighting and the electrical lighting concept will be highlighted.

System concept: task/ambient versus ambient

The resurgence of daylighting has been brought about primarily by the need to reduce electrical energy used in

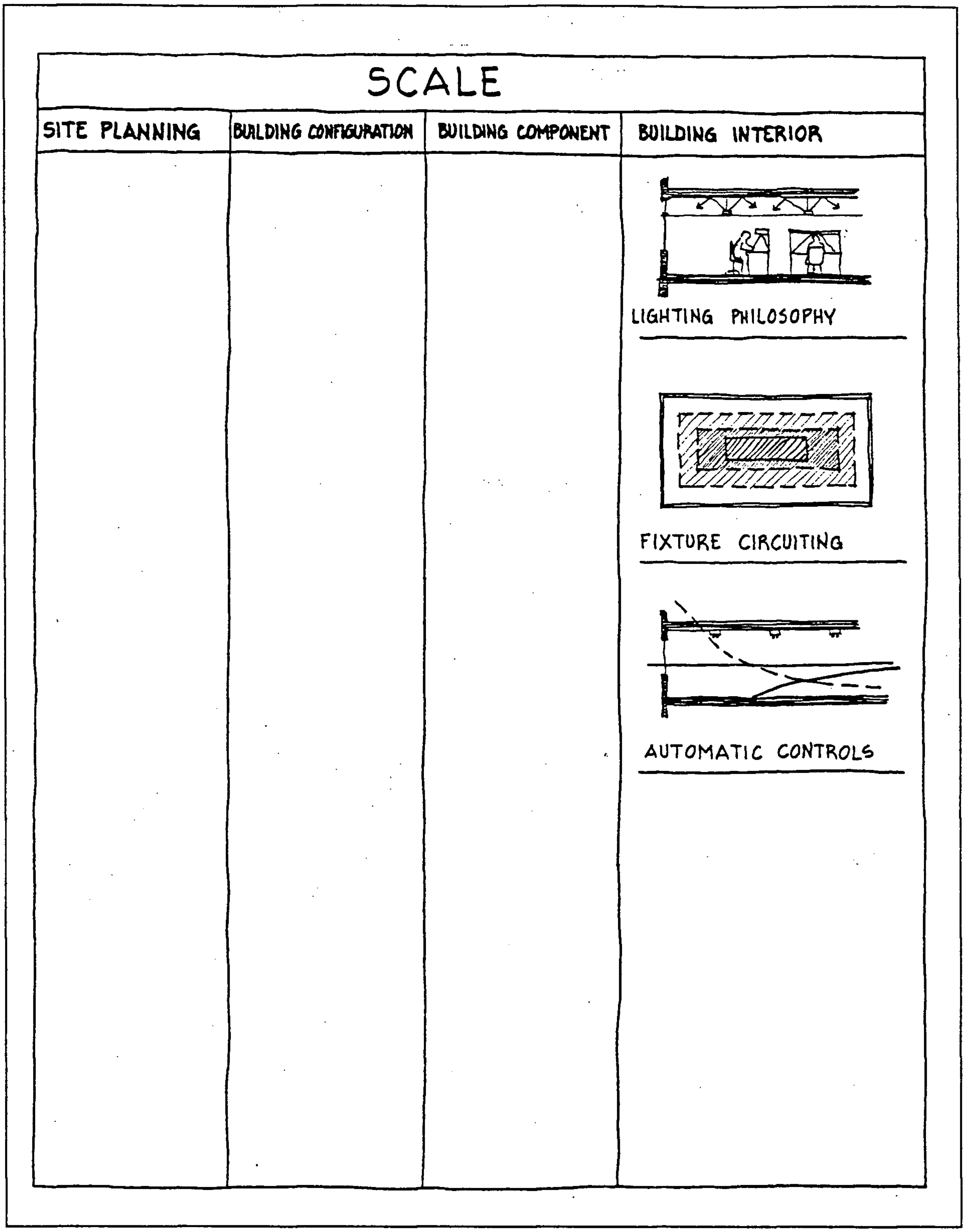

Figure 90 - Summary of techniques for integrating daylighting with electrical lighting

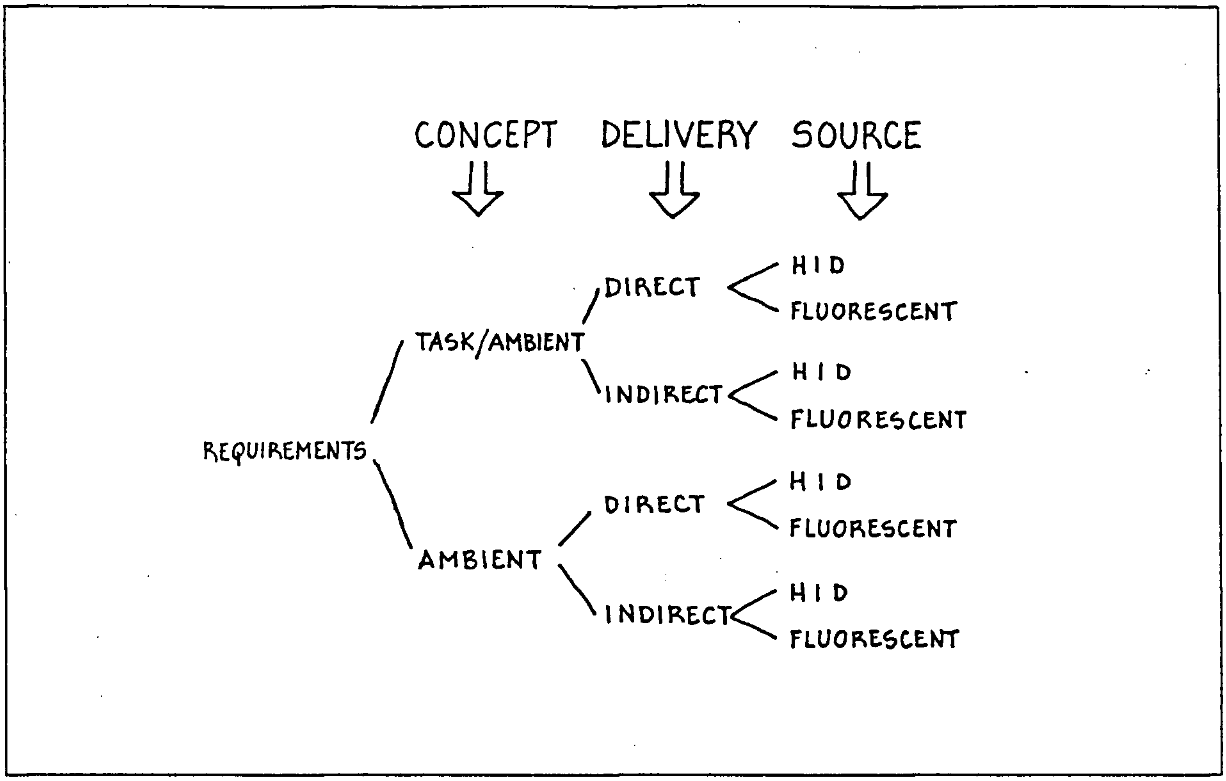

Figure 91 - Decision tree for office lighting

commercial buildings. The search to reduce energy consumption has, in turn, led to a re-evaluation of illuminance levels and has also prompted experimentation with non-uniform interior lighting, and more specifically, with task/ambient lighting.

In a "task/ambient" lighting system, illumination of the office task is managed locally and separate from the general, ambient lighting. The ambient illumination in this case is secondary to the task illumination, and generally at considerably lower level[7]. By contradistinction, in an "ambient" system, the general, ambient illumination delivers the illuminance for task requirements. The task illuminance requirement is, in effect, extended across the whole space[8].

As seen in figure 92 [9], the installation and operating

CONCEPT	TASK/AMBIENT	• WATTS/DENSITY • KNOWN TASK POSITIONS • NON-UNIFORM • DYNAMIC CONTROL
	AMBIENT	• WATTS/AREA • UNKNOWN TASK POSITIONS • CONFLICTS WITH FURNITURE
DELIVERY	DIRECT	• HIGHER LUMEN EFFICIENCY • CONFLICTS WITH FURNITURE • AIR CONDITIONING ENERGY USE • REDUCED ACOUSTIC PERFORMANCE
	INDIRECT	• LOWER MAINTENANCE COST • SHADOWLESS • MINIMUM GLARE • TAX WRITE-OFF • CEILING DEPENDENT
SOURCE	FLUORESCENT	• INEXPENSIVE • COLOR SELECTION • GOOD LUMEN MAINTENANCE
	H.I.D.	• HIGH LUMEN OUTPUT • POOR LUMEN MAINTENANCE • LIMITED COLOUR SELECTION • COLOUR VARIATION • SLOW STARTING

Table XVI - Summary of characteristics of the three office lighting parameters

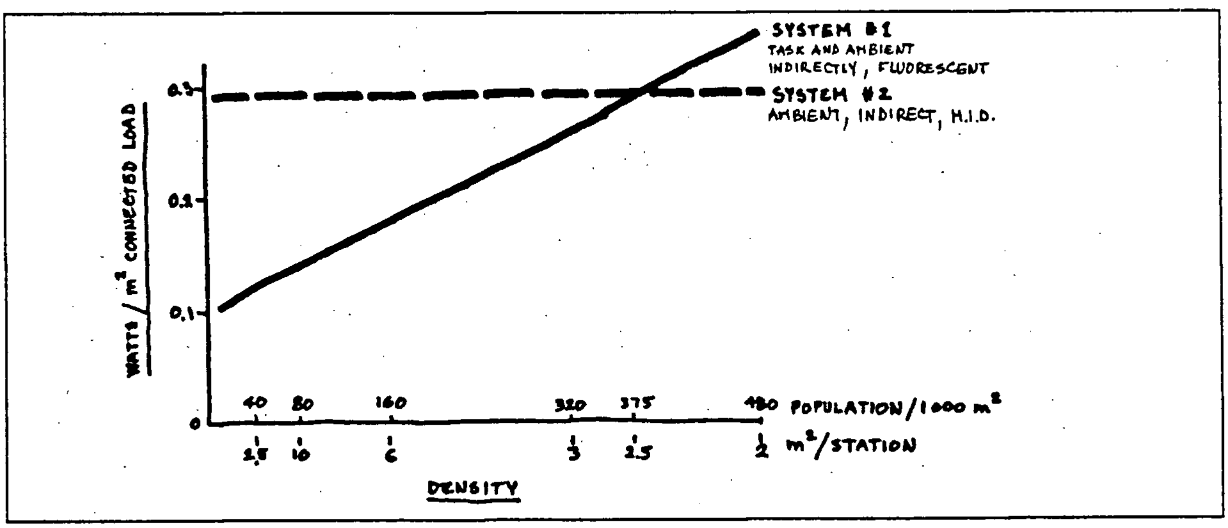

Figure 92 - Relative cost of task/ambient and ambient systems

costs of task/ambient systems varies with the density of occupancy, whereas the cost of ambient systems varies with the floor area, unrelated to the density[10]. This means that ambient systems are generally economical in high density office areas, whereas task/ambient systems are generally more economical in low to medium dense areas[11,12].

The installation and operating costs for furniture-mounted lighting systems (for either ambient or task lighting) is greater than that of ceiling-mounted systems because of the voltage limitations (and resulting inefficiencies) imposed by the electrical code[13]. Air conditioning costs, per kilowatts installed, can also be greater[14]. On the other hand, furniture-mounted systems provide tax advantages, as they have a much a much higher allowable depreciation rate than fixtures that are part of the building. It appears that from the view point of energy use, a combination of ceiling-mounted fixtures for ambient lighting and furniture-mounted systems for task lighting, will generally be an economical choice[15]. Ultimately, the choice of a lighting system is made not on the basis of technical criteria alone, but of aesthetic ones as well[16,17].

Delivery method: direct versus indirect

Daylighting can be integrated with both indirect and direct lighting. Direct lighting schemes--of the pendant, cove-mounted, or furniture-mounted type--allow a ceiling clear of sound-reflective elements, thereby improving acoustical performance in open plan offices. Simultaneously, this provides more light-reflective surfaces for daylighting.

Direct systems need not be obtrusive or glare producing. New luminaire designs, using 'bat-wing' light distribution, lower cut-off angles, and parabolic lenses, can result in direct lighting that is cost effective, has high efficacy, is unobtrusive and glare-free[18]. At least one company markets a lighting system for task lighting, utilizing standard 1 x 4 luminaires, with parabolic lens, pendant-mounted from the ceiling, independently controlled, and easily movable with changes in office layout[19].

Indirect lighting schemes avoid the glare found in many direct delivery methods that utilize (generally low cost) luminaires and lenses, with poor light distribution characteristics. They also avoid the dark spots and impression of burned out bulbs as the lamps are switched off or dimmed in response to daylighting.

<u>Light source: fluorescent versus HID</u>

Fluorescent lamps are the most widely used source for office lighting. They come in a wide range of colour rendering characteristics, each suitable for different applications, budgets and interior colour schemes. The "cooler" whites, with high colour rendering, blend best with daylight[20]. Because of their inefficiency, incandescent lamps are used in offices only for decoration and highlight[21], and for these purposes, their warm colour can be used to advantage.

The very efficient high pressure sodium (HPS) lamps[22], with characteristic gold tone light, are becoming popular in offices[23]. The Willow Creek office building, in Idaho Falls, Idaho, is an example of a very successful daylit building, utilizing HPS lamps, in an indirect lighting system. The designers chose this system after careful study and it appears that the colour of the electric light combined with daylight is acceptable to the users[24].

Similarity in spectral distribution between daylight and the electric light, although very helpful, does not appear to be essential for their compatibility. A glare-free electrical lighting installation, utilizing luminaires that do not allow view of the lamp; and the selection of an interior colour scheme, using colours that are strengthened by the light source, thus enhancing the colour perception in the space[25], are two factors that will greatly increase the chances that the electrical light will be perceived as pleasantly blending with daylight.

Fluorescent lamps maintain good colour rendition throughout their life and when they are dimmed[26,27]. The colour rendition of HID lamps generally deteriorates with the age of the lamp[28]. The deterioration in colour rendition is even more pronounced as the lamps are dimmed[29]. However, the extent varies among the three lamp types--metal halide, mercury and HPS--and with manufacturer. Further, the technology of these lamps is rapidly evolving and improvements are imminent.

At this stage of the profession's experience with daylight and electrical light integration, mockups of different lighting alternatives--including luminaires, lamps and controls--and the corresponding interior colour concept, should be tested before a final choice is made.

2.2 Fixture Circuiting

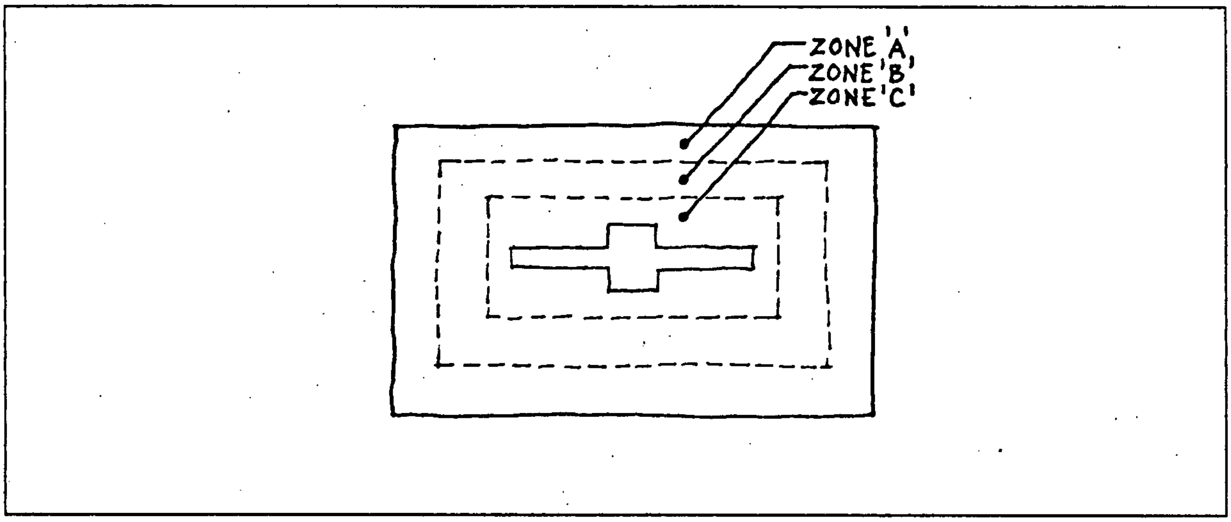

Figure 93 - Zones of varying daylight penetration in a building

As may be seen in figure 93 , the floor area of a daylit building can be readily divided into concentric zones (or bands) of varying daylight penetration. The daylight penetration varies from the perimeter zone--where daylight is sufficient for both task and ambient lighting during most of working hours; through an intermediate zone, where daylight is generally sufficient for ambient lighting, but not for task lighting; to an interior zone, where electric light must always be used for both task and ambient lighting, with daylight providing psychological benefit only.

Economic advantage of daylight can only be had if electric lights are turned off or dimmed when sufficient daylight is available[30], and for greatest economy, electrical fixture layout and circuiting should correspond with the zones of daylight penetration. The fixtures in each zone may then be controlled independently, to take advantage of whatever daylight is available in each zone.

The actual number of daylight control zones chosen will vary with each project, and will depend on various factors such as the building plan shape, ceiling height, fixture spacing, cost of fixtures, circuiting and controls, etc. There may thus be three bands[31], two bands[32] or just one band[33,34] of independently controllable fixtures.

2.3 Automatic Controls

Manual control of electric lighting in response to changes in daylight levels cannot be depended upon to save energy[35,36,37]. In the past, the use of automatic controls was uneconomical[38], but developments in hardware within the past ten years have changed this.

All automatic systems for controlling electric lighting to respond to fluctuating daylight levels are composed of two generic components:

i. a sensor for measuring the light level

ii. a controller for raising or lowering the electrical light levels in response to these daylight fluctuations.[39]

Automatic control systems may be either of the switching type (on/off or staged) or of the dimming type.

Switching control systems

Switching control systems may be classified as one of two types:

i. Task switching devices have the light level sensor located above the task. They must be capable of sensing two light levels--the design illuminance and two times the design illuminance (in order to provide a signal when to switch lights off)--and must be adjustable to different design illuminance values[40].

ii. Source switching devices have the light level sensor located on the exterior (usually the walls) and sense the amount of daylight at the "source". These devices require only one sensing level, although the mechanism must be able to sense high levels of daylight[41]. Periodic cleaning, (perhaps incorporated into the window cleaning process) is necessary for accurate functioning of the sensors.

    One characteristic of this type of control is that it preempts the possibility of the occupant undermining the daylighting concept: as shown in figure 94 , shades drawn too far down result in too little light (since the electrical light level is controlled by the exterior light

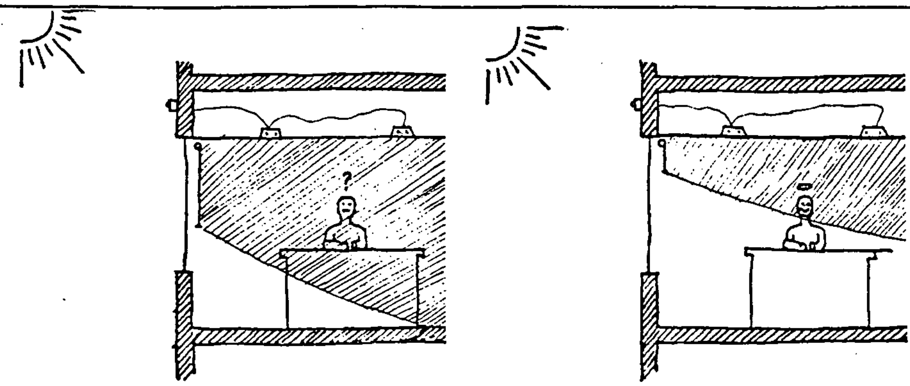

Figure 94 - Advantage of source-switching device

level), whereas the appropriate adjustment of the shade either manually or automatically, will result in design levels of interior illuminance[42].

Figure 95 a.[43] shows the light levels produced by typical switching devices. In all switching systems, a time delay feature of 30-90 seconds and/or a "deadband" zone, will avoid annoying on-off switching during partly cloudy days[44].

<u>Dimming control systems</u>

Dimming of incandescent lamps is closest to "ideal" dimming (figure 95 b. and c.).dimming of fluorescent lamps down to 50% of light output can be accomplished with standard ballasts[45] (figure 95 d.) for full dimming, electronic dimming ballasts must be used (figure 95 f.). However, combining of lamps, ballasts and dimmers must be done with care[46]. A combination dimmer and on/off switching system is also available--it saves operating costs--and may be suitable for industrial applications

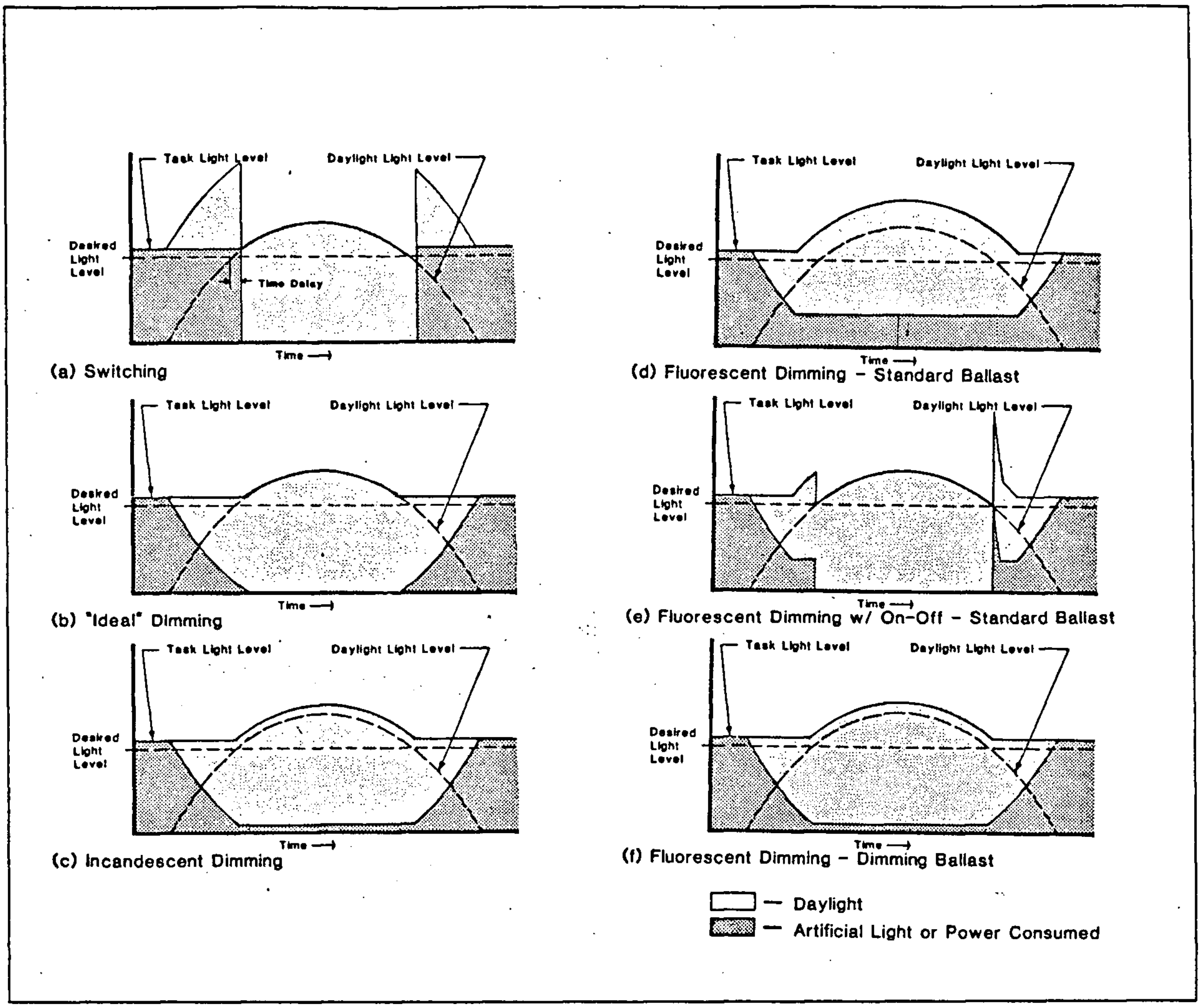

Figure 95 - Schematics for various control devices

or for non-task areas in office buildings (figure 95 e.)[47,48].

Switching versus dimming controls

The choice between switching and dimming controls is determined primarily by the percentage of illuminance which can be supplied by daylight at the luminaire locations being considered.

i. Where a large percentage of the design illuminance can be met by daylight, i.e. where the daylight level is high

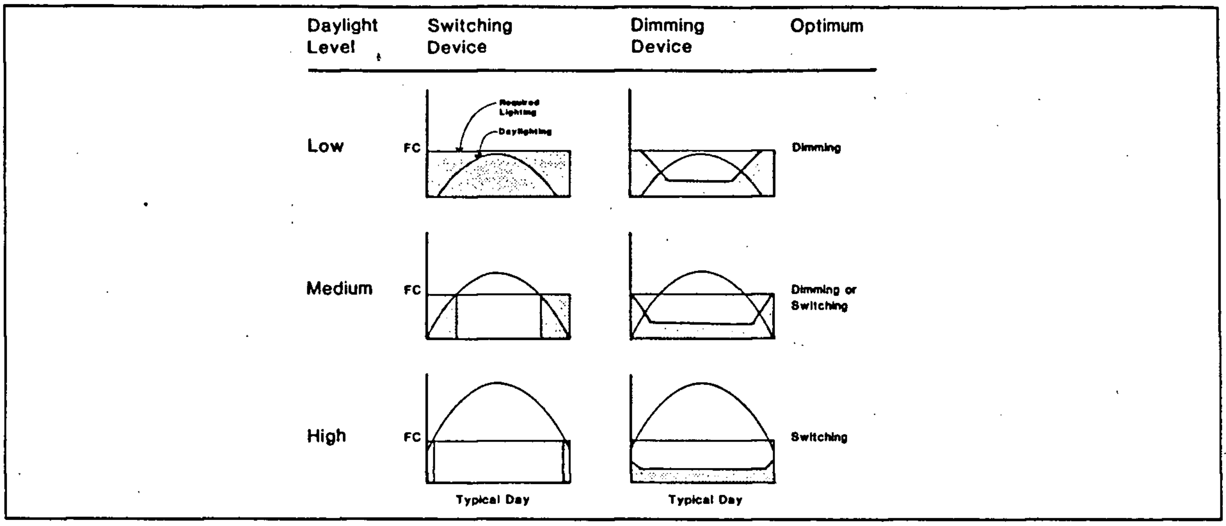

Figure 96 - Appropriate controls for various daylight levels

and/or low light levels are required, switching is warranted[49,50]. Where only a small percentage of the light needed can be supplied by daylight, i.e. daylight levels are low and/or high light levels are required, dimming is the appropriate choice, since a switching system may never operate[51,52].

ii. In situations of medium daylight levels, i.e. if at midday the daylight exceeds the amount needed, either switching or dimming, or a combination, may be appropriate. The choice will depend mainly on initial cost, maintenance and occupant acceptance of the system[53,54]. The above considerations are summarized in figure 96 [55]. A summary of the characteristics of various electric lighting controls is given in table XVII [56].

Occupant acceptance of switching and dimming systems depends to a large measure on their inobtrusiveness. Annoying

CONTROL TYPE	LIGHT QUALITY	SYSTEM MAINTENANCE	APPLICABILITY TO NEW PROJECTS	APPLICABILITY TO RETROFIT PROJECTS	SPACES BEST SUITED FOR USE
Task-Switching	1 May be annoying in task areas 2 Perceived burn-outs	1 May reduce life of some lamps and ballasts	1 Non-task areas 2 Large ratio of daylight to artificial light 3 Hybrid systems 4 All lamp types	1 Non-task areas 2 All lamp types 3 Many fixtures on one power panel 4 Large ratio of daylight to artificial light	1 Corridors/ Stairs 2 Gymnasium 3 Cafeteria 4 Entry/Lobby
Source-Switching	1 & 2	1 2 Outdoor sensor must be cleaned	1, 2, 3 & 4 5 Where screening devices will be installed 6 Vandal areas	1, 2, 3 & 4 5 Where screening devices are not being used properly	1, 2, 3 & 4
Incandescent Dimming	2		3 7 Any task or non-task area	3 7 Any area 8 Incand. lamps only 9 Add sensor to exist. dim. system	5 Any daylit space with incand. lighting
H.I.D. Dimming	3 Poor color rendition	1	1, 2, 3 9 H.I.D. lamps only	1, 3, 4 10 H.I.D. lamps only	1, 2 6 Warehouses
Fluor. Dimming Multi-Fixture (Stand, Ballast)		3 Few additional components	3, 7 10 Fluor. lamps only 11 High req'd light level	3, 7 11 Fluor. lamps only	7 Any daylit space with a large no. of fluor. lights
Fluor. Dimming Single-Fixture (Stand, Ballast)		4 Many additional components	13, 7, 10, 11 12 Small daylit room with fluor. lights	7, 11 12 Small daylit rooms with fluor. lights	8 Any daylit space with fluor. fixtures
Fluor. Dimming Multi-Fixture (Dimming Ballast)		3	13, 7, 10, 11	9, 11	7

Table XVII - Summary of electric lighting controls

changes in light levels, poor colour rendering and impression of burned out lamps, impression of gloom during cloudy days[57], must all be avoided, as they will lead to a loss of productivity and/or reduced rentability of the space[58,59].

<u>Integration with other energy saving strategies</u>

The control system for fabric shades or horizontal blinds, aiming at a reduction of solar heat gain, while allowing daylighting, can be combined with that of the electric lighting[60].

Occupancy sensors, consisting of ultrasonic movement detectors wired in series with the switching and/or dimming controls, can save energy by turning off lights when rooms are vacant[61]. Large savings have been reported for office buildings using this strategy[62].

Scheduling devices, such as time clocks and other, more sophisticated, central energy management systems, will switch off electric lighting nights and weekends. Microprocessors can be connected in series to the daylighting system, and be used to dim lights at peak demand times[63]. A microprocessor can switch individual fixtures, or groups of them, without wiring, by sending coded signals over the current powering the lamps, with each switch responding only to its own signal[64]. Complex switching arrangements, that are adaptable to changing partition layouts, can thus be accomodated.

Fluorescent lamps lose 20-35% of their light output over their lifetimes[65]. Some dimming systems can compensate for this lamp lumen depreciation, thus eliminating overlighting in the early part of the lamp life, and possibly, underlighting in the latter part[66,67].

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2. A. M. Sain, "Daylighting and Artificial Lighting Controls," Proceedings of the 1983 International Daylighting Conference, 16-18 February 1983 in Phoenix, Arizona. Washington, D. C.: 1983 International Daylighting Conference, 1983, pp. 363-68.

3. Ibid.

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6. Terry Lautzenheiser, "A Decision Model for Office Lighting Design," Lighting Design and Applications, November 1981, pp. 36.

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10. Ibid., p. 34.

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13. Harry B. Zackrison, "Interior Lighting and Energy Consciousness," Lighting Design and Applications, April 1978, pp. 31-33.

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19. Architectural Record, "High Quality Light, Low Energy Light In One Ingenious System: Tascon," Architectural Record, November 1981.

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33. IBM building in Southfield, Michigan, in Walter F. Wagner, Jr., Energy-Efficient Buildings (New York: McGraw-Hill, 1980), p. 143.

34. Robert S. Hastings and Richard W. Crenshaw, Window Design Strategies to Conserve Energy (NBS Building Science Series 104, Washington D.C.: Department of Commerce, 1977), p. 6.3.

35. Aitken, p. 16.

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37. See, however, the concept of pull-cord switching, which

can apparently be very cost-effective and workable-- A. W. Levy, "Lighting Controls, Patterns of Lighting Consumption, and Energy Conservation," IEEE Transactions on Industry Applications Vol 1a-16, No 3, May/June 1980, p. 426.

38. R. G. Hopkinson, Architectural Physics: Lighting (London: Her Majesty's Stationery Office, 1963), pp. 116-17.

39. Sain, p. 363.

40. Ibid.

41. Ibid.

42. Ibid., pp. 363-64.

43. Ibid., figure from p. 364.

44. Francis Rubinstein, "Photo-Electric Controls in Daylit Buildings", Talk given at the Plennary Session of The 1983 International Daylighting Conference, 16-18 February 1983 in Phoenix, Arizona .

45. Aitken, p. 18.

46. Ibid.

47. Ibid.

48. Sain, p. 364. However, the large light level fluctuations, inevitable with fluorescent lamps utilizing standard ballasts, especially when lamps are switched back on, may be annoying.

49. Aitken, p. 16.

50. Sain, p. 366.

51. Ibid.

52. Aitken, p. 16.

53. Ibid.

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55. Sain, p. 366.

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57. William M. C. Lam, "Sunlighting as Formgiver for Architecture," Proceedings of the 1983 International Daylighting Conference, 16-18 February 1983 in Phoenix, Arizona. Washington, D. C.: 1983 International Daylighting Conference, 1983, p. 79. Lam recommends that additional electrical lighting be used to counteract the gloomy quality of daylight under cloudy conditions.

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VIII.

DAYLIGHTING AND THE DESIGN PROCESS

The design of energy-responsive commercial buildings is not a one-shot leap to the best possible solution. It is a combination of education and exploration that becomes easier and less time-consuming as knowledge and insight are gained.

Ternoey et al.[1]

There is no finality in Architecture, only continuous change.

Walter Gropius[2]

1. INTRODUCTION

This chapter consists of a discussion on the means whereby the techniques for daylighting, which have been presented in the previous chapters, may be assimilated into the design process. A knowledge of the general daylighting techniques available and the part these play in daylit buildings, is necessary for designers: these form their "stock in trade" of ideas and possibilities during the design process. Still, buildings are unique in function, location and character, and the general techniques must be tested and adapted to suit the particulars of the project. Tools are needed to test the performance--in terms of quality and quantity of light--of the daylighting concept embodied in a design. Further, daylighting must also be considered part of the larger context of energy-responsive design. Finally, energy-responsive design must, in turn, be considered in the context of the total design problem. This chapter addresses itself to these three issues.

2. DAYLIGHTING DESIGN TOOLS

Daylighting design tools are techniques for predicting the interior daylight levels that can be achieved with a given design. These tools fall into three categories:

i. computational methods

ii. graphic techniques

iii. physical scale models [3,4]

Each type of design tool has different capabilities and various strengths and weaknesses[5]. The appropriate daylighting design tool will vary with the skill, experience and background of the design team, the type and scale of the project, as well as the stage of design for the given project. Some tools, such as long-hand computational methods and some graphic techniques, are primarily useful as tools for the exploration of basic, general daylighting principles. Other tools, such as nomographs and models are versatile enough to be utilized throughout the design phase. Table XVIII lists the range of design tools available and their usefulness at various stages of the design process. A brief description of the three main types of design tools follows, along with their respective advantages and disadvantages.

DESIGN TOOL	STAGE OF DESIGN					
	STUDY / EXPLORATION	ENERGY INTEG WITH DAYLIGHT	PREDESIGN	SCHEMATIC DESIGN	DESIGN DEVELOPMENT	DESIGN FINALIZATION
COMPUTATIONAL						
• FORMULAS/TABLES	FAIR				FAIR	
• NOMOGRAPHS		FAIR	GOOD	FAIR		
• COMPUTERS						
• PROGRAMMABLE CALCULATOR	FAIR					
• MICROCOMPUTER	GOOD	GOOD		FAIR	FAIR	
• LARGE COMPUTER	GOOD	GOOD		FAIR	FAIR	FAIR
GRAPHIC						
• PROJECTIONS ON GRID				FAIR	FAIR	FAIR
• B.R.S. PROTRACTORS				FAIR	GOOD	FAIR
• DAYLIGHTING FOOTPRINTS	GOOD			FAIR		
PHYSICAL MODELLING						
• SMALLER THAN 1:50				FAIR		
• BETWEEN 1:50 AND 1:20	GOOD			FAIR	GOOD	FAIR
• LARGER THAN 1:20	GOOD				GOOD	GOOD
• FULL SIZE						GOOD

Table XVIII - Usefulness of various daylighting tools at each design phase

2.1 Computational Methods

Formulas and tables

Computational methods for daylighting analysis have been in use since the 1920s[6,7]. They can be divided into two main groupings: those using the Daylight Factor (DF) method and those using the Lumen method.

The DF method is based on the principle that for a given design configuration and location on the interior of a building, the ratio of the interior to the exterior daylight illuminance is a constant. Thus, designs may be assessed under fluctuating exterior illuminance levels. The DF method is used in Europe and is recommended by the Commission Internationale de l'Eclairage (CIE). The method is comprehensive: it represents a non-uniform sky luminance distribution (the standard CIE overcast sky), has no limit on room size and shape, allows non-vertical glazing, can be used with a wide range of window configurations, and can calculate daylight distribution throughout a room. Until recently, it could only be used with overcast skies[8,9]. Either tables or direct calculations may be used. Detailed procedures using this method are found in many texts[10,11,12].

The Lumen method uses direct illuminance measurements to compare daylight levels at various points in a room. Primarily used in the USA, it can consider both overcast and clear sky conditions. It cannot, however, deal with obstructions in front of the daylighting aperture, and is applicable to a limited range of window configurations and calculation points within a room[13]. Typically, tables are utilized. The Lumen method has also been widely documented[14,15].

Of the two methods, the DF method is more versatile and can be used with a wider range of design situations. Because of the limited versatility of the Lumen method, its usefulness is primarily in the study of basic daylighting principles[16]. However, both methods are time consuming if parametric studies have to be carried out.

Nomographs

Nomographs are versatile extensions of calculation procedures and can examine a large range of alternative designs relatively quickly. They generally consist of several graphs, each showing the interrelationship between two parameters, with several graphs being related sequentially. The sensitivity of daylight levels to any parameter can be quickly evaluated. Recently, researchers at the Lawrence Berkeley Laboratories have developed nomographs that can provide feedback at the predesign stage on the viability of daylighting for a given site and geographic location[17]. Another group of researchers have developed a set of nomographs that can analyze, at the schematic design stage, the effectiveness of various daylighting solutions, can point to the type of controls to be used, the location of the controls, the effect of daylighting on the electric lighting, and the reduction in energy costs that can be achieved through daylighting[18].

Computer programs

Computer programs are another extension of calculation methods: daylighting parameters are fed in and the resulting daylighting patterns are automatically calculated and displayed. These programs may be based either on the DF method or on the Lumen method. Programs have been developed for programmable calculators[19], micro-computers[20] and mainframe computers[21].

The sophisticated computer programs used on mainframe machines are extremely versatile and can model complex daylighting and solar control systems, and both overcast and clear skies[22]. At least one program has the capability to calculate energy savings at the whole building level due to daylighting[23]. The complexity and large memory requirements of mainframe computer programs, precludes their use for all but very large projects. Considerable skill is required to run these, since they are not designed with simplicity of use--"user-friendliness"--in mind. Their main value is as research tools and in validating simpler computer programs.

Microcomputer programs have been developed to be "user-friendly", requiring little training in their use, and enabling quick exploration of alternatives during the schematic design stage. They may include a graphic plot as part of the output[24]. Bryan, who has pioneered in the development of one such daylighting program[25], is of the opinion that the usefulness of such programs as design tools is limited, due to the simplifying assumptions built into them and their inability to model complex daylighting conditions. Because of their ability to calculate quickly the effects of parameters on resulting daylight penetration, they are valuable as tools for the study of basic daylighting concepts[26,27].

2.2 Graphic Techniques

Graphic techniques for the evaluation of daylighting have been in use since the 1930s. These can be used directly with architectural drawings to provide information on daylight levels in interiors. They partly or totally bypass calculations.

Lynes[28] has presented techniques for analyzing daylight penetration and glare utilyzing interior elevations of window-walls plotted on a grid. Hopkinson et al.[29] have also described a similar method.

The BRS (Building Research Station) protractors[30] were developed in the 1940s, for direct use on drawings. Like all graphic techniques, these evaluate the sky component (SC) and the externally reflected component (ERC) separately. The internally reflected component (IRC) is estimated from tables. Protractors were developed to save time in daylighting analysis, and were widely used in Europe in the 1950s and '60s. Their major drawbacks are their limitation to overcast sky conditions, an inability to deal with complex daylighting aperture configurations, and the need to estimate the value of the ERC and IRC from assumed average reflectances.

In the late 1970s, Millet et al.[31,32] developed a graphic daylighting design tool consisting of a catalogue of patterns, each showing differently configured daylighting apertures and their respective isolux contours over a horizontal plane. The catalogue contains contours for both overcast and clear skies. This package is useful primarily as a tool for the study and exploration of basic concepts in daylighting. A limited number of these daylighting patterns have been published by Brown et al.[33]

2.3 Physical Modelling

Various authorities on daylighting concur that physical models provide the most versatile and most reliable method of evaluating a daylighting design, both quantitatively and qualitatively[34,35,36,37]. The advantages of physical scale models are[38,39]:

i. Models, even very crude ones, can provide accurate performance comparisons between alternate window configurations, interior reflectances, and other daylighting elements.

ii. Scale model building is a common practice among architectural firms. With slight modifications (e.g. accurate representation of interior reflectances, allowance for placement of photocells, portholes for camera), models can become sensitive design tools for daylight analysis.

iii. Physical scale models offer an opportunity for qualitative evaluation of the interior visual environment, including the identification of potential glare problems. This can be done either through visual observation or photography.

iv. Beside their usefulness in daylighting, models are effective in volumetric and spatial studies and are an excellent communication device.

The scale of the model depends on the stage of the project, since design information with different degree of accuracy is required at each stage. The size of the photosensors (and the increasing error introduced by their size at smaller model scales) limits how small the model may be. Cost and portability limit how large it may be. Daylighting models scaled 3/4"=1'-0" (approximating 1:20) are recommended[40,41]. Larger buildings may be studied with models as small as 3/8"=1'-0" (approx. 1:30) if care is exercised in their construction[42]. Models as small as 1/8"=1'-0" (approx. 1:100) have been used to study the effect of general layout and massing in a large project[43]. More than one model, each at different scale, may be utilized at various stages in the design process[44].

The testing of daylighting designs with models may be done under a sky simulator or under an actual sky. Sky simulators (or artificial skies)--either of the hemispherical or the rectilinear type--are preferred by researchers, since they can reproduce a fixed sky condition, making it possible to identically compare design alternatives[45]. However, the limited number of sky simulators in use in North America makes the testing of models under an actual sky the only option for most design offices[46]. This method has the advantage of being the least costly and easy to perform[47], but it is more error prone, primarily because sky luminance values can change in quick succession. Also, sky measurements on two "identical" days may vary by 10-15% or more[48]. The problem of rainy or windy weather, is another disadvantage, which may be overcome at the expense of constructing a glazed shelter over the testing area. The details for building daylighting models, and the procedures, equipment and pitfalls associated with testing them, have been thoroughly discussed by Evans[49], Bryan et al.[50], and by various contributors in the Workbook for the Daylighting Design Tools Workshop[51].

The construction of full scale prototypes for the evaluation of daylighting, can in a sense be considered an extension of physical modelling. Full scale mock-ups have been found to be cost-effective in very large projects[52]. With these, the daylighting concept can be tested and fine tuned, as can the HVAC and electrical systems. The final co-ordination of interior furnishings and colour scheme is also possible.

3. DAYLIGHTING IN THE WIDER DESIGN CONTEXT

3.1 Daylighting In The Context Of Energy-responsive Office Building Design

For purposes of study, this thesis has isolated daylighting design from other aspects of the design process. It was thus possible to make a systematic study and evaluation of daylighting techniques. However, daylighting design in office buildings must alweys be considered in the larger context of energy-responsive design.

In the design of energy-responsive office buildings, two types of buildings, resulting from two distinct conceptual approaches, can be identified (figure 97 [53]):

i. climate rejecting buildings

ii. climate adapted buildings

Ternoey et al.[54] have described the differences between these two building types:

> Whereas climate-rejecting buildings are evolving toward a smaller skin area and volume to better use concentrated energy sources, the climate-adapted building extends form and surface area to connect a larger portion of occupied space to diffuse climatic energy sources. For these reasons, we consider the two building types to be opposites in design intent: they represent divergent solution types that follow two fundamentally different design track choices.

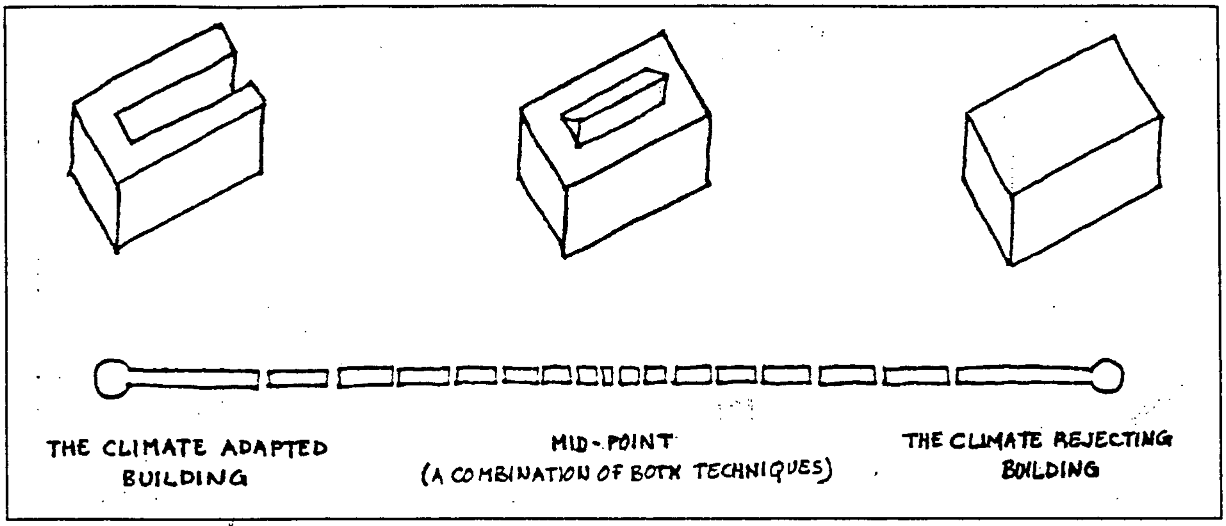

Figure 97 - Range of possible solutions for energy-responsive office buildings

Role of daylighting in climate-rejecting buildings

Climate rejecting buildings are characterized by total artificial environmental control. Most conventional buildings built for the last thirty years fall under this category. Climate rejecting buildings isolate themselves from the natural sources of energy (heat, light, wind) surrounding them. The task of the environmental control system consists largely in responding to internally generated cooling loads. Energy responsiveness in such buildings consists primarily in:

i. A reduction in lighting loads (achieved by a combination of lower light levels, task/ambient lighting, efficient luminaires and light sources, and daylighting with automatic lighting controls)

ii. An efficient HVAC system (achieved by using advanced engineering concepts, efficient equipment and computerized control system)

Daylighting in such builidngs is seen as one of many strategies for lowering non-renewable energy use. Daylighting is one of a few climate-adaptive components[55], in an essentially climate-rejecting concept.

Design methodologies for the design of energy-responsive climate-rejecting commercial buildings have been described by, among others, Dubin and Long[56], and more recently, by Ternoey et al.[57] The latter discuss at length the role of daylighting in such buildings.

Many authors have dealt with the integration of daylighting with specific components of climate-rejecting commercial buildings. Zoning, legal and other broad-scale issues related to daylighting have been addressed by Kwartler and Masters[58] and Moore[59]. The impact of daylighting on energy use at both the whole building and component scale have been treated by Arumi[60], Sanchez[61], Bobenhausen and Lewis[62], Ternoey et al.[63], and many others. Pike and Golubov[64], Evans[65], Meyer[66] and Ternoey et al.[67] have studied the cost/benefits of daylighting. The issue of integrating daylighting with electrical lighting has been dealt with by Pike and Rizzuto[68], Rubinstein[69], Aitken[70], Sain[71], Ternoey et al.[72] and others.

<u>Role of daylighting in climate adapted buildings</u>

Climate-adapted buildings seek to utilize the climatic energy sources surrounding them to provide a major portion of the light, heat, cooling and ventilation needed by the occupants. The building envelope becomes the boundary by which the climatic energy sources are captured or rejected, and building form, layout and organization are the means to achieving adaptation to climate. While it is not generally feasible to design a climate-adapted office building without any additional energy input from electrical lighting, fans, etc., it is feasible to design buildings in which the large majority of energy needs is provided by natural energy sources. Because lighting and associated cooling loads are the dominant loads in office buildings, daylighting is the main energy saving strategy in climate adapted office buildings. Typically, daylighting thus becomes a strong form determinant.

Methodologies for the design of climate-adapted commercial buildings have been described by Ubbelohde et al.[73], Lakin and Millet[74], and Ternoey et al.[75], among others. In all of these approaches, daylighting is a predominant element in the design process.

Ternoey et al[76] have compared the implications of each of the two design strategies on the design process:

> Energy-responsive climate-rejecting buildings can be described as a linear evolutionary change in commercial buildings. The basic objective is to maintain sameness while increasing effectiveness. Climate-adapted buildings on the other hand, can be seen as a non-linear design change that requires a new perception of the relationship between architecture and environmental control. Climate-adapted buildings represent a departure from the 1950s perspective that commercial buildings are intrinsically internally load dominated.
>
> The impact of this nonlinear change on people, design, and building ownwership is substantial. Typically, the degree of change requires that new perceived advantages must be found for all parties. Therefore, climate-adapted buildings are as much a

study of the needs, desires, and motives of people as it is the application of technology.

3.2 Daylighting In The Wider Design Context

Ternoey et al. have explored in depth the issue of integrating energy concerns, and particularly daylighting, into the larger design context. They have described the state of the art of energy-responsive commercial building design as follows:

> Numerous approaches have been developed to limiting the non-renewable energy needs of commercial and institutional buildings... [As yet,] there is no consensus by either clients or designers of the specific problem to be solved, or of the type of solutions... The present state of the art of the design of energy -responsive commercial buildings can be described as an unresolved design challenge...[77] It is ultimately the [designer's] responsibility to formulate a personal opinion of the key variables and best means to address energy-related issues in commercial buildings[78].

The same authors point out that daylighting and energy responsiveness should serve and complement the specific project goals: to respond to the client's programmatic needs, his expected rate of return on investment, the comfort and satisfaction of the occupants. For example, if the goal of the client is to improve productivity, then daylighting must contribute towards this. If a sense of spaciousness is wanted, then the daylighting concept must address itself to that goal. If a specific corporate image is aimed at, daylighting must respond positively to this requirement. Given the existing social and economic structure, energy issues in general must be made subservient to these goals: the concern of most clients with energy is pragmatic not philosophical. Only with this attitude by the designer, can energy issues have the possibility of being addressed at all in the design process[79].

While the integrative process may be cumbersome when the design team is inexperienced--involving checking and cross-checking procedures, evaluation, and redesign--it gets easier with increasing experience.

> Most design teams report that after a few projects the design team's collective intuition improves significantly and various items can be omitted. Some design teams have even reported that at a certain point, the designers' energy intuition is developed to the point that energy can simply be treated along with other variables such as form,function, and cost.[80]

According to Ternoey et al., "at this point in the design of energy-responsive buildings it appears that the best way to derive successful solutions is to constantly inform and educate intuition"[81]. Intuition is educated by successive problem analysis and synthesis:

> We really must...go back and forth; starting from the whole, taking it apart, putting it together, taking it apart, and so forth. Everything is that way in our business.[82]

The analysis of the components of daylighting presented in this thesis aims at helping in the "taking apart" steps of the process. The integration--the "putting together"--of daylighting considerations in the wider context of design, involves study and a commitment to exploration and discovery.

4. NOTES

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IX.

CONCLUSIONS

Since the late 1970s, daylighting has been acknowledged as a major strategy for reducing energy costs in office buildings. While energy issues have been catalytic in the rediscovery of daylighting, it is now clear that the advantages of daylighting extend beyond these factors. The high luminous efficacy and balanced spectral characteristics of daylight make it an effective light source. Daylit spaces exhibit modelling characteristics and a sense of spaciousness superior to those lit with conventional electrical installations. For the building user, therefore, daylighting can provide an improvement in the quality of the interior visual environment. As a consequence of these advantages, the value of the building is increased, to the benefit of the owner.

With the re-emergence of daylighting as a viable method of interior illumination and energy conservation strategy in office buildings, there has been a large body of information emerging on all facets of the problem. Yet, there has been to date no published work on establishing a comprehensive conceptual framework for daylighting techniques. Design proceeds by intuition, but it has been shown that uninformed intuition is not generally accurate when applied to an unfamiliar design challenge, such as daylighting. Intuition can be educated by study, and the main goal of this thesis has been to provide a conceptual framework for studying daylighting phenomena and techniques.

The essential problem of designing a daylit space arises from two facts:

i. Daylight originates outside the space being lit

ii. Daylight is variable

The science and art of daylighting consists largely of responses to these two issues in terms of design techniques whose aim is bringing daylight into interiors under controlled conditions and compensating for its variability.

The conceptual framework presented in the thesis organized these daylighting design techniques into five broad objectives:

i. provision of access to available daylight

ii. detailing of daylighting elements to promote penetration of daylight into the building interior

iii. planning the interior space to take advantage of daylight

iv. controlling brightness extremes

v. integrating daylight with electrical lighting

The first three objectives aim at maximizing daylight potential, while the last two aim at its control and integration. Design proceeds from the general architectural problem statement and response, to more detailed problem statements and specific responses; from the large scale to the progressively smaller scale. The daylighting techniques presented in the thesis were therefore organized in a matrix, with one dimension consisting of the objectives being aimed at (as outlined above), and the other dimension consisting of scale, encompassing progressively more specific concerns: site planning (including landscaping and building clustering); building configuration (including massing and plan); building component; and building interior. This arrangement would thus provide a ready reference during the process of design.

Daylighting design (and that of energy-responsive commercial buildings in general), has been described as an "unresolved design challenge". There is no consensus as yet within the design profession either concerning the nature of the problem or the best means to solve it. The state of the art of daylighting design is one of experimentation and discovery.

Many researchers are resolving various aspects of daylighting and its integration with other design concerns. Many designers are incorporating daylighting successfully in the design of office buildings. However, these designers are still a small percentage of the total who are not committed to daylighting, or to energy issues in general. If daylighting design is eventually to be absorbed into the mainstream of architectual practice, the following issues will need to be addressed:

i. Designers will need to have a grasp of daylighting principles and techniques; these will form the "stock-in-trade" of ideas and possibilities during the design process. Such understanding is gained by study, exploration in design, and the willingness to accept the risks associated with any such exploration.

ii. The interrelationship between daylighting and other energy-related issues will need to be understood. This is partly an interdisciplinary effort between the architect, the mechanical engineer and the electrical engineer.

iii. Savings in energy cost is a necessary, but not sufficient, reason for daylighting. Daylighting can provide an interior visual environment that can improve user satisfaction and enhance productivity. The designer should therefore be able to "sell" daylighting mainly on the basis of an improved visual environment.

iv. Daylighting will need to be subordinated to the larger goals of the client, and daylighting goals will need to be defined in terms of these larger goals. For example, if the goals are to improve productivity, then daylighting must address itself to that goal. If the goal is to convey a specific corporate image, then daylighting techniques can be employed to reinforce that. In the present economic and social structure, this is the only attitude that will enable more daylit buildings to be designed and built, increasing the experience base and the social awareness of the potentials of daylighting.

There will perhaps come a stage when daylighting, environmental concerns and energy issues will become (along with form, function, cost, etc.) part of the philosophical axioms of the architectual profession and that of society. Until that time, much individual and collective work remains to be done.

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