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Discomfort glare, light scatter, and scene structure

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DISCOMFORT GLARE, LIGHT SCATTER, AND SCENE STRUCTURE

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This dissertation is dedicated to the fond
memory of Professor Fergus Campbell,
with thanks for his inspiration and
encouragement.

It is also dedicated to Tina, Frances and
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Summary

Since the start of the Industrial Revolution there has been a general improvement in working conditions. As part of this process, light in the work place was recognised as an important environmental factor. In the early years of the 20th century it was also recognised that in providing adequate lighting for a particular working environment, there was a need to avoid the potential negative effects of too much, or inappropriately distributed, light. One of the negative effects of light in the work place was glare.

Holladay (Holladay, (1926)) attributed the negative effects of glare to impairment of vision caused by light scatter. Stiles (Stiles, 1929)) refuted Holladay's case by arguing that only a small proportion of the reduction in task visibility could be attributed to light scatter effects (where task visibility is a measure of how far above the visual threshold a task's contrast is). Stiles distinguished disability glare, a light scatter effect, from discomfort glare which was glare that could not be attributed to light scatter. The distinction made by Stiles resulted in the separate development of discomfort and disability glare models. Very few, if any, studies since Stiles have re-evaluated the potential association between subjectively rated discomfort glare, and physically based disability glare.

In the study reported here, subjects were asked to set the appearance of a 2° glare source so that it appeared at the Borderline between Comfort and Discomfort, or BCD (Guth, (1963)). Each subject's visual threshold for a 4 cycle per degree spatial grating was measured under BCD and control conditions, and a comparison made to assess if light scatter effects from the glare source influenced threshold contrast, C_{th}.

The results of the study indicate that C_{th} can be lower in the presence of the glare source set to BCD. This anomaly may be explained by improvement in image quality caused by the glare source driving the pupil to a smaller diameter.

More significantly, there was found to be a strong correlation between subjective BCD settings and age, and also between BCD settings and control condition C_{th}. Both of these results suggest an influence of light scatter on BCD settings of discomfort glare. This conclusion was further supported by the fitting to the data of the independently reported stray light function of Ijspeert et al (Ijspeert et al, (1990). Thus the results strongly suggest a correlation between subjective BCD settings of a glare source and light scatter function. A conclusion that substantially weakens Stiles' argument that discomfort glare is not dependent on light scatter effects. Using the results of the study, a new threshold type model for assessing discomfort glare is proposed, which explicitly includes age as a parameter.

However, much variance remains to be explained in the glare data. Therefore, a second theme investigated in the dissertation is the possible association between scene visual structure and visual discomfort. The results of this study indicate that there is a small but significant difference in the image structure of natural and man made environments. This difference may contribute to visual discomfort, but will require further investigation.

CONTENTS

Chapter 1   Summary of the History of the Factory and the Office, and the Significance of the Physical Environment of the Work Place

1.1   The Industrial Revolution and the Development of the Factory

1.1.1   From Cottage Industry to Factory

Until the start of the industrial revolution in Europe the working environment of the factory and the office as it is understood today had not even started to develop. Most, if not all of the contemporary 'industrial' production was carried out in small units, which were predominantly located in workers' homes. The production unit was either a room in the worker's home or a workshop attached to the home premises; see for example (Quiney (1986), Sundstrom, (1986)). Hence the term 'cottage industry' . The layout of the work place in these home based production units was almost sure to have been determined by pragmatism, guided by the requirements of the work to be carried out. The recognition of the need to design the work place to satisfy elementary ergonomic principles and safety requirements was nearly one and a half centuries away at the start of the main stream of the Industrial Revolution in the middle of the eighteenth century.

During the course of the 18th century there was an increase in the demand for industrial output. The reasons for the increased demand and the resultant increased output, which initiated the Industrial Revolution, are based on a complex set of political, social, and technological interactions; see for example (Quiney (1986), Hill CP (1985), Hobsbawm (1969)). A direct consequence of the increase in demand for consumer items was that industrial production moved from cottage industry to factory based production. The transfer to factory production was paralleled by the necessary technological developments to allow mass production in the new industrial environment. In the first phase of the Industrial Revolution much of the increased industrial output and technological innovation focused on the cotton trade. Thus many of the early factories were cotton mills, or were connected indirectly with the production of cotton.

As the Industrial Revolution progressed there was an expansion in the industrial base, to cope with the demand for industrial output other than cotton. By the mid 19th century a wide range of goods were mass produced in the new factories. The need to supply the new

factories with equipment complemented the growth in consumer based industries.

The growth in the industrial base led to a corresponding increase in the numbers of workers needed to man the machinery in the factories. There was a dramatic increase in the population of the industrial towns during the course of the Industrial revolution. Manchester for example grew from a population of approximately 75 000 in 1801, to 182 000 in 1831 to 351 000 in 1871, with a large proportion of the town's proportion working in the mills servicing the cotton industry (Hill, CP (1985), Hobsbawm (1969)). This growth in the industrial population was paralleled in the other industrial centres of Great Britain, and subsequently in other industrialising nations of Europe and the North American Continent, particularly the USA. Thus the concept of the factory which barely existed before the middle of the eighteenth century had become an established part of the landscape by the mid-19th century.

1.1.2 The Development of the Early Factories

At the start of the industrial revolution there was a transfer of production away from integral home production units to the larger premises. The very early factories were separate buildings such as sheds and barns, which were later supplanted by purpose built premises. The first of these purpose built factories, probably attributable to John Lombe and pre-dating the main stream industrial revolution by some three decades, was a silk-throwing mill built in England in 1719. Descriptions of this factory differ, but it is reported to have had the appearance of a barracks, was about 500 feet long and four to six stories high, and was glazed with more than 400 windows (Nelson (1975), Pierson (1949)). Many of the factories built between the start of the industrial revolution and the beginning of the 20th century adopted this form.

The layout of the first factories was limited by practical constraints imposed by technological limitations. Electric lighting was not commercially available until the end of the 19th century thus for many years of the Industrial Revolution daylighting was the dominant form of lighting. As daylight does not penetrate into a building much more than 9 metres horizontally the early factories were not often wider than 18 metres. The power to drive the machinery was initially derived from the water wheel, which was superseded

by the steam engine in the 19th century. Both of these forms of power required that a central power shaft run the length of the factory, with belt drives run from the central shaft to drive machinery on the factory floor. The need to use daylight and central drive shafts helps to explain the long and narrow aspect of many of the early factories. It was quite common to see factories 15 - 18 metres wide, five to seven stories high, and anywhere between 90 - 185 metres long (Nelson (1975)).

It was not until the advent of commercially available electric power during the latter part of the 19th century that factories began to depart from the narrow aspect, multi-storied form. The availability of electric light lessened the dependence on daylight, which meant that factories could now be built wider than 18 meters; electric motors which could be positioned freely anywhere on the floor space of the factory replaced the requirement for the machinery to be placed about a central drive shaft. Also, the introduction of steel frame and concrete construction during the latter part of the 19th meant that structurally the factory building was not limited in form to what could be achieved by using traditional brick, or timber, construction. Not surprisingly, the introduction of electric power into industrial use and the advent of steel and concrete construction initiated major changes in the traditional form and layout of factories.

1.1.3   Working Conditions

Working conditions inside the early factories were often very grim (Barnum (1971), Scott (1905)). The need to provide elementary levels of safety and comfort for the work force was totally subservient to the function of the factory, the production of manufactured goods. The factories were frequently dark, dirty, inadequately ventilated and often suffered from infestation with vermin such as cockroaches and rats.

The poor working conditions were frequently attributable to social attitudes of the factory owners and managers towards a poor, uneducated, cheap and disenfranchised labour force. Some managers may have been ignorant of the effects of the poor working conditions on their workers. Others thought that they held no responsibility for the social conditions of the work force, as they only hired their labour. There was also a hard nosed philosophy adopted by some managers that the work force should be kept in poor conditions to

discourage slack attitudes and laziness among the workers; in any event providing better working conditions was believed to be uneconomic because it would cost money (Lescohier and Brandeis, (1936)).

In Britain particularly, it was thought that providing workers with too higher wages and social expectations would undermine the existence of the established social and political structures of the day, which operated very much in favour of the ruling minority. It was in the perceived interest of this ruling minority to ensure that the working population were kept very much in their place. Poor social and working conditions in Britain led ultimately to social unrest in the 1830s and 1840s. This unrest initiated the formation of various political pressure groups such as the Luddites and the Chartists; the growth in these pressure groups led eventually to the emergence of the trade union movement which was given formal recognition in the early 1870s.

Social unrest, coupled with the work of reformers, produced the realisation that working conditions were in need of legislation to ensure that at least the very worst working conditions were avoided. Thus Acts controlling some aspects of the factory working environment were passed by Parliament in 1833 and in 1847 (Ten Hours Act, (1847)). The introduction of this legislation was not universally welcomed at the time; by some these Acts were viewed as '..wanton and ruinous interferences with private enterprise, opinion was reconciled to them' (Hobsbawm, (1969), p 124). However, in retrospect no one ' had any doubt *now* of the wisdom of these measures' (cited in Clapham, Vol II.). These early Acts were directed at regulation of the textile industry. From 1867 onwards further regulation was introduced to control working conditions across the wider spectrum of the industrial environment. For example in 1867 a Royal Commission initiated legislation, passed by parliament in the Acts of 1871 and 1875, which gave legal recognition of the trade union movement; in 1872 the yearly bond which operated in the north-east was abolished, and in 1875 the Master and Servant Code was also abolished (Hobsbawm, (1969)).

Improvement in the lot of the labour force was not left entirely to statutory instrument. By the mid-19th century the newly emergent industries of the Industrial Revolution were sufficiently well established to not feel threatened by any proposed change in the status of the labour force. By the 1850s and 1860s some of the more enlightened British

industrialists felt sufficiently rich and secure to initiate changes for the better in their factories by promoting relatively high wages, taking a conciliatory view of workers demands and encouraging investment in grand municipal monuments such as Leeds Town Hall, which at the time of its construction, in the late 1840s, cost £ 122 000. The investment in these grand schemes was believed to be of general benefit to the community.

Thus in Britain and Europe in the middle years of the 19th century there was a general change in the attitude of the industrialists about their responsibilities towards their labour force. However, these improvements were not universal, and in countries such as the USA would have to wait until the early 1900s (Sundstrom, (1986)), if not considerably later. In some parts of the world working conditions may still compare with the worst conditions found in industry in Britain, Europe, and USA during the 19th and early 20th centuries.

Improvements in working conditions initiated by legislation, and encouraged by the philanthropic outlook of some industrialists, were subsequently verified to have beneficial effects on productivity. Companies, particularly in America, adopted 'welfare work' as a way of improving the physical working conditions of their workers. This was also seen to be a way of diverting workers' attention away from the growing influence of the trade unions. Companies carrying out welfare work reported that the money invested in improving working conditions was more than repaid by the improvements in productivity and in quality of finished items (Nimmons, (1919)).

There were also economic benefits to ensuring that workers were paid more than a subsistence wage. The workers disposable income could be used to purchase the output of the factories, thus significantly increasing the size and profitability of the home markets (Hobsbawm, (1969), pp73-74).

The change in attitude towards the management of the labour force produced the belief that workers could be treated like machinery:

>'It is only where high spirits and enthusiasm enter the human machine that, like a well-oiled engine, all parts work smoothly and produce the greatest effect with the least friction' (Meakin, (1905)).

This attitude was still prevalent among some groups of management until the 1950s, when it was realised that there were other factors influencing workers satisfaction, apart from safe, clean and appealing working conditions. However, if providing a pleasant working environment were not the entire explanation of worker satisfaction the importance of providing an ergonomically acceptable factory environment had been established in Britain, Europe and America by the late 19th century.

1.2 The Development of the Office

The development of the office lagged behind that of the factory, which was a well established part of the Industrial Revolution by the mid-19th century. By comparison some of the first buildings exclusively built as offices were not constructed until the 1840s.

The earliest form of the office was no more than a meeting place where professional people such as lawyers, bankers, brokers, and merchants met to conduct their business. These meeting places could be a room in a house, a desk in a corner of a shop or a table in a tavern (Logan, (1961)). A well known historical example of a company meeting place where business transactions were carried out was Lloyd's of London which initially met in a London coffee house (Duffy, (1980)).

The first office buildings constructed during the mid-19th century comprised single rooms which were rented out to companies. An example of one such early purpose built office building was Oriel Chambers, Liverpool which had single rooms each fitted with a fire place. During this period successful companies took to financing the construction of office buildings for their exclusive use. One such building was the three storey Sun Insurance Company offices constructed in London in 1849 (Duffy, (1980))

Sundstrom (Sundstrom, (1986)) argues that the development of large office complexes was initiated by the formation of large corporations in America following the American Civil War. These newly formed companies required central administration centres to carry out the many day to day clerical tasks necessary in a large organisation. The Standard Oil company and Woolworth's are two examples of large organisations formed in America during the latter part of the 19th century. The requirement for large purpose built office

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complexes was paralleled by the development of technology which allowed the many different tasks of a large organisations to be carried out at least semi-automatically; the new technology for example the typewriter and the mechanical typewriter, both of which were introduced into general use in the last two decades of the 19th century (Armstrong, (1972)).

1.2.1 Office Buildings

Before the advent of purpose built offices commercial premises were developed by a process of assimilation, particularly in America. Companies located on the ground floor of a building expanded their premises sideways into adjacent buildings if there were need for larger premises (Logan, (1961)). This process of horizontal expansion was ultimately choked off because of the scarcity of land in the central districts of large towns and cities. The options available were to expand further horizontally, but in the suburbs some distance removed from the established central business districts, or to build vertically in locations near to the business districts.

The first brick or masonry built multi-storeyed office buildings were six floors high. The earliest office buildings were constructed before the invention of the lift, or elevator. This imposed a limit of about six floors because this was as far as anyone was prepared to walk vertically up to gain access to the upper floors of a building. As businesses prospered they progressed downwards to the more expensive lower floors of the office building (Logan, (1961)).

Elisha Graves Otis invented the safety brake for the freight hoist in 1853, which allowed the development of a passenger carrying lift. The advent of the lift allowed the construction of office buildings higher than six floors. The limit of vertical height now became ten floors as this was the maximum practical height that offices could be built with bricks or masonry. Office buildings ten floors high required base walls 1.2 metres thick to support the mass of the building. Taller buildings became prohibitively expensive because of the volume of building material required, but also with increasing thickness of walls there was a corresponding reduction in the usable area on the lower floors of the building. The additional costs of construction could not be recovered in rents. Additionally

thick walls on lower floors restricted daylight access, often making the interior appear dingy and underlit, a further disincentive to prospective leaseholders (Shultz and Simmons, (1959), Hill, G, (1893)).

By 1865 the iron girder was introduced into the method of construction. The girder was initially used to support walls and then floors. Iron girders were superseded by structural steelwork in the 1880s. The use of steel in the structure of high rise office developments allowed buildings to increase their height very dramatically. Towards the end of the 19th century high rise office developments reached 30 storeys in 1899, Park Row, Manhattan, 50 storeys in 1909, Metropolitan Life Insurance, and 58 storeys in 1913, Woolworth Building.

Electric lighting and mechanical ventilation were in common use in office buildings by the 1930s. The use of these technologies freed the designers of offices from total dependence on natural lighting and natural ventilation. Since the introduction of these technologies the basic forms of office construction, developed during the first decades of the 20th century, have not changed significantly. The architectural detailing changes to suit current tastes; in recent years there has been a move away from hard angular lines to softer forms of detailing (Sundstrom, (1986), p 29).

1.2.2   Office Working Conditions

Historically working conditions in offices lagged behind the more strictly controlled working conditions of factories. There is a plausible two part explanation of this situation:

* The first office buildings did not appear until almost a century after the start of the main stream of the Industrial Revolution. The separation in time of the development of the two types of working environment may have created the perception that there was no need for the control the working conditions in both environments.

* The work carried out in the office environment was never as physically demanding, dirty or potentially dangerous as the work carried out in factories.

There was therefore not the same imperative requirement to control working conditions for office workers.

As a consequence working conditions in offices were often very poor until well into the 20th century. Offices commonly had poor lighting and ventilation; noise levels in offices of the late 19th and early 20th centuries were often excessive; toilet facilities were frequently located long distances from where people worked; there may also been excessive levels of dirt to add to the untidy clutter of the office environment. The layout of many early offices could also be cluttered leading to inefficiency (McCord, (1894), Wylie, (1958)); although this problem may still be found in modern offices despite all legislative and technological advances.

Working conditions in offices began to improve once reports of the beneficial effects of improving working conditions on productivity filtered through from the industrial environment. This took until the 1920s and 1930s. The initial improvements focused almost exclusively on those parts of the environment that had a direct influence on productivity; for example electric lighting, ventilation, and chairs.

The new electric technologies of lighting, heating and ventilation were common place by the 1940s, along with the introduction of acoustic tiles to reduce noise levels. These technologies represented a significant improvement in the physical environment of even the decade spanning the 1930s. By the 1950s extra-office facilities were being introduced, for example sports halls. Since the 1950s both office technology and office furniture have continued to develop, mostly although not always improving upon existing working conditions; see for example (McGregor, (1960), Shoshkes, (1976)).

Probably the most significant technological change in the office environment since the 1950s has been first the introduction of the computer, which led to the introduction of the VDU. The presence of the VDU work station, either attached to a remote computer or to a smaller local computer, is now ubiquitous. The extensive use of what is now called 'display screen technology', which includes as a sub-class VDUs, has initiated the formulation of British, European and international standards giving guidance on the use of this equipment (British Standards Institute, BSEN 29241 (1993), International Organization for Standardization, IS 9241 (1992)). These standards further led to the formulation of

binding regulations in the UK (Department of Employment, Statutory Instrument 2792 (1992)) which came into effect on 1 January 1993.

1.2.3   Open Plan Offices

Besides the introduction of the computer, the other major development of the office environment was the advent of the open plan office. Although this concept is popularly perceived as being a recent introduction, open plan offices have ben used from at least as early as the 1880s. Open plan offices were made possible following the introduction of structural steel work which allowed large open spaces to be constructed without intervening support pillars. The advantages of these large open areas became immediately obvious (Barnaby, (1924)).

> 'Large open offices are better than the same space cut into smaller rooms, because they make control and communications easier and provide better light and ventilation.'

One of the principal advantages of the open plan office was that it allowed for the easy flow of work, especially clerical work, from one part of the office environment to another. Some open plan offices implemented a literal interpretation of the flow principle by installing conveyor belts to carry work from one part of the office to another (Lefingwell and Robinson, (1943)). Cellular offices for clerical workers became less common after the introduction of the open plan office, although private offices were still used by managers and professionals.

The philosophy of the open plan office was taken to its limit with the 'office landscape', or *Burolandschaft*. This concept was introduced by the Schnelle brothers working in Germany in the 1960s. *Burolanschaft* allowed for no private offices at all, and in its purest form even partitioning of the open plan space was not allowed. Some concessions to privacy were subsequently introduced by the use of moveable partitions to define workers' space.

At first the office landscape met with an enthusiastic response. The office landscape had a number of advantages:

-       It was possible to re-arrange the open spaces very quickly, with minimal
        expense.

-       It saved space as more people could be accommodated.

-       It saved on maintenance

However the office landscape was not popular with users of the space; its primary
disadvantage was that it allowed no privacy (eg Business Week, (1978), cited in
Sundstrom (1986) p 38) workers did not like having their status removed by all working
together in a homogeneous space. With the continued reports of the problems of
Burolandschaft offices the original concept became diluted with the return to mixed open
spaces and private offices, particularly for managers (Ellis and Duffy, (1980), Rout,
(1980)).

1.3   The Contribution of the Physical Environment to Worker Job Satisfaction

There are many factors influencing the complex relationship between an individual and his
working environment. A comprehensive understanding of this relationship will probably
await the development of a full explanation of the fundamental physiological and
psychological mechanisms that underlie the relationship, if such a full explanation is both
scientifically attainable and desirable.

The development of both statutory controls and accepted good practice for the physical
aspects of the working environment, summarised for the factory and office environments
in Sections 1.1 and 1.2 above, indicate that the physical environment is an important
component of the relationship. Numerous studies have been carried out to investigate what
are the most significant factors influencing workers in their environment. Comparison of
these studies puts the importance of the physical aspects of the working environment into
perspective against other important factors. A sample of these studies is reviewed in
Section 1.3.1 below.

1.3.1 Surveys of Worker Responses about Their Work Priorities

As might be anticipated the sample of surveys, which have been carried out over a period of about two decades and in different countries, do not all show the same rank ordering of workers' priorities. This might be expected for at least three reasons:

- Different questions were asked between the surveys.

- Even if it were practicable to formulate a standard survey that could be carried out internationally, it would be reasonable to expect differences in responses because of sociological differences between countries.

- Over the period that the surveys were carried out it might be reasonable to anticipate a significant shift in workers' expectations about their working environment.

Accepting these constraints it is useful to compare the results of from a small sample of surveys to at least obtain some grasp of what, from the workers' point of view, are the important components of their work and work place, and to derive from this the relative importance of the physical environment.

Survey 1: Factory Workers 1958

Table 1.1 shows the results of a survey given in Hugh-Jones, and cited in Handy, (Handy, (1985)). The survey, carried out in the late 1950s, questioned three groups of factory workers, shop floor workers, their foremen and their general foremen. The survey investigated the ordering of 10 work related variables each classified into one of three general headings: economic variables; human-satisfaction variables and other variables. Each of the three groups of men was asked to answer all of the questions directly; additionally the foremen and the general foremen were asked to give the answers that they thought that their immediate subordinates would give.

Table 1.1 shows as a percentage the responses of each of the groups of men. The figure in parentheses besides each percentage figure gives the rank position of the variable. A

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	As men	As foremen		As general foremen	
	Rated the variable for themselves	Estimated the variable for subordinates	Rated the variable for themselves	Estimated how foremen would rate the variables	Rated variable for themselves
Economic Variables					
Steady work and steady wages	61 (1)	79 (1)	62 (1)	86 (1)	52 (1)
High wages	28 (3=)	61 (2)	17 (8)	58 (2)	11 (8=)
Pensions and other old-age security benefits	13 (9=)	17 (6=)	12 (9)	29 (3)	15 (7)
Not having to work to hard	13 (9=)	30 (3)	4 (10)	25 (4)	2 (10)
Human satisfaction variables					
Getting along with people I work with	36 (2)	17 (6=)	39 (3)	22 (6)	43 (3=)
Getting along with my supervisor	28 (3=)	14 (8)	28 (5)	15 (7)	24 (6)
Good chance to turn ot good quality work	16 (8)	11 (10)	18 (6=)	13 (9)	27 (5)
Good chance to do interesting work	22 (6)	12 (9)	38 (4)	14 (8)	43 (3=)
Other variables					
Good chance for promotion	25 (5)	23 (4)	42 (2)	24 (5)	47 (2)
Good physical working conditions	21 (7)	19 (5)	18 (6=)	4 (10)	11 (8=)
Total number of cases	2499	196	196	45	45

Table 1.1

simple analysis was carried out on the data in Table 1.1 . The 'score' value was calculated by obtaining the average position value for each of the variables in Table 1.1. The highest possible score is 1.0, which indicates that the workers associated a very high priority to the variable; the lowest score is 10.0 which shows that the workers assigned the variable a very low priority. The results of this analysis are shown in Table 1.2 .

Table 1.2

Position	Variable	Score
1	1) Steady work and steady wages	1.0
2	5) Getting along with the people I work with	2.7
3	9) Good chance for promotion	3.0
4	8) Good chance to do interesting work	4.3
5	6) Getting along well with my supervisor	4.7
6	2) High wages	6.3
7	7) Good chance to turn out good quality work	6.3
8	10) Good physical working condition	7.0
9	3) Pension and other old-age security benefits	8.3
10	4) Not having to work too hard	9.7

The ranking of the variables shows that, as might have been anticipated, the physical environment takes a fairly low priority among the factory workers included in this survey. Matters of job security, social standing and promotion prospects are foremost of the priorities. It is also true however that the physical environment is not at the bottom of the list.

Survey 2: London Office workers 1966

Table 1.3 below shows the results of a survey reported by Langdon in 1966 (Langdon, (1966)) of 2 287 London office workers. The survey again included 10 variables, or job factors. The workers were asked to select from the list of factors the two most important for 'making the job enjoyable and satisfying'.

Table 1.3

Position	Variable	Percentage Responding
1	Interesting work	32%
2	Responsibility	16%
3	Good pay	14%
4	Nice people to work with	13%
5	Plenty to do	4%
6	Security	4%
7	Pleasant office	4%
8	Comfortable and convenient office	2%
9	Convenient location of work	2%
10	Short hours	2%

Similar to the results of Survey 1, the results of Langdon's survey show that the physical environment is low on the list of priorities of the office workers included in the survey. The factors relating to the physical environment are placed at positions 7 and 8, which is consistent with the results of Survey 1, although the ordering in Survey 2 is based on percentage responding rather than a rank order.

Survey 3: Swedish Office Workers 1974

A survey reported by Lunden (Lunden, (1972)) included nine office buildings and recorded responses from 450 office workers from Sweden. Again ten variables were included in the survey questionnaire. The objective of the survey was to determine how the included variables contributed to 'contentment in the office'. Consistent with the results of the Surveys 1 and 2 above the office environment was ranked seventh.

Survey 4: Survey of American Office Workers 1978

In a survey carried out by Louis Harris & Associates in America in 1978 respondents were asked to rank in order of importance 19 job related variables. The sample size was 1 047. The two variables that were concerned with aspects of the physical environment were ranked fourteenth and seventeenth, and were rated by 45% and 37% respectively as being 'very important' by the respondents (Louis Harris & Associates Inc. (1978)). If the rank values from this survey are normalised to a variable list of ten then the two environmental variables have a normalised position of 7 and 8, rounding down the value 8.5. This is consistent with the positions of the environmental variables in Surveys 1,2 and 3.

1.3.2 Interpretation of the Survey Results

The four surveys summarised above consistently showed that the physical environment was not rated very high in workers' assessments of the variables influencing their jobs. This could be interpreted as showing that the levels of comfort and amenity of the work place environment at the time that the surveys were carried out at least satisfied minimum expectations, and probably were far beyond minimum expectations, particularly in the offices. As a result the physical environment did not figure as a variable of great importance to the workers included in the surveys.

The results of the surveys are circumstantially consistent with Maslow's exposition on the need to satisfy, at first, environmental 'deficiencies' and then strive to achieve what he has called 'self-actualization' (Taylor, Sluckin, Davies, Reason, Thomson, Colman, (1982)

pp 581 - 583). Deficiencies are generally associated with basic requirements, such as the need to satisfy the requirements for food, drink, shelter and warmth. Beyond environmental deficiencies there are also psychological deficiencies to be satisfied which include the need for self-respect and respect from others. Failure to sate the basic requirements, or deficiencies, can result in frustration and unrest. Maslow calls the striving to satisfy these basic requirements 'deficiency motivation'.

Once deficiency requirements have been satisfied psychological the individual focuses on growth motivation, so called self-actualization. This psychological focus drives individuals to attain personality growth in order to enjoy higher forms of satisfaction, for example aesthetic appreciation of art and music.

Maslow's hypothesis about the need to satisfy the basic deficiencies is intuitively appealing; the extension of his argument into self-actualization is more controversial; see for example (Taylor et al, (1982), pp 581 - 583).

As the physical environment was not placed very high in the list of factors influencing workers attitudes to their work it is reasonable to assume that the physical environments in which the respondents worked satisfied the environmental deficiency requirements of Maslow's hypothesis. This proposition is supported by the rating assigned to the environmental parameters (Survey 4). Forty five percent and thirty seven percent of the respondents in this survey rated the environmental variables as 'very important', despite the variables being ranked 14 and 17 out of 19. This indicates that the respondents in this survey appreciated that although their physical environment more than satisfied their current expectations, if the physical environment were to change for the worse then the environmental variables would probably be placed higher in their rank ordering.

There is indirect evidence to support Maslow's hypothesis about environmental deficiency motivation and the effects on productivity of not satisfying the basic environmental requirements. Elton (Boyce, PR. (1981) p 81) reported on the variation in the output of silk weavers over a fifteen week winter period. Figure 1.1 and Figure 1.2 show how the output of the silk weavers varied with the availability of daylight during the period of the study. There is clearly a strong correlation between output and daylight availability. Thus the absence of adequate light at the work place of the silk weavers had a direct impact on
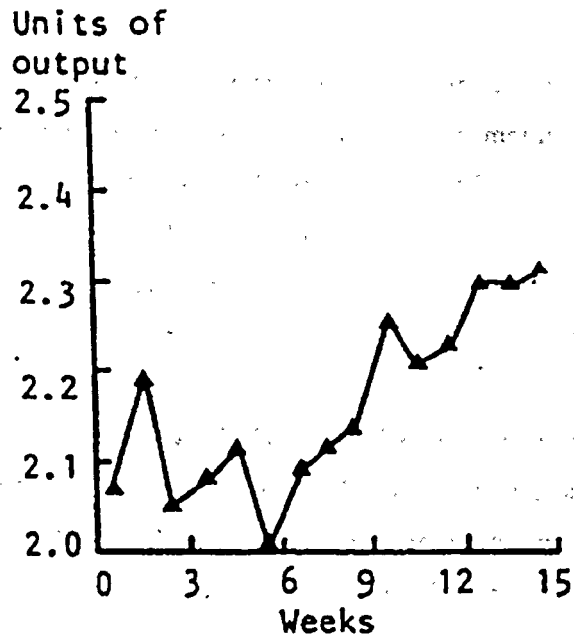
Figure 1.1   Output of silk weavers over a 15-week period
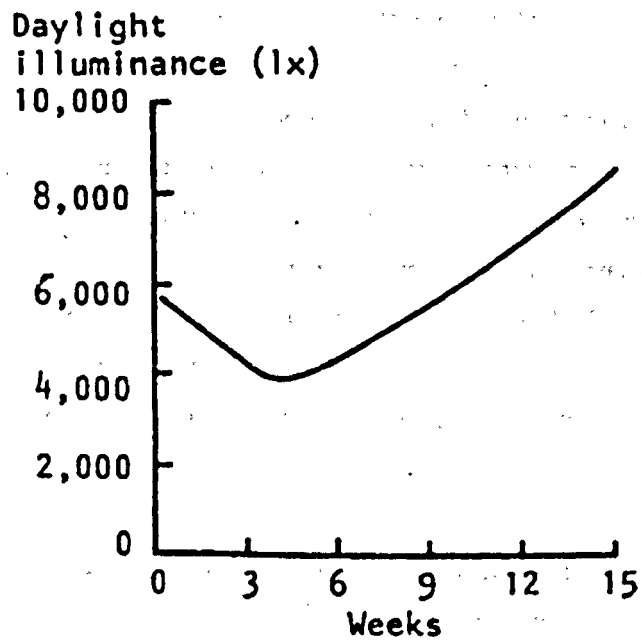
Figure 1.2   Daylight availability for the same period shown in Figure 1.1; there is a strong correlation between output and daylight availability; [after Elton, (1920)]

their productivity. At certain times over the fifteen week period the quantity, and perhaps distribution, of light was not adequate for the visual task; there was an environmental visual deficiency in the silk weaving sheds.

A further example offering indirect support to the environmental deficiency hypothesis comes from Vernon (Vernon, (1919)). His report showed that there was an apparently direct influence of different rates of ventilation on the relative output of five tinplate factories. Thus during the summer months when ambient temperatures rose poor ventilation resulted in decreased output relative to the winter maximum. Factories where 'good ventilation' systems were installed maintained an approximately constant output throughout the year, Figure 1.3 . The inference that can be drawn from this study is that if body temperatures become too high then it is not possible for workers to operate as efficiently compared to their efficiency at normal body temperatures.

Despite the low apparent rank ordering of the physical environment by workers there also appears to be an appreciation that this is because the present levels of comfort in some industrial environments, but more particularly in the general office environment, are adequate to at least satisfy minimum physiological and psychological expectations. Additionally, field studies have shown that there is a persistent correlation between worker satisfaction with the work space and job satisfaction; see for example (Sundstrom, (1986), p 78 ff).

Sundstrom (Sundstrom, (1986), p 80) has suggested the schema shown in Figure 1.4 which shows the range of factors likely to influence the workers attitudes. The components included in the model shown in the schema may not be exhaustive, but it illustrates the broader context into which the physical environment fits.

Of course it is possible to find exceptions to prove the rule that workers generally prefer to operate in a comfortable and pleasant environment given the choice. Brown (Brown, (1954)) cites the case of six women working in a small dimly lit and cold basement of a London slaughter room. The work carried out by the women was sorting pig offal in extremely unpleasant conditions, the floor being covered in viscera and blood. Visitors to the room reported that the stench from the room was overpowering. Despite these appalling conditions the group of six women were happy in their work and strongly
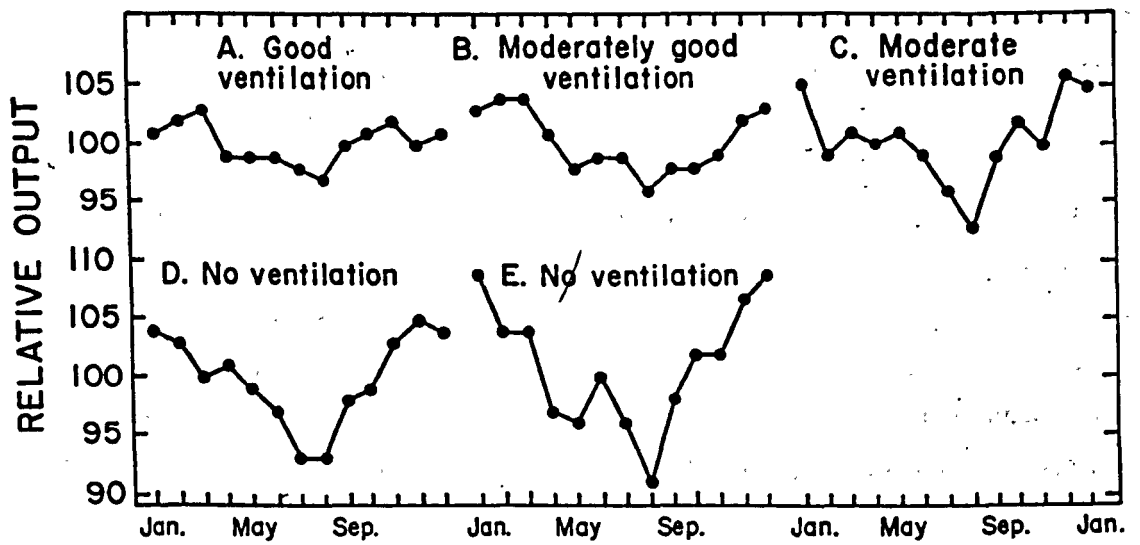
Figure 1.3   Plot showing variation in 'relative output' of five tinplate factories correlated with time of year, and different ventilation rates; note the split scale on the ordinate;[after Vernon, (1919)]
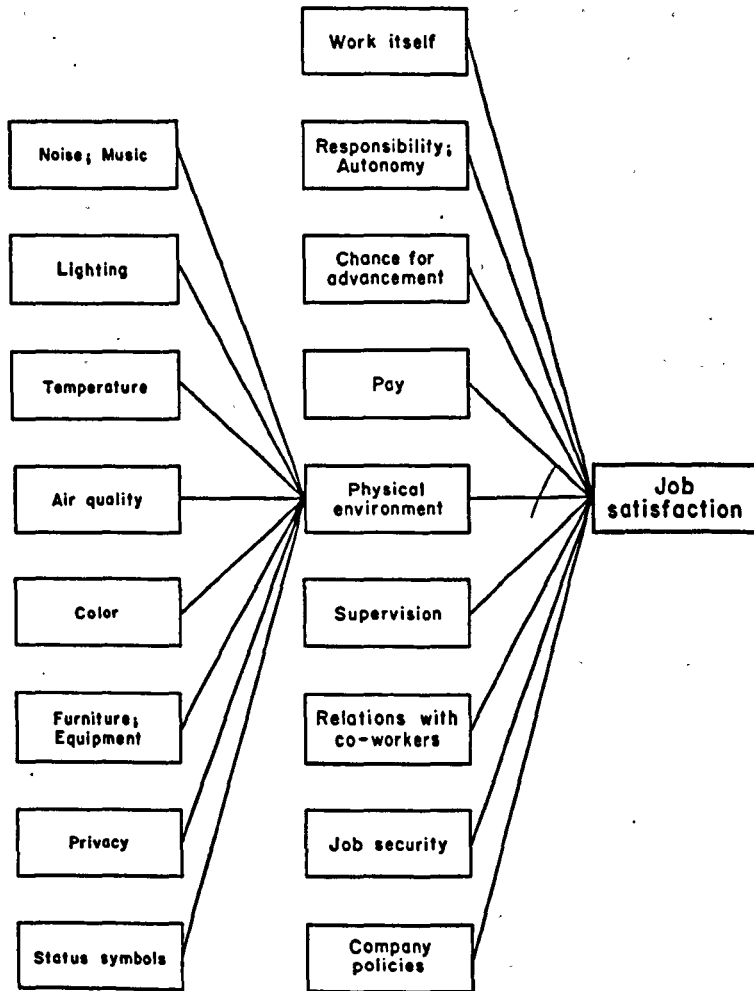
Figure 1.4   Schema proposed by Sundstrom, placing in context the importance to workers of the physical environment, among the broader set of issues contributing to job satisfaction; [after Sundstrom, (1986)]

resisted efforts to improve their working conditions. It was thought that in this particular instance the group cohesiveness was far more important to the women than working in a pleasanter environment; doubtless other examples could be found of workers resisting efforts to improve very poor working conditions.

The general principle, however, is clear to owners of industrial or commercial premises, architects, building services engineers, interior designers and all other parties directly or indirectly concerned with providing, designing and maintaining work place environments: Within practical and economical constraints workers should have a safe, comfortable and where possible pleasant environment. Failure to provide a reasonable work place environment may result in a high level of complaints from the labour force. There may also be significant adverse effects on productivity.

1.3.3 The Rationale for Continuing Research into Human Interaction with the Physical Work Place Environment

The question arises:

> If there is sufficient knowledge available to allow work place environments, both industrial and commercial, to be designed to provide at very least the minimum requirements of safety and comfort, why is there the need to continue to research into the human interaction with the physical work place environment?

There exists sufficient scientific and technical knowledge to allow safe and comfortable work place environments to be designed and built. That it is possible to cite examples, in the industrially developed and developing countries, of work place environments that clearly do not satisfy minimum safety or comfort requirements is a matter to be addressed by social policy acted upon and implemented by politicians.

There are at least three answers to the question:

i.   Many existing models concerned with predicting the human response to the physical environment are empirically derived and are therefore *ad hoc*. These

ad hoc models should be strictly limited to predicting human responses to the range of physical conditions which were used in the experiments from which the models were derived.

The models are in many cases applied generally and with success; this however does not surmount the fundamental limitation inherent in the models. This situation can lead to circumstances where model predictions or derived recommendations are applied beyond valid limits. Consequently design decisions based on predictions and recommendations may be in error or wholly invalid. Without understanding of the fundamental processes that underlie the human factor models it is not possible to derive limits of application for the models.

Research is desirable because there is continual change in the physical working environment; consider for example the dramatic changes that have taken place in the office environment in the past two decades. If efficient models of the human interaction with the physical environment are to be maintained then one of two philosophies will need to be adopted:

* The models of the human response will need to be continually updated to ensure that the models are derived from experiments and studies using contemporary technology.

* Research should be carried out to determine the fundamental mechanisms that determine the human response to the physical environment. Once developed a fundamentally based model will be technology independent and should be applicable over all conditions.

It could be argued that one of the long term aims of research concerned with modelling of human perception is to develop fundamental understanding of the human interaction with the physical environment.

ii.   Although existing empirical models provide adequate levels of comfort they may be energy inefficient. There is currently much emphasis on the need for

energy efficient building services. This emphasis is set to continue for the foreseeable future, and is likely to become even stronger than at present. It is plausible that in the medium term future there will be a 'carbon tax ' imposed so that energy inefficient buildings will be taxed according to how far short they fall of some agreed energy use standard. It will be to necessary to ensure that all concerned with the construction and maintenance of buildings and building services have at there disposal techniques that will allow for energy efficient design and use.

The drive for energy efficient design should not incur uncomfortable working conditions on the labour force. Research is needed to ensure that the interaction between energy efficient design and ergonomic design is understood, and that the optimal conditions where maximum energy efficiency can be achieved while providing a working environment that allows the potential for maximum productivity from the labour force.

iii.   Developing understanding of the fundamental mechanisms underlying the human interaction with the physical environment is scientifically desirable.

1.4 The Current Status of Research into Human Factors and Lighting

Research into human factors and the physical environment can be classified into five general headings. These are:

i.   Lighting and the visual environment

ii. Thermal comfort

iii. Ventilation

iv. Noise

v.   Layout of the physical environment; both of individuals work stations and of the

Table 1.4 Empirical Studies Concerning the physical environment in offices and factories [after Sunstrom, (1986)]

Level of analysis and topic of study	Number of studies in each category						
	Laboratory experiments	Field experiments	Surveys	Field studies	Totals	%'age of grand total	%'age of Individual
* Individual							
Lighting	13	1	-	5	19	6.6%	9.6%
Windows	-	-	3	1	4	1.4%	2.0%
Temperature	27	2	2	8	39	13.4%	19.8%
Air quality	4	-	2	1	7	2.4%	3.6%
Noise	72	1	1	1	75	25.9%	38.1%
Music	9	9	1	-	19	6.6%	9.6%
Colour	25	-	1	-	26	9.0%	13.2%
Work-stations	2	-	5	1	8	2.8%	4.1%
Sub-total					197		100.0%
* Interpersonal relations							
Status	-	-	1	1	2	0.7%	
Personalization and participation	-	1	1	3	5	1.7%	
Ambient conditions and interaction	8	-	-	-	8	2.8%	
Proximity of workspaces and interaction of workgroups	-	-	-	9	9	3.1%	
Room layout and interaction	11	-	1	9	21	7.2%	
Privacy and enclosure	-	-	4	8	12	4.1%	
Seating arrangements and group discussions	12	-	-	-	12	4.1%	
* Organisation							
Organisation, structural and physical layout	-	-	-	1	1	0.3%	
* Comprehensive studies and post-occupancy evaluations	-	2	15	6	23	7.9%	
Totals	183	16	37	54	290	100%	

whole work space

Sundstrom (Sundstrom, (1986)) has carried out an analysis of a sample of 290 references on empirical studies of human factors and the physical environment of factories and offices. His analysis is replicated in Table 1.4 with the addition of percentages for the different categories of research; the percentages are relative to both the total number of references included in the survey, and the number of references in the individual category.

The analysis shows that for this sample, which is assumed to representative of the population of references on human factors and the physical environment, 68.1% of all of the cited references have investigated individual responses to the physical environment. Within this category, individuals' responses to noise has been the most extensively researched subject. If all of the categories relating to lighting and vision, colour, lighting and windows, are summed to form a single category then this represents the second largest research category, indicating the relative importance of human factors and, lighting and vision research.

That lighting and vision research represents a high proportion of the cited references has at least two plausible explanations:

i.   Under normal working conditions the designed luminous environment has the greatest immediate sensory and psychological impact on workers. A poorly designed luminous environment is likely to cause many complaints from workers, and may also have a significant adverse effect on productivity.

ii. In the office environment annual lighting energy costs can be the single largest component of the annual energy bill (Building Research Energy Conservation Support Unit, (October 1991). There is a need to derive lighting design models, procedures and recommendations that are both ergonomically acceptable and energy efficient.

There is clearly an imperative need to get the lit visual environment 'right'.

Chapter 2 Lighting Design: Quantity and Imponderables and the Development of Contemporary Glare Models

2.1 The Quantifiable and Unquantifiable Parameters of Lighting Design

The constituent parts of lighting design practice, such as models, procedures, codes, recommendations, and general guidance, can be classified under two general headings:

    i.   'Quantity'

    ii.   'Imponderables'

Quantity is generally concerned with sensory attributes of the human visual, and possibly psychological, response to the luminous and chromatic environment eg can a visual task be seen; and with the physics of the luminous environment together with the hardware of a lighting installation eg working plane illuminances, surface reflectances, inter-reflection components, light sources and luminaires.

Imponderables are more difficult to define. Variables in this class are concerned with perceptual attributes of the visual and psychological response to the luminous environment, and with their consequent affect on subjective responses eg does a particular luminous environment produce positive, negative or indifferent responses.

A proposal for a definition of the two categories of human factors in lighting variables Quantity and Imponderables is given below:

> **Quantity:** The components of lighting design practice classified as belonging to the category of Quantity are defined as being directly, or indirectly, affecting the distribution of visible radiation in a luminous environment that results in an objective and measurable response from human subjects.
>
> In general the responses to variables belonging to Quantity are sensory. For example, if it were required the responses to a particular lighting variable belonging to the category Quantity could, in principle, be measured directly eg physiologically. An example of such a response would be the measurement of the

visual system's output detecting a task at just above threshold contrast (eg Barlow and Mollon, (1982); for a general and philosophical discussion of sensory and perceptual experiences see Lacy, (1986); Ayers, (1979); Davidson, (1979); Hampshire, (1979)).

Imponderables: The components of lighting design practice classified as belonging to this category are defined as being those aspects of the luminous environment for which it is not possible to measure an objective response in the sense that it can be made for Quantity parameters. Responses to Imponderable variables are then, by definition, subjective and can generally be regarded as being perceptual in origin. Examples of Imponderable invoked responses are those related to aesthetics and certain classes of comfort response.

The primary difference between observer responses to Imponderable and Quantity variables is that for Quantity variables it is possible to identify and define a criterion, or criteria, which has a common identity across a wide range of observers. In experimental studies the use of such a criterion by subjects for assessing their response to an independent stimulus variable invokes a class of response common across subjects. The analysis of experimental results will indicate that much of the experimental variance can be attributed to changes in the magnitude of the independent stimulus variable.

It is not possible to provide the same rigorous class of criterion for use by observers in assessing Imponderable variables. Thus the responses of observers to an Imponderable variable will display a much wider range of variance , as there is no common identity for the assessment criterion across observers. In experiments it will not be possible to attribute the same proportion of experimental variance to the independent stimulus variable as it would be for responses to a Quantity stimulus variable.

The perceptual responses produced by Imponderable variables must ultimately be founded on the sensory responses initiated by Quantity variables. The causal links between perceptual responses and sensory input channels are in many cases not established, and are the subject of continuing and intensive research in the field of perception research (eg Blakemore, (1990)). 'Tongue-in-cheek' estimates (Taylor, (1991)) of the time required to establish and fully explain all of the causal links between sensory input channels and

perceptual response mechanisms as being of the order of 1 000 years; the moral is clear: our current understanding of perceptual mechanisms is very limited. This is generally true, and therefore must also be true for lighting design.

At the present time many of the lighting variables classified as Imponderable may have a significant influence on the perception of quality in the luminous environment. With advances in knowledge about the sensory mechanisms underlying perceptual responses it is possible that variables should change their classification from Imponderable to Quantity. By defining, and if possible quantifying, the influence of Imponderable variables on perceived quality it should be possible to provide lighting practitioners with more rigorous methods for designing-in the appropriate type and level of quality into an installation. It is the theme of this dissertation to explore the development of an objective scale for the measurement of one particular Imponderable lighting variable.

One of the long term aims of lighting design research is to place all lighting design models, recommendations and guidance in the Quantity category; to explain all responses to lighting and visual variables by physics and physiology (Campbell), if this is a scientifically achievable objective.

2.1.1 The Significance of Imponderables

Changes in the magnitude of a Quantity variable can have a direct influence on the ability to carry out a visual task eg task contrast, and hence directly affect productivity. The influence of changes in an Imponderable variable on worker productivity is generally less well defined, and may well show no measurable effect, using contemporary experimental methods, on specific performance or general productivity.

However, the surveys reviewed in Chapter 1, Section 1.3.1 above indicated that the physical environment, given an adequate level of safety and comfort, was not a high priority for workers. So many of the lighting variables that have a direct and objective effect on productivity do not have anything other than a superficial effect on workers' perceptions on the work place.

The ambience, or perceived quality, of the work place environment created by Imponderable environmental variables may have a more profound, but indirect effect, on productivity. Consider as an example of this argument the results of Survey 1 in Chapter 1, Section 1.3.1. This survey showed that the 'Human-satisfaction' variable 'getting along with the people I work with' was high on the list of priorities of all three groups of workers interviewed; 2/10, 3/10, 3/10. It might be reasonably expected from the results of this survey that if a worker's relations with his colleagues are poor then his productivity may be adversely effected, even though for industrial processes there is no direct link between variable and the work being carried out. Unless that is relations deteriorate to the point where colleagues physically interfere with a worker in the execution of a work process; at this stage the poor relationship will probably require arbitration by personnel management!

Perceived quality of the work place could also have an indirect, but significant effect on productivity. This might be because perceived quality might have implications for self-actualization as hypothesised by Maslow, and discussed in Chapter 1, Section 1.3.2 above. Consider a fictitious and exaggerated example. Some groups of workers might aspire to working in an environment of grand surroundings such as a stately manor, in the role of a caretaker, because the perceived quality of the environment may have an influence on social standing among peers.

There are a gamut of matters relating to the perceived quality of the work place environment, ranging from those which have an influence on high order psychological responses associated with self-actualization to those which are more closely related to sensory and primary psychological responses. One of the established and important lighting Imponderables thought to affect peoples perceived quality of the work place environment is the so called discomfort glare.

2.1.2   Discomfort Glare is an Imponderable Lighting Variable

There is no definitive understanding of what causes discomfort glare. A consensus agreed upon by most researchers in the subject is that discomfort glare is an aversive response to the presence of a luminance in the visual field of an observer that is of too great a value

relative to the ambient background luminance. An alternative statement is that discomfort glare is caused by excessive luminance contrast, more usually with the source of discomfort glare at a luminance higher than the ambient luminance. The luminance contrast that is the source of the discomfort glare normally forms a significant proportion of the total area of the visual field, and has greatest effect close to the line of sight of the observer. The so called glare source can be present either as a few large areas of luminance, or can be distributed throughout the visual field as a larger number of small high luminance sources (Petherbridge and Hopkinson, (1950)).

There are several models available which will calculate numerical estimates of the subjectively perceived levels of discomfort glare. These models are all based on empirical studies, and include no fundamental understanding of the phenomenon. All discomfort glare experimental data sets exhibit large variance, see for example (Bodmann, Sollner and Senger, (1966); Manabe, (1976); Perry, (Melbourne, 1991)). This implies that as yet no suitable criteria have been developed that have a common interpretation between observers.

This condition, together with the absence of any definitive understanding of the underlying mechanisms of discomfort glare, place the phenomenon in the category of Imponderable lighting variable.

There are incidental effects of this argument for the existing discomfort glare models. The absence of both fundamental understanding and suitably well defined experimental criteria imply that any scales developed to indicate the magnitude of discomfort glare are not well founded. The precision apparent in the mantissa places quoted in calculated values of discomfort glare is spurious and is a result of the arithmetic carried out in the calculation process; discomfort glare levels quoted to even the first mantissa place are excessively precise. The numerical values of discomfort glare produced by the models are no more than superficial indicators of the perceived level of discomfort glare.

2.2   The Historical Development of Models of Glare

It is difficult to define the precise historical sequence of events that led to scientific interest in the concept of glare. Research investigating glare seems to have its origin at the beginning of the 20th century. As described in Chapter 1, Sections 1.1 and 1.2 above, there was during this period a great interest in how the physical environment of the work place might be improved which had, until recently, been left unregulated by statute or design guidance, resulting in appalling physical environments for the workforce. As part of this movement one of the components of the physical environment which was found to significantly affect productivity was lighting.

2.2.1   A Flood of Lighting

Interpreting in retrospect the sequence of events in lighting research during this period, the first realisation was that increasing the amount of light in the work space had a beneficial effect in productivity. This realisation produced a great enthusiasm for lighting of the work place, and as a consequence the philosophy that 'more light was *de facto* better'. For example Lukiesh (Lukiesh, (1924)) thought that:

> 'Well lighted surroundings promote cheerfulness...There is no danger of over lighting in this respect. Certainly working men are depressed by improper and inadequate lighting.'

In the same report Lukiesh catalogued the benefits of improved lighting claimed by management . These included production increases of 79% and a decrease in accident rate of up to 60%.

Hollingworth & Poffenberger (Hollingworth, and Poffenberger, (1926)) reported that, under controlled conditions, improved lighting resulted in increased productivity in the range 8% - 27%, with an average increase of 15%. These increases in productivity were obtained at the expense of only '5% of the payroll for the period'. Exciting days indeed for lighting research!

The impetus to provide more light was complemented by the increasing use of electric lighting in the work place environment. Electric lighting was a useful supplement to natural light; it could be used when there was not sufficient light to light a space or at night time when there was no natural light at all. By about 1930 the transition from an almost exclusive reliance on natural lighting to the use of natural lighting supplemented by electric lighting was complete.

2.2.2   The Flood Stemmed

The discovery that increased lighting levels led to improved productivity was paralleled by the realisation that too much light could have an adverse effect on productivity. Too much light could directly affect productivity by reducing task contrast, or visibility, because of the veiling effect of the scattering of light in the optic media of the eye. As early as 1883 (Urbantschitsch (1883), cited in Cobb, PW, (1911); Sewall, (1884) ibid) reports were published of the effects of light scatter on the visibility of visual tasks.

The reduction of task visibility by scattered light was called glare. Uhtoff (Uhtoff, ibid, (1899)) and Depene (Depene, ibid, (1900)) were two of early researchers investigating the effects of glare. They reported that:

> '...that visibility was influenced by the angle of the eccentric light source and the direct line of vision.'

Brorschke (Brorschke, ibid, (1904)) attempted to quantify the effects of glare. In his study the glare source was a circle of six diffused lamps surrounding a test object. He defined the effect of the glare source on task visibility geometrically using the ratio M/N as:

> '...the measure of the disturbance of vision by the glare.

[Where:]

> M was the distance of a lamp to the test object
> N was a modified distance when the test object was surrounded by a glare-light'

In accord with the growth of interest in lighting the British Illuminating Engineering Society was formed in 1907. A paper presented by Sir John Parsons (Parsons, (1922)) at one of the first meetings of the Society was on the subject of glare. In the discussion period after the presentation Professor L Weber proposed ways in which glare might be avoided, and suggested that to minimise the incidence of glare interior light sources should be limited to the luminance of an ordinary candle flame, about 4 000 cd m^{-2}.

During the same discussion period Weber also proposed that glare was most likely to be dependent on the luminance of the glare source, the luminance of the background, and the position of the source relative to the line of sight of the observer. These three glare variables are included in all of the present day models of discomfort glare.

2.2.3   Nutting's Work: A Precursor to Contemporary Glare Research

Further research into glare was reported by Nutting in 1916 (Nutting, (1928)). His paper was entitled 'Effects of Brightness and Contrast in Vision' (Nutting, (1916)) and was presented to the Optical Society of America, of which Nutting was a founder member.

Nutting discussed in his paper the effects of lighting on seeing. He concluded that although the visual sensations could not be measured directly, derivatives of the visual sensation, ' sensibilities', could be measured. One of the sensibilities described by Nutting was the Glare Sensibility, which was defined by a threshold type measure. In Nutting's words:

> 'In this case the eye previously adapted to a given known brightness is suddenly exposed to a field just bright enough to appear glaring.'

Nutting presented a further paper on the subject of glare to the IES of North America in 1920 (Nutting, (1920)), which described the experiments carried out in 1916. The paper included a description of the method used to intermittently present the glare source to subjects. The method of intermittent presentation of glare source was to form a major component of many of the glare studies which followed. The next series of studies carried out in North America was initiated by Lukiesh, and by Holladay, both collaboratively and

independently of each other (Lukiesh, (1924); Lukiesh and Holladay, (1925); Holladay, (1926)).

The period ending with Nutting's studies laid the foundations for the investigations of glare carried out during the 1920s. The sequence of studies, of which Nutting's was the precursor, eventually led to the formulation the models of disability and discomfort glare in use today.

By the early 1920s the concept of glare was well established. The introduction of the concept of glare brought with it the understanding that not only was it necessary to have an adequate amount of light in the work place, but that the light had to be distributed to avoid the problem of glare. Thus glare was the first lighting 'quality' variable to be introduced.

The distinction between disability and discomfort glare did not exist at the time that Nutting carried out his experiments. The division of glare into two categories had to await the work of Holladay and of Stiles which was carried out during the last half of the decade of the 1920s.

2.3   The Development of Contemporary Glare Models

2.3.1   The Work of Holladay

There is no definite date that marks the genesis of contemporary glare research. If a survey were carried out among researchers interested in glare asking for their assessment of when they thought glare research had started there would probably be a significant proportion of responses which cited Holladay's 1926 paper (Holladay, (1926)) as one of the seminal papers in contemporary glare research. Holladay working in America, and who had also carried out collaborative research with Lukiesh into glare (Lukiesh and Holladay, (1925)), carried out a very extensive investigation into the effects of light scatter on the task visibility. The paper reporting the results was entitled 'The Fundamentals of Glare and Visibility', confirming the association of the noun 'glare' with the effects of scattered light on task visibility in the vocabulary of lighting practitioners.

Holladay's principal interest lay in characterising the effects of different types of light scatter on task visibility. From his previous work with Lukiesh (Lukiesh and Holladay, (1925)) three types of light scatter effect were identified, definitions which also adopted the main recommendations of the 1922 IES of North America sub-committee on glare (Nutting (1920) opt cit, p 251). The three glare types defined were:

i. Veiling glare; subsequently called veiling luminance

ii. Dazzle glare; became associated with discomfort glare

iii. Blinding glare; identified by Stiles as disability glare (Stiles, (1929))

The principal theme of Holladay' s 1926 reported a range of models, empirical findings , and definitions about each of the three types of glare. Each of these light scatter, or glare, effects were reported to have different influences on task visibility. The central assumption of each of the reported glare effects was that reductions in task visibility, which caused increases in the contrast of a task to reach threshold, could be attributed to light scatter effects.

Holladay also discussed what he called the 'psycho-physiological effects of light-sources'. These effects were associated with sensations of '...pleasure or discomfort...', and were identified as being influenced by the size and brightness of the light source and by the brightness of the background to the light source. The degree of 'pleasure' or 'discomfort was assessed using the method of intermittent presentation that was to be used by a majority of the subsequent American discomfort glare researchers. The psycho-physiological effects identified by Holladay were a precursor to the type of glare that was later called discomfort glare by Stiles.

The results of Holladay's study of the psycho-physiological effects produced a twelve point numeric scale which identified different levels of 'sensation' or 'shock'. These semantic definitions ranged from 'when sensation is scarcely noticeable' ,numeric scale value 0.3, to 'when sensation is irritating (higher levels painful)', numeric scale value 2.8. The scale proposed by Holladay resembles in principle the multiple criterion scale developed by Hopkinson for use in the discomfort glare studies that were carried out in Britain during the 1940s and 1950s and from which was derived the British Glare Index system.

The most visually debilitating form of glare was the so called blinding glare. It was blinding glare that was to be subsequently identified by Stiles as disability glare (Stiles, (1929)). It was to come to mean the type of glare that would produce a reduction of task visibility because of light scatter effects.

Thus Holladay's study and report, although it may have been subsequently developed upon or shown to be wrong in detail, covered much of the ground that was to be investigated in the study of both disability glare and discomfort glare for the period up until the 1960s.

2.3.2   Stiles' Theoretical Riposte to Holladay

During the same period that Holladay was carrying out his investigations into glare Stiles, working independently in England, was also investigating glare. Stiles reported a series of papers on glare. His 1929 paper reported to the Royal Society in 1929 (Stiles, (1929)) was a detailed theoretical study of the contribution of light scatter from a glare source to retinal illumination, and its effect on the 'smallest perceptual difference of retinal illumination'.

Stiles concluded that in order to produce the observed effects on task visibility reported by Holladay there had to be 35.5% loss of light due to scatter in the optic media of the eye. At the time of Stiles' study there were no results available reporting the optical properties of human eyes. To estimate these properties he extrapolated the optical properties of ox's eyes to human eyes. From these deduced properties Stiles argued that the maximum likely light loss that could be attributed to light scatter was 15%. Therefore the changes in task visibility reported by Holladay had to be attributed to factors other than light scatter. To quote Stiles (Stiles, (1929) opt cit):

> 'It may be concluded that the observed rise in the threshold in the presence of glare
> is due principally to causes other than the light scattered in the eye media, and that
> the scattering effect can only play a minor role in the phenomenon.'

Later in 1929 Stiles published another paper entitled 'The Nature and Effects of Glare' (Stiles, (December 1929)) which was presented to the British IES in November 1929. It

was in this paper made explicit the distinction between 'disability' and 'discomfort glare' (Stiles, (December 1929), opt cit):

> 'Perhaps I may be permitted at this stage to coin a new term and speak of "disability glare" as distinct from "discomfort glare".'

In an editorial of the Journal of Good Lighting for December 1929 (Stiles, (December, 1929) op cit) Stiles' presentation received a favourable review. The editorial commented on disability and discomfort glare:

> 'The former [disability glare] impairs the ability of the eye to distinguish small changes in brightness, the latter [discomfort glare] causes discomfort...

> 'Both forms of glare usually occur simultaneously, but not necessarily to the same degree, and the relation to such factors as brightness, candle-power and angular position of the source may not be the same in the two cases.'

2.3.3   Foundations Laid

The work of Holladay investigated the effects of light scatter and tentatively identified the psycho-physiological effects of glare sources. The work of Stiles had theoretically argued the existence of non-scattering mechanisms to explain threshold contrast elevation and positively distinguished between light scatter effects, called disability glare, and non-light scatter effects of glare sources, called discomfort glare. The work of these two men laid the foundations for much of the glare research that was to follow, and which eventually led to the formulation of the British Glare Index system (circa 1950), the American Visual Comfort Probability system (circa 1960), and the German Limiting Glare system (circa 1965).

2.4 Disability Glare

The effect of scattered light, or disability glare, on task visibility can be intuitively understood by considering that task visibility reduction due to light scatter from a glare source is equivalent to placing a uniform luminance veil in front of the task. The equivalence of disability glare and veiling luminance provides a basis for quantifying the effect. Not surprisingly the veiling luminance that is deemed to produce the same effect as light scatter from a glare source is called the 'equivalent veiling luminance', L_v. It is the variable L_v which is used as a measure of the disability glare effect from a glare source. Both Holladay and Stiles agreed on the general form of the function for calculating L_v for a single disability glare source (Holladay, (1926); Stiles, (1929)) which was:

$$L_v = k \frac{E_G}{\theta_G{}^n}$$

Where: L_v = Equivalent veiling luminance

E_G = Equivalent retinal illuminance due to the glare source

θ_G = Angle subtended by the glare source to the line of sight

k, n = constants

This formula became known as the Holladay-Stiles expression. There was disagreement between Holladay and Stiles over the values of the constants k and n. Much of the research carried out since Holladay and Stiles identified the general form of the disability glare function has focused on evaluating values of the constants k and n.

In the 1950s Fry (Fry, (1954)) offered a rebuttal to Stiles' discussion about the values of the two constants, and generally supported the values discussed by Holladay. Fry's arguments seem to have won the day as the values of the constants k, n used in the present form of the disability glare function as used in Britain (CIBSE Code) are similar to those proposed by Holladay; that is:

k = 10 or 9.2

n = 2 or 3.44

Vos carried out a long series of studies into disability glare, and published an extensive review of the subject in 1984 (Vos, (1984)).

There is a consensus that the constant k is an age dependent parameter, and that n is a viewing geometry parameter. Some researchers have also assigned a varying index, m, to E_G (Christie and Fisher, (1966)).

In general the development of a model of disability glare seems to have been an uncontroversial process. The form of the model given in the CIBSE Code for Interior Lighting (CIBSE, (1994)) is recognisably of the same general form initially discussed by Holladay and by Stiles. In the present form of the disability glare function the meaning of the variable E_G has been modified. E_G is now taken to be 'the illuminance at the eye on a plane perpendicular to the line of sight' (CIBSE (1994)) from the glare source. Also the evaluation function is given assuming that in general there will be more than one glare source in the field of view. Also there are two forms of the function which are applicable over different ranges of θ. The summation of the individual glare source effects is given by:

$$L_v = k \sum_{i=1}^{m} \frac{E_i}{\theta_i^n}$$

Where: E_i = The illuminance at the eye on a plane perpendicular to the line of sight from the ith glare source

θ_i = The angle between the line of sight and the ith glare source

m = The number of glare sources

For the two different ranges of θ the indices k, n take different values. These are:

i. $1.5° \leq \theta < 60°$:

k = 10

n = 2

ii. $\theta < 1.5°$
      $k = 9.2$
      $\theta = 3.44$

The straightforward development of the disability glare model may be attributable to the fact that the model is founded on well understood and well defined physical and geometrical optic properties. This plausibly permitted the formulation of well defined experimental criteria that had a common interpretation across subjects. This would have resulted in data sets with small variances. The choice of appropriate model functions to fit to the data sets would have been eased by the small variance in the data.

It is clear that disability glare is a well understood phenomenon. What is less well understood is whether disability glare in any way influences the subjective assessment of discomfort glare. Although the established view is that the two glare types are distinct phenomena which can occur concurrently. This matter is discussed in more detail below in Chapters 3 - 5.

2.5   The Development of the Major Discomfort Glare Models

2.5.1   Summary of the Development of the Major Discomfort Glare Models

In addition to identifying the two major types of glare, the work of Holladay and Stiles also implicitly set the precedent for the division of national research interests in glare. In Britain Stiles' work on glare in the late 1920s and early 1930s provided the foundation for Hopkinson's first studies of discomfort glare in the late 1930s, and subsequently to the development what was to become the British Glare Index system by Hopkinson and Petherbridge in the 1950s and early 1960s. Hopkinson also modified some of the experimental techniques used by Holladay; for example Hopkinson's 4-point multiple criterion scale was a derivative of Holladay's 12-point scale (Hopkinson, (1940)).

On a different development path was the work of the American glare researchers who used the methods and concepts proposed by Holladay as the progenitor for the American Visual

Comfort Probability (VCP) system. The work of Holladay initiated further glare studies by Fowler and Crouch (Fowler and Crouch, (1941)), Harrison (Harrison, (1945)), Fry (Fry, (1956)), Meaker (Meaker and Oetting, (1953)) and Guth (Guth, (1963)). It was the work of Guth through the 1950s and into the early 1960s that produced the VCP system. The national division of interests was more than superficial. The British glare researchers used a method of continuous presentation of glare sources to their subjects, while the Americans following the precedent set by Nutting (Nutting, (1916)) and Holladay used an intermittent presentation method.

The German research interest in discomfort glare started relatively late. Their interest was prompted by the desire to develop a simple method of discomfort glare calculation. Sollner carried out a series of studies between 1963 - 1965. The results of these studies were subsequently translated into the German Glare Limiting system with Fischer as the prime mover of the development work.

During the period that the British and American and glare research were busiest other national research communities were also active. Notable among these were the Australians, whose most prominent glare researcher was Lowson, see for example (Poulton, (1991)). For many years Lowson promoted efforts, mainly under the auspices of the CIE, to adopt a universally applicable discomfort glare method. Also active in the role of mediator working to achieve a common model of discomfort glare was the South African Einhorn (Einhorn, (1969)).

Since the early 1950s, as befits the international representative body of lighting, the CIE has been active in promoting the adoption of a single glare assessment method. CIE Committee E-3.1.1.2 'Estimation of Comfort in Lighting' was one of the earliest committees set up to report on visual comfort in the luminous environment and to develop a visual comfort evaluation method. This committee was set up at the 12th Session of the CIE held in Stockholm in 1951, and kept its initial identity up until 1972 when it changed to CIE Technical Committee 3.4: Discomfort Glare. This committee was to re-emerge as CIE TC 3.13: Discomfort Glare Evaluation System at the 21st Session CIE in Venice, 1987.

Provisionally at least the brief of the first CIE discomfort glare committee to formulate a single and internationally acceptable method of discomfort glare evaluation has been discharged by CIE TC 3.13. The committee produced a first draft report for circulation at the 22nd Session CIE, Melbourne , Australia, 1991. The contents of the draft report proposes the adoption of a discomfort glare model that assimilates many of the features of the existing glare systems. The report has at the time of writing to pass through its several draft stages, and agreement has to be reached about its contents. It is to be hoped that by the end of the quadrennium in 1995 the draft report will be formally adopted by the CIE and will make available a universal method of discomfort glare calculation. Persuading CIE member nations to adopt the model as their national standard model is of course another problem!

2.5.2   The Development of the British Glare Index System

2.5.2.1   Hopkinson's First Glare Study

After his theoretical studies (Stiles, (1929)) on the effects of light scatter on threshold elevation Stiles continued his work on glare into the 1930s, at times in collaboration with Crawford. Stiles' interest in glare research during this period focused on a number of different areas, including:

* The measurement of glare (Stiles, (1930); Crawford and Stiles, (1935)).

* Glare from street and car lighting (Stiles, (1931); Stiles, (1935)).

* Retinal effects of glare (Crawford and Stiles (1937)).

This series of studies laid the groundwork, together with the work of Holladay, for Hopkinson's first major study of discomfort glare. There was clearly an interest in the glaring effects of street lighting during the 1930s because Hopkinson's first glare study also investigated street lighting (Hopkinson, (1940)); the investigation of street lighting was presumably very topical as the wide spread introduction of electric street lighting would have a recent innovation during the late 1920s and into the 1930s. It was in his first

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paper on the subject of glare that Hopkinson observed, reinforcing the theoretical conclusion of Stiles' 1929 paper (Hopkinson, (1940)), that:

> 'The present work was inspired by the fact that some installations which were generally described as "glaring" could be shown by the application of the Holladay-Stiles expression to be affected only in small degree by disability glare.'

Poulton (Poulton, (1991) p 95) comments that Hopkinson's study of street lighting was probably the first systematic laboratory based study of glare. The study investigated the effects on glare of:

- Source size
- Source Luminance
- Source position
- Background luminance provided by luminance reflections at the road surface

Hopkinson used the photographic technique which was developed and used extensively in his later glare studies with Petherbridge. A street scene was photographed and holes cut at the locations of the street lanterns. An adjustable source of luminance was placed behind the holes, or so called 'flashed apertures'. For a range of different values of the experimental variables, listed above, the subjects were asked to rate the degree of discomfort glare in the simulated road scene according to the four criteria:

A - Just intolerable
B - Just uncomfortable
C - Satisfactory
D - Just not perceptible

The results of this study showed that for a single lantern the sensation of discomfort glare, or the glare constant, could be estimated using the empirical function:

$$k = \frac{L_s^{1.3}\,\omega}{L_b\,\theta^{0.75}}$$

Where: k = The [discomfort] glare constant; not to be confused with the constant k
for the Holladay-Stiles expression

L_s = Luminance of the source

ω = The angular subtense of the source as seen by the subject

L_b = Luminance of the background

θ = The angle of view between the subject's line of sight and the glare source

Hopkinson went on to derive numerical glare constant values for each of the four categories used to rate the glare appearance of the street lanterns. These assigned glare constant values were:

Criterion Category	Criterion Definition	Glare Constant 'k'
A	Just intolerable	7000
B	Just uncomfortable	1700
C	Satisfactory	450
D	Just not perceptible	115

The resemblance between this first glare constant equation and the later BRS glare sensation equation makes clear that this first study by Hopkinson was a precursor to the subsequent studies by Hopkinson and Petherbridge that led to the formulation of the British Glare Index system.

2.5.2.2   The BRS Discomfort Glare Studies

Hopkinson resumed his investigations of discomfort glare at the Building Research Station (BRS) during the late 1940s, collaborating with Petherbridge for much of this work. The

theme of the series of glare studies carried out at the BRS was to derive a method for calculating the level of discomfort glare sensation perceived by subjects for interior lighting use; the earlier study had focused on discomfort glare from street lighting; see Section 2.5.2.1 above. The seminal work from this period was reported in 1950 (Petherbridge and Hopkinson, (1950)). The study detailed in this report had investigated the effects on the perceived level of discomfort glare of glare source:

- Intensity
- Brightness
- Area
- Shape
- Position

Petherbridge and Hopkinson also derived in this report their method for summing the effects of individual sources of discomfort glare. They also described the effects on perceived discomfort glare of placing a surround to the glare source with a luminance intermediate between the luminance of the glare source and its background.

The study was carried out using the method that Hopkinson had employed in his earlier discomfort glare study (Hopkinson, (1940)). A series of black and white photographs of school classrooms were mounted vertically in a box. At the locations in the photograph where the luminaires appeared holes were cut . These holes were back illuminated by using a condensing lens arrangement that could be adjusted for brightness; the projecting lens system was arranged so that each cut aperture received the same illuminance. The front of the photograph was uniformly illuminated by front mounted light sources controlled independently of the back illumination light sources.

For each of the photographs the experimenter set a number of luminances for the back illuminated apertures. For each of the aperture luminances the subjects had to adjust the illuminance on the front of the photo so that the flashed apertures, simulating luminaires, appeared to be at one of four different conditions, which were (Petherbridge and Hopkinson, (1950)):

'A   Just intolerable - the changeover point between intolerable and uncomfortable glare.

'B   Just uncomfortable - the changeover point between uncomfortable and merely distracting glare.

'C   Just acceptable - the changeover point between distracting and acceptable glare.

'D   Just imperceptible - the changeover point where *glare* from the sources is just no longer noticeable; the sources themselves are still noticeable, but they merge into the general field of view in such a way that they no longer form any source of attraction.'

The ratings were repeated for each of the experimental conditions used in the experiment.

The principal result of the study was the derivation of the BRS glare constant equation:

$$Glare\ constant = \frac{L_s^{1.6} \cdot \omega^{0.8}}{L_b^{1.0}}$$

Where: L_s = Luminance of the glare source
   ω = The angular subtense of the glare source as seen by the observer
   L_b = The background luminance

The total glare constant from a number of individual glare sources in an installation was given by:

$$Glare\ constant = \sum_{i=1}^{n} \frac{(L_{s_i}^{1.6} \omega_i^{0.8})}{L_b^{1.0}}$$

As in Hopkinson's earlier 1940 study the data were used to assign numerical values of the glare constant to the four multiple criterion categories, thus:

Criterion Category	Criterion Definition	Glare Constant
A	Just intolerable	600
B	Just uncomfortable	150
C	Just acceptable	35
D	Just imperceptible	8

The equations for glare constant and total glare constant derived from this study did not contain the position index parameter, which was to be added later. The basic equations from this study also had to undergo some modification before they were to become the British Glare Index system.

The report also included a discussion of the methods used to ensure that consistent subjective ratings were given by subjects. Essentially the method was to record responses to a discomfort glare source from subjects. If, after a certain number of observations taken over a period of time, the subject's responses showed more than about $\pm$ 0.15 log units of variance they were excluded from the study. This method amounted to training the subjects to see and recognise the different glare conditions. It might therefore have been anticipated that the results of the experiment would be self-determining. A number of criticisms making this point were made, particularly by Markus (Markus, (1974)).

Markus commented that he doubted whether 'glare' had any inherent meaning for most naive subjects. He suggested that '...it is an abstraction which does not correspond to any unitary experience.' (Boyce, (1981)). This criticism is certainly consistent with the general discussion of Section 2.1 about the need to define suitable criteria which have some common interpretation between observers, and the particular discussion of Section 2.1.2 about the absence of a definitive set of criteria for discomfort glare.

In mitigation of the criticism any number of studies carried out since Holladay's and Stiles' initial work on discomfort glare have consistently reported that subjects report a sensation of discomfort when presented with excessive luminance differences, or contrasts, in the field of view; see for example (Stone, (1966); Bennett, (1972); Lynes, (1977)).

The initial discomfort glare study by Hopkinson and Petherbridge was the first of a series carried out during the 1950s and into the early 1960s. These subsequent studies investigated different aspects of the phenomenon of discomfort glare; see for example (Hopkinson, (1962); Hopkinson, (1956); Hopkinson and Petherbridge, (1955)). But the essential contribution to the British Glare Index system was in place on completion of the first study.

2.5.2.3   The Emergence of the British Glare Index System

During the early 1960s the British IES carried out one of its perennial revisions of the IES lighting code, which at that time was entitled 'The IES Code. Recommendations for Good Interior Lighting' (which in its present form is the 'CIBSE Code for Interior Lighting' (CIBSE, (1994)). As part of this revision the Luminance Study Panel of the IES Technical Committee wished to incorporate in the code a method for calculating discomfort glare in the interior luminous environment. The model selected on merit for inclusion in the code was the BRS formula, which was at that stage the most developed of the three major national systems. However, the Panel had some reservations about the BRS formula, which would require alteration before it became the British Glare Index system.

The first concern of the Panel was that the range of glare constants reported by Petherbridge and Hopkinson from their study was very large; the lowest value was less than 10, the highest more than 1000. To circumvent this criticism Hopkinson proposed (Hopkinson, (1960)) that the BRS glare constant should be transformed by taking the common logarithm and multiplying by 10:

$$\text{Glare sensation} = 10 \, \text{Log}_{10}(\text{glare constant})$$

A more fundamental concern was the absence in the BRS glare constant equation showing the inverse relationship between perceived discomfort glare and position of the glare source to the line of sight. As part of the revisions to the BRS glare constant equation (IES Technical Committee, (1962)) a position index was added so that the IES glare sensation equation became:

$$\text{Glare sensation} = G = 10.Log_{10}\{\frac{L_s^{1.6} \; \omega^{0.8}}{L_b^{1.0} \; P^{1.6}}\}$$

Where the symbols have their usual meanings and P = the Position Index. The parameter P was initially defined in terms of the vertical and lateral displacement of the glare source relative to the line of sight, and normalised to the Position Index at a vertical displacement of 10° and a horizontal displacement of 0°.

The individual effects of glare sources in an installation were summed to give the IES Glare Index, which was to become known as the British Glare Index:

$$\text{Glare Index} = 10.Log_{10}\{\sum_{i=1}^{n}(G)\}$$

The Glare Index formula was by now beginning to take on the resemblance of its final form.

2.5.2.4   Environmental Dependence of Glare Index and Minimum Perceptible Glare Index Changes

Hopkinson (IES Technical Committee, (1962)) noted that the subjective ratings assigned to a glare source were context dependent. Thus he stated :

> 'In a place where one sits and thinks, or just sits, relatively inoffensive luminaires may obtrude on the consciousness and cause discomfort, whereas the same luminaires, used in a place where every one is busy and pre-occupied, may go completely unnoticed.'

This observation by Hopkinson is supported by later work carried out by Ostberg, Stone & Benson (Ostberg, Stone and Benson, (1975)).

There is an inconsistency in Hopkinson's statement. If '...one sits and thinks...', statically, then it could be argued that the consciousness is pre-occupied, at least as much as, say, an

office worker actively moving around an office space attending to a variety of different tasks.

The primary difference between the two situations is that if a subject is static the glare source can be present in the same part of the visual field for a larger proportion of time. Allowing for eye movements, the source may therefore become distracting, or glaring.

For subjects moving around a space there is a continual change in the visual image contents. Thus any potential sources of discomfort , or disability, glare will not appear consistently at the same approximate retinal location. Thus the glare source does not appear to be as glaring as when subjects are static. There is perhaps a case for including a temporal parameter in the discomfort glare models.

Hopkinson included in his proposals (Hopkinson, (1960)) a table of different Glare Index values for different environments which explicitly recognised the environmental influence on the subjective acceptability of discomfort glare. The table is reproduced below:

Location	Room Type	Upper Glare Index Limit
Schools	Classrooms	16
	Libraries	12
	Laboratories	16
	Sewing rooms	10
Offices	General offices	16
	Drawing offices	12
Railway	Platforms	22
	Station waiting rooms	20
Factories	General workshops	20
	Specialised workshops	18
	Storerooms and racks	26

Hopkinson also made the recommendation that in any luminous environment that was continuously occupied then the 'Amenity' level of Glare Index should not be greater than 24.

During the same period that the BRS glare formula was being revised to become the IES Glare Index, Collins (Collins, WM, (1962)) carried out an experiment investigating the minimum detectable change in the subjectively perceived level of discomfort glare. In the laboratory studies her results indicated that the minimum reliable detectable change was one Glare Index unit. As part of the study Collins also carried out a series of field studies in a number of installations. The results from these field trials indicated that the 'average variability of judgement in the assessment of glare...' (Poulton, (1991), p 101) was approximately three Glare Index units.

2.5.2.5 Glare Indices and the British Zonal System

To derive from first principles the Glare Index for an installation was a laborious process. What was required was a method for deriving the Glare Index using some standardised system, which assumed certain properties about room geometry, surface or cavity reflectances, luminaire arrangements and, luminaire distribution properties.

During the same period that the IES Glare Index system was being derived from the BRS glare constant equation the British Zonal system was also introduced. The British Zonal (BZ) system was a method for classifying luminaires into one of ten standard distribution types. The ten standard distributions were defined in terms of polar curves, which are shown in Figure 2.1. The BZ system was well suited for use with the emergent IES Glare Index system.

The method for calculating the IES Glare Index using the standardised tabular method, including the BZ system, went as follows. For each of the BZ types, BZ1 to BZ10, Initial Glare Indices were tabulated for a range of ceiling, wall and floor reflectance values; ceiling reflectances were 70%, 50% and 30%; wall reflectances were 50% and 30%; floor reflectances were given for one value only at 14%.

The Initial Glare Indices were also tabulated for each range of reflectances for four different Flux Fraction Ratios, a measure of the amount of light that was distributed down towards the horizontal working plane. The Flux Fraction Ratios were defined as the ratio of Upward Flux Fraction to Lower Flux Fraction.

Table 2.1 is an example of an Initial Glare Index table for a luminaire type BZ5.

In use the lighting practitioner would identify the luminaire he wished to use as one of the ten BZ distributions. He would also know the Flux Fraction ratio. In most instances these data would be supplied by the manufacturer. He would also know the approximate values of the room surface reflectances. Having identified these installation data the practitioner would read off from the table the Initial Glare Index value.

To this value he would apply a number of correction factors which were separately tabulated. These correction factors were for:

- Actual downward flux, obtained by multiplying the total luminaire flux by the Lower Flux fraction.

- The luminous area of the luminaire measured in square inches.

- The height above the 4 foot (1.22 metres) eye level plane.

A correction factor table is shown in Table 2.2. Conversion factors were also available for converting from endwise to crosswise viewing for linear fittings, and for different values of floor reflectance.

The final value that was arrived at after the application of the various correction factors was the Glare Index for the installation. The final values were compared with limiting values of Glare Index tabulated for different types of installation. If the final Glare Index was less than the tabulated limiting value then the installation was deemed to satisfy minimum Glare Index requirements. If the final value was greater than the limiting then modifications to the glare characteristics of the installation were recommended to bring the final Glare Index to less than the limiting value.
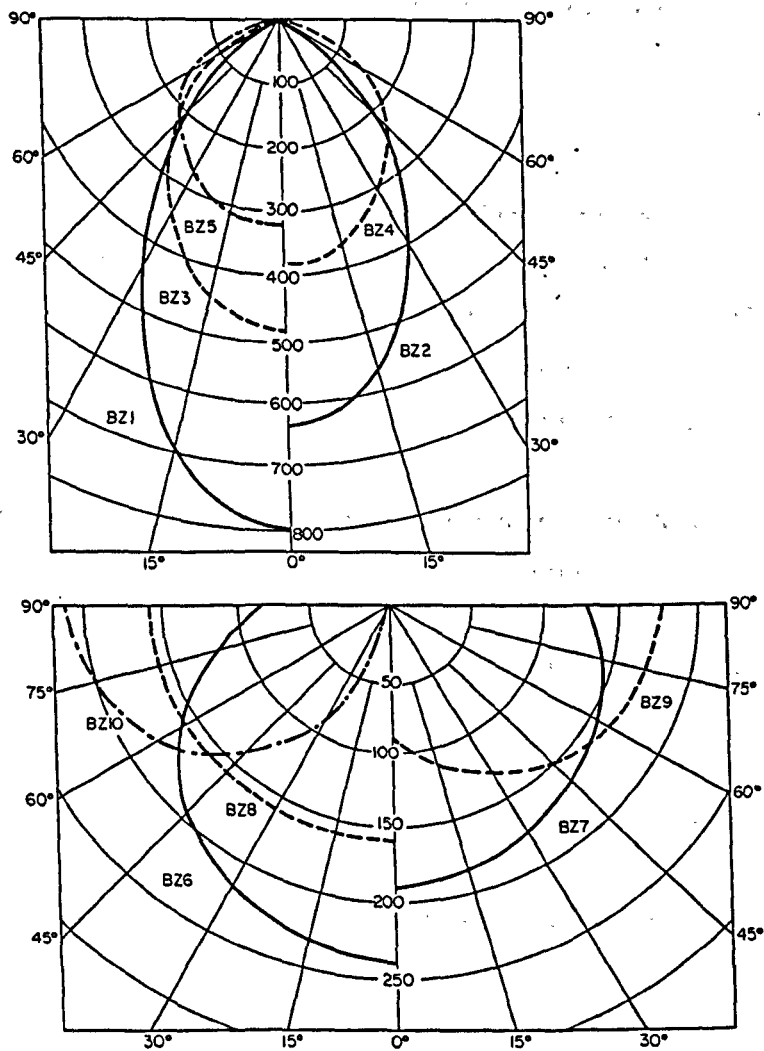
Fig. 4.2 *Polar curves in the BZ classification*

BZ 1	$I \propto \cos^4 \theta$	BZ 6	$I \propto (1 + 2 \cos \theta)$
BZ 2	$I \propto \cos^3 \theta$	BZ 7	$I \propto (2 + \cos \theta)$
BZ 3	$I \propto \cos^2 \theta$	BZ 8	I constant
BZ 4	$I \propto \cos^{1.5} \theta$	BZ 9	$I \propto (1 + \sin \theta)$
BZ 5	$I \propto \cos \theta$	BZ 10	$I \propto \sin \theta$

The BZ classification relates to the lower hemisphere only; the polar curves above are scaled to give 1000 lumens in the lower hemisphere for purposes of comparison

Figure 2.1   Polar curve set for the British Zonal Classification system; [after Hopkinson and Collins, (1970)]

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Flux fraction ratios of lighting fittings (upper/lower)

$$0 \left(\frac{UFF}{LFF} = \frac{0\%}{100\%}\right) \qquad 0.33 \left(\frac{UFF}{LFF} = \frac{25\%}{75\%}\right) \qquad 1.0 \left(\frac{UFF}{LFF} = \frac{50\%}{50\%}\right) \qquad 3.0 \left(\frac{UFF}{LFF} = \frac{75\%}{25\%}\right)$$

Reflection factors of room surfaces (per cent)

Ceiling	70	70	50	50	30	70	70	50	50	30	70	70	50	50	30	70	70	50	50	30
Walls	50	30	50	30	30	50	30	50	30	30	50	30	50	30	30	50	30	50	30	30
Floor	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14

Room dimension

X	Y	Initial Glare Indices
2H	2H	18.0	20.4	18.4	20.9	21.3	15.7	17.7	16.5	18.6	19.7	13.2	14.8	14.4	16.0	17.7	9.6	10.8	11.0	12.2	14.2
	3H	20.7	23.0	21.1	23.3	23.7	18.4	20.2	19.2	21.0	22.1	15.7	17.1	16.8	18.3	20.1	12.0	13.3	13.4	14.7	16.6
	4H	21.9	24.1	22.4	24.5	24.8	19.5	21.1	20.5	22.0	23.1	16.9	18.1	18.1	19.3	20.9	13.1	14.1	14.5	15.6	17.5
	6H	22.9	25.1	23.4	25.4	25.8	20.5	22.1	21.4	23.0	24.1	17.7	18.9	18.9	20.2	21.8	14.1	15.0	15.5	16.5	18.5
	8H	23.2	25.3	23.8	25.8	26.2	20.9	22.3	21.8	23.3	24.4	18.2	19.3	19.5	20.6	22.2	14.4	15.4	15.9	16.9	18.8
	12H	23.9	25.9	24.5	26.4	26.7	21.6	22.8	22.5	23.9	25.0	18.6	19.7	19.8	21.0	22.7	14.9	15.7	16.3	17.2	19.2
4H	2H	19.2	21.5	19.7	21.8	22.2	16.9	18.4	17.8	19.3	20.4	14.2	15.4	15.4	16.6	18.3	10.4	11.4	11.9	12.9	14.9
	3H	22.2	24.2	22.7	24.6	25.0	19.8	21.1	20.8	22.2	23.3	16.9	18.0	18.1	19.3	21.0	13.1	13.9	14.6	15.5	17.5
	4H	23.8	25.6	24.3	26.0	26.5	21.2	22.3	22.2	23.4	24.6	18.5	19.3	19.8	20.6	22.3	14.4	15.0	15.9	16.7	18.5
	6H	24.7	26.5	25.3	26.9	27.5	22.1	23.3	23.1	24.3	25.5	19.3	20.0	20.5	21.5	23.2	15.4	16.0	16.9	17.6	19.5
	8H	25.5	26.9	26.0	27.4	28.0	22.8	23.7	23.7	24.8	26.0	19.9	20.7	21.2	22.1	23.7	16.0	16.5	17.5	18.1	19.9
	12H	26.0	27.5	26.5	27.9	28.5	23.3	24.2	24.3	25.3	26.5	20.5	21.1	21.7	22.5	24.1	16.6	17.0	18.1	18.7	20.5

Table 4.2 (contd.)

X	Y																				
8H	4H	24.4	25.9	24.9	26.3	26.9	21.7	22.6	22.7	23.7	24.9	18.9	19.6	20.1	21.0	22.6	14.8	15.5	16.3	17.1	18.9
	6H	26.1	27.3	26.7	27.8	28.5	23.4	24.1	24.4	25.1	26.5	20.4	20.9	21.7	22.2	23.9	16.4	16.8	17.8	18.5	20.4
	8H	26.8	28.0	27.5	28.6	29.2	24.0	24.8	25.1	26.0	27.2	21.0	21.6	22.4	23.0	24.6	17.1	17.5	18.6	19.2	21.1
	12H	27.3	28.5	28.0	29.1	29.7	24.6	25.3	25.6	26.5	27.7	21.7	22.2	23.0	23.7	25.3	17.7	18.0	19.2	19.7	21.6
12H	4H	24.6	26.1	25.1	26.5	27.1	21.9	22.8	22.9	23.9	25.1	19.1	19.7	20.3	21.1	22.7	15.2	15.7	16.6	17.3	19.1
	6H	26.3	27.5	27.0	28.1	28.7	23.6	24.3	24.7	25.5	26.7	20.6	21.1	21.9	22.6	24.2	16.7	17.1	18.2	18.8	20.6
	8H	27.0	28.2	27.7	28.7	29.4	24.2	25.0	25.3	26.2	27.4	21.3	21.9	22.7	23.4	25.0	17.4	17.7	18.8	19.4	21.3
	12H	27.5	28.8	28.3	29.4	30.0	24.8	25.6	26.0	26.6	28.0	22.0	22.6	23.4	23.9	25.7	18.1	18.3	19.5	19.9	22.0

H Height of fitting above 4 ft eye level.
X Room dimension at right angles to the line of sight in terms of the height H.
Y Room dimension parallel to the line of sight in terms of the height H.
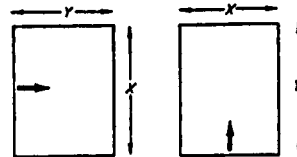
Table 2.1 Initial Glare Index table for a BZ 5 luminaire; [after Hopkinson and Collins, (1970)]

Conversion terms corresponding to the values of downward flux F, luminous area A and mounting height H above a 4 ft eye level for the fittings actually used are obtained from the Table interpolating where necessary. These three conversion terms are added algebraically, taking account of the positive and negative signs, and the sum (which may be positive or negative) is then added to or subtracted from the Initial Glare Index for the installation taken from Table 4.2.

The downward flux F is the total flux output per fitting in lumens multiplied by the lower flux fraction.

The area A is the luminous area in square inches of each fitting.

The height H is the height in feet of the fittings above a 4 ft eye level.

Downward flux F (lm)	Conversion term	Luminous area A (in²)	Conversion term	Height H above 4 ft eye level (ft)	Conversion term
100	−6·0	10	+8·0	3	−1·3
150	−4·9	15	+6·6	4	−1·0
200	−4·2	20	+5·6	6	−0·6
300	−3·1	30	+4·2	8	−0·3
500	−1·8	50	+2·4	10	0·0
700	−0·9	70	+1·2	12	+0·3
1000	0·0	100	0·0	15	+0·6
1500	+1·1	150	−1·4	20	+1·0
2000	+1·8	200	−2·4	25	+1·3
3000	+2·9	300	−3·8	30	+1·6
5000	+4·2	500	−5·6	40	+2·1
7000	+5·1	700	−6·8		
10 000	+6·0	1000	−8·0		
15 000	+7·1	1500	−9·4		
20 000	+7·8	2000	−10·4		
30 000	+8·9	3000	−11·8		
50 000	+10·2	5000	−13·6		

The data on which the IES Glare Index System is based are restricted at present to sources which have a maximum solid angle subtense at the eye of 0·1 steradian. Therefore, for the larger luminous areas quoted here, while the system is applicable when they are used at high mounting, it cannot strictly be employed for them at low mounting, but the errors involved are likely to be small.

Table 2.2 Table of correction factors for the Initial Glare values given in Table 2.1; [after Hopkinson and Collins, (1970)]

The principle underlying this stylised calculation method was that it reduced an otherwise complicated, and extended, arithmetical procedure to a simpler process involving far fewer operations. The implicit cost in the simplification was the loss of accuracy in the final value of Glare Index.

2.5.2.6   Limiting Glare Values

Hopkinson and Petherbridge derived from their 1950 study (Petherbridge and Hopkinson, (1950)) four different quantitative levels of glare constant, corresponding to the four subjective glare categories that they had asked their subjects to set in the experiment. The glare constant values, and their corresponding subjective definitions are repeated below:

Glare Constant	Adjusted Glare Constant	Glare Index	Criterion Definition
8	10	10	Just perceptible
35	40	16	Just acceptable
150	160	22	Just uncomfortable
600	640	28	Just intolerable

Hopkinson and Petherbridge carried out an expedient, but arbitrary, adjustment of these initial glare constants to obtain a constant ratio of four between each criterion category (Hopkinson and Collins, (1970)). To these adjusted values was applied the IES Glare Index formula to obtain the listed Glare Index values.

The results of the field studies carried out by Collins (Collins WM, (1962) opt cit) had shown that the minimum reliable change in Glare Index in a real installation was three Glare Index units. The corollary to this result was that if it were necessary to improve an installation's glare characteristics, then the existing Glare Index had to be reduced by three units to achieve any noticeable improvement. This result was used in the derivation of the limiting Glare Index values given for different types of installation. The initial limiting values are given below (Hopkinson and Collins, (1970)):

'1. Environments where no glare at all is permissible; [upper] Glare Index limit 10.

'2. Environments where glare must be kept to a minimum; [upper] Glare Index limit 13.

'3. Environments where glare of different degrees can be permitted depending upon the nature of the work, the likely sensitivity of people (children, elderly workers, sick people) and the time to be spent in the room, together with the degree of attention demanded by the work; [upper] Glare Index limits 16-28.'

These limiting values were not derived in abstract. Teams of observers were employed to rate the glare appearance of a wide range of different types of installation. The teams were comprised of observers who had demonstrated consistency in their subjective rating of discomfort glare; alternatively the observers were well trained. The teams made several complete appraisals of the range of buildings included in the study. In these appraisals the observers used the multiple criterion scale used by Hopkinson and Petherbridge in their studies; ie the observers had to rate the glare from the installation as:

- Just imperceptible
- Just acceptable
- Just uncomfortable
- Just intolerable

The observers were also told that their assessment of the glare from an installation should make allowance for:

- The type of task carried out in the space
- The type of environment
- Duration for which people would normally expect to occupy the space
- The options allowed for turning the gaze away from a source of glare
- The level of attention, or concentration, required by the work; a glare source might act as a distracting annoyance for some tasks requiring a lot of attention, while in other cases 'might alternatively so command attention that the

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awareness of the environment might be reduced.' (Hopkinson and Collins, (1970)).

The ratings of acceptability or unacceptability from the observers were equated to the Glare Indices derived from photometric and geometric measurements of the installations. The limiting Glare Indices for the different types of installation used in the study were derived from correlation of the subjective ratings with the objective glare measurements, while also allowing for the results of Collins' (Collins WM, (1962) opt cit) as discussed above. These general recommendations were subsequently used as guidelines for the limiting glare values given in the lighting schedule of the CIBSE Code for Interior Lighting (CIBSE, (1994)).

With the formulation of the IES Glare Index formula completed, the tabulated method for calculating Glare Index using the BZ system and, the limiting Glare Index values derived all of the component parts of the British Glare Index system were in place.

It was a logical part of the development of the British Glare Index system for the model, tabulated method and the limiting values to be put into one formal document, giving details of the method for the calculating Glare Index values. This step was taken with the publication in 1967 of the IES Technical Report N° 10 'Evaluation of Discomfort Glare: The IES Glare Index System for Artificial Lighting Installations.' (IES Technical Report N° 10, (1967))

It was almost as logical that once formalised the system would come under scrutiny by the lighting community and subjected to peer review. Critical assessments came from a variety of sources; one of the more extensive critical assessments was carried out by Bedocs and Simons (Bedocs and Simons, (1972)). Their analysis is given in the next section.

2.5.2.7   Critical Assessment of IES Technical Report N° 10

One of the first technical evaluations of this report was published by Bedocs and Simons (Bedocs and Simons, (1972)). The observations by Bedocs and Simons were based on two

'serious arithmetical errors', and on the means for deriving the vertical illuminance component at the eye.

Bedocs and Simons thought that the two arithmetical errors were:

i. The incorrect calculation of the background luminance using the BZ system. The BZ system is a method for classifying luminaires based on intensity distributions which were compared with mathematical functions defining each particular distribution's characteristics.

They thought that this method was suitable for deriving utilisation factors, which in turn could be used to calculate background luminance. It was not valid to use of the BZ curves to calculate source luminance. This was because source luminance was set by the intensity distribution at angles above 60° to the downward vertical. Significant errors were introduced when there was a sharp run-back in the distribution.

ii. They also observed that in the tables of initial glare indices π, usually 3.142..., had a power of unity, which should have been 1.6.

The combined effect of these two arithmetical errors was estimated to produce errors in the initial glare index values of 4 units (Bedocs and Simons, (1972), opt cit).

Additionally, inaccuracies were introduced by the effects of luminous side panels on luminaires with a BZ classification of 5 or less. In the BZ system BZ5 curves, or less, assumed that the luminaires were flat horizontal panels. In practice this resulted in measured luminances at high angles being less than those attributed by the BZ system.

Bedocs and Simons' were also concerned about errors introduced by the method for calculating the vertical illuminance at the plane of the eye produced by an installation. The BRS method assumed that the vertical illuminance at the eye was produced by a uniform background luminance, and that this luminance was only produced by the inter-reflected component of light within the space.

This contrasted with the method adopted by the IES in Technical Report N° 10. The vertical illuminance at the plane of the eye was taken to be equal to the inter-reflected component of the wall illuminance. In TR N° 10 the inter-reflection component tables of Moon and Spencer (Moon and Spencer, (1946)) were adopted to facilitate the calculation of the vertical illuminance at the plane of the eye.

Additional to the differences in the methods of calculating vertical illuminance components at the eye of the observer, a further source of error was introduced into the calculation of the vertical illuminance component by approximations made in the use of the tables. These errors were quantified as being up to 16% by Potter and Russell (Potter and Russell, (1954)).

Despite the reservations about the arithmetical correctness of the IES Glare Index system, Bedocs and Simons concluded that (Bedocs and Simons, (1972), opt cit):

> 'In many respects the IES Glare Index system is a closed system and therefore, with a very few minor exceptions, the errors [reported] in this paper have not resulted in lighting schemes designed using the IES Technical Report N° 10 being unsatisfactory as regards glare. On the contrary, by alerting designers to the necessity of controlling glare, the IES Glare Index system has undoubtedly produced an improvement in the quality of lighting installations.'

Besides the detailed evaluation carried out by Bedocs and Simons criticism of the system was also voiced by other authors. Sørensen (Sørensen, (1987)) observed in 1987 that substantial changes had occurred in lighting technology since the IES Glare Index system had been developed. The glare characteristics of the more recent technology were different from those of the older technology. Thus glare predictions for the modern lighting fittings based on the IES Glare Index system could be significantly in error; Sørensen estimated that the errors between calculated and nominally correct Glare Indices were typically in the range 10-25%.

2.5.2.8   CIBSE Technical Memorandum N° 10

The basis to many of the criticisms of the IES Glare Index system were, directly or indirectly, comments of the limitations of the BZ luminaire classification system. By the late 1970s the weight of these criticisms was putting pressure on the Lighting Division of the CIBS, formerly the IES, to amend IES TR N° 10.

At the 19th Session CIE, Kyoto, Japan in 1979 Boyce et al (Boyce, Crisp, Simons, and Rowlands, (1979)) reported a series of experiments that had evaluated the effects of four parameters on the perceived level of discomfort glare. The parameters included:

- Luminaires with non-uniform luminance distributions
- Room length
- Illuminance
- High luminance, small area metal halide sources

The paper concluded that these parameters had a significant affect on glare perception, but that the IES Glare Index system did not adequately account for the effects.

This report precipitated the setting up of a CIBS discomfort glare study group to investigate the modification of the existing IES Glare Index system with the aim of eliminating the BZ system from the calculation procedure for Glare Index. The work of the study group led to the publication in 1984 of the CIBSE Technical Memorandum N° 10 (CIBSE Technical Memorandum N° 10, (1984)).

The first part of Technical Memorandum N° 10 (TM N° 10) describes the calculation of Glare Index by the use of the formula. This system is very flexible and allows the designer to calculate the Glare Index for any room or arrangement of luminaires. The disadvantage is that the calculation process involves many steps, and is arithmetically very complex.

Part two of TM N° 10 provides a schedule for the preparation of standard Glare Index tables, via the basic Glare Index equations. This schedule is principally directed at luminaire manufacturers who have the facilities to produce the standard tables. The use of

the standard tables, similar to the use of the BZ system, much simplifies the calculation of Glare Indices, at the price of some loss of accuracy. The Initial Glare Indices (IGI) for each luminaire produced by a particular manufacturer are generally published as tables integral with tables of the photometric properties of the luminaires; see for example Thorn Lighting Photometric Data Handbook, Volume 1, Commercial and Industrial Fittings (Thorn Technical Handbook, 1991)).

The IGI are modified to produce the Final Glare Index value by the use of conversion tables, which are also provided in TM N° 10. The conversion tables are given for:

- Correction for total luminaire flux
- Correction for mounting height
- Correction for lamp length

There are many similarities between the calculation procedures detailed in TR N° 10 and TM N° 10, which is intuitively reasonable as both documents are based on the method derived by Hopkinson and Petherbridge (Petherbridge and Hopkinson, (1950)). TM N° 10 does not include the BZ tables, but relies on luminaire manufacturers to provide glare, and other photometric, data to allow the lighting practitioner to calculate Glare Indices. The exclusion of the BZ tables circumvents the criticisms directed at the earlier TR N° 10.

At the present time CIBSE Technical Memorandum N° 10 is the recommended standard procedure for calculating Glare Indices; however with the publication of the Draft Report by CIE Technical Committee 3.13 detailing the CIE Unified Glare Rating system (CIE TC 3-13, (1994)) it is possible that the method given in TM N° 10 may soon be superseded by the CIE UGR system (Perry, (Orlando, 1991)).

2.5.3 The Development of the American 'Visual Comfort Probability' System

From the earliest days of research into glare there was a significant overlap between the research interests of the British and Americans. This is perhaps not surprising when it is considered that the new lighting technology was being developed in both countries at the same time and at approximately the same pace. Thus it might be anticipated that the

advantages, and the problems, associated with the use of the technology would become apparent at about the same time in both countries.

During the same period that Parsons was commenting to the newly formed British IES about glare in 1909 (J of Good Lighting, XXII, (December, 1929)) AJ Sweet was actively researching glare in America. One of earliest American papers on glare was published by Sweet in 1910 in the Journal of the Franklin Institute (Sweet, (1910)). This paper reported on the reduction of visibility of a task in the visual field with a glare source present compared to the visibility of the same task with the glare source absent.

Task visibility reduction was assessed by the perceived increase in task illuminance required to bring the task to the same level of visibility as it would have in the absence of the glare source. The results of Sweets investigations showed that this so called 'blinding effect' of the glare source was inversely proportional to both glare source distance from the task and to the angle subtended between the source and the line of sight. The blinding effect was also found to be directly proportional to the intensity of the glare source; the effect increased up to about 300 candelas, with diminishing effect above this intensity.

Sweet (Sweet, (1915)) identified two distinct types of glare:

- 'Blinding Glare' which he had reported in his 1910 paper and was defined as being 'a factor of the candle power emission of the glare source towards the eye; of the angle with the line of vision at which the glaring light enters the eye and of the distance of the glare source from the eye' (Sweet, (1915)).

  Also the blinding effect was 'is substantially , probably wholly independent of the brilliancy of the glare source.' (Sweet, (1915)).

- 'Immediate ocular discomfort' was defined to be 'a factor of the intrinsic brilliancy of the glare source and its contrast with its surroundings (Sweet, (1915)).'

Working during the same period as Sweet, Millar (Millar, (1910)) published a paper on the glare effects of street lighting. Millar used a visual task that could be varied in contrast.

The task was used to determine the minimum perceptible contrast between the glare and no glare conditions, which was converted into a percentage reduction in task illuminance due to light scatter. This illuminance reduction was deemed to be a measure of the glare effect.

Millar noted three glare effects of street lighting:

- A measurable reduction in the visibility of a task attributable to the presence of a light source in the visual field

- A reduced probability of seeing a low contrast task if scanned quickly

- A temporary dazzling effect, causing transitory glare. Poulton has speculated that this transitory glare may predate by several decades the work of Blackwell (Poulton, (1991), p 166) on the 'transient adaptation factor' of the visual performance model described in CIE 19/2 (Commission Internationale de l'Eclairage, (1972)).

Another active American glare researcher during this period was Cobb (Cobb, (1911)). He discussed the physiological effects of glare, and included in this paper a review of very early glare research carried out in the late 19th and early 20th centuries. Cobb also identified three types of glare effect:

- A veiling effect caused by light scatter in the optic media of the eye

- A transitory glare which influenced the sensitivity of the retina

- A persistent effect on the sensitivity of the retina which could be attributed to the presence in the visual field of a high brightness source

Thus by the middle of the second decade of the 20th century some tentative foundations had been laid to the causes of glare. It can be seen in this early work that there was already some appreciation that there were a number of different types of glare, most of which influenced the physiology of vision, but some of the effects were identified with

less direct action such as Sweet's indirect ocular discomfort. These early foundations would be subsequently built upon by glare researchers such as Nutting, Lukiesh and Holladay, summarised in sections 2.2.3 and 2.3.1 above.

2.5.3.1   Holladay's Work on the 'Fundamentals of Glare and Visibility'

As described in section 2.3.1 defining the genesis of contemporary glare research is very difficult; some sort of consensus might be found assigning Holladay's work as the start in earnest of glare research. Holladay first came to notice in 1924 when he presented a paper which had been produced in collaboration with Lukiesh (Moon, Dover Edition). Subsequently he carried out a very extensive investigation in to the effects of glare on the visibility of visual tasks. The results of this study were described in ' The Fundamentals of Glare and Visibility' (Holladay, (1926)).

As indicated by the title Holladay was primarily interested in the effects of glare on task visibility, effects attributable in the main to light scatter in the optic media of the eye. Lukiesh and Holladay had adopted the recommendations of the 1922 IESNA committee on Glare, which became known as the Bell Committee. The committee had identified three types of glare. These were (Nutting, (1928), page 251):

- 'Veiling glare produced by light somewhat uniformly superimposed on the retinal image, thus reducing the contrast and hence visibility.

- 'Dazzle glare produced by adventitious light so refracted and scattered so as not to form part of the retinal image.

- 'Scotomatic glare produced by light of intensity such as to fatigue the retinal sensitivity to below the concurrent limit of the visual images'

It was investigations into these three types of glare that Holladay reported in his paper. The three types of glare reported on were as identified by the Bell Committee but were given modified names by Holladay.

- Veiling glare was called veiling-brightness

- Dazzle glare was unchanged in Holladay's paper

- Scotomatic glare became blinding glare

It was dazzle glare that was subsequently identified as discomfort glare, following the debate carried out between Holladay in America and Stiles in the UK, as summarised in sections 2.3.1 and 2.3.2 above.

In the same paper Holladay also reported on investigations into:

- The 'growth and decay of after images' (Holladay, (1926) p 298 ff)

- The effect on visibility of a task appearing against a brighter background, an effect which Holladay called 'irradiation' (Holladay, (1926) p 301 ff)

- Variations in pupil diameter, their causes and their effects on vision (Holladay, (1926) p 307 ff). Fugate and Fry (Fugate and Fry, (1956)) subsequently reported on the influence of pupil variations on discomfort glare perception approximately fifty years later.

- One of the most significant parts of Holladay's investigations with regard to the development of a discomfort glare model was his investigation into the psychophysical effects of light sources (Holladay, (1926) p 304 ff).

Holladay's extensive investigations had a significant impact on the subsequent development of discomfort glare models, particularly the American Visual Comfort Probability system. Holladay's work also influenced related areas of research for several decades after its publication, for example Fugate and Fry's study of pupil oscillations and discomfort glare (Fugate and Fry, (1956)), and Blackwell's investigations of the 'Transient Adaptation Factor' included in the development of the visual performance model (CIE (1972)).

The parts of Holladay's paper relevant to the present discussion are summarised below:

Dazzle glare: Holladay argued that dazzle glare was caused by the appearance in the visual field of bright lights:

> '...which form images upon peripheral portions of the retina and which in one way or another reduce the sensitivity of the eye for seeing objects imaged upon the central or foveal region of the retina.' (Holladay, (1926) pp 279-280)

This was distinct from the mechanism causing veiling brightness, which was attributed to the reduction of task contrast caused by the scattering of light in the optic media of the eye.

Holladay investigated the effects of a number of different parameters upon dazzle glare. These included:

i.   The influence of illumination at [the] eye from dazzle source

ii.   The effect of viewing the dazzle source eccentrically, or non-foveally

iii.   The analogy between dazzle glare and veiling brightness

iv.   The effect of fixed viewing angle rotated about the dazzle glare source in the vertical plane

v.   The additive effects of a number of dazzle glare sources

vi.   The effect of brightness and source size on dazzle glare

vii.   The effect of colour of the source

viii.   The effect of visual angle on contrast sensitivity

ix.   The perception of dazzle glare when the source appeared in the blind spot

x.   The effect of different states of accommodation upon dazzle glare

xi.   The influence of changes in pupil diameter on dazzle glare

Of these the items numbered i, ii, v and vi were parameters that were to be included in the subsequent development of discomfort glare models.

i.   The influence of illumination at [the] eye from dazzle source

In this part of his experiment Holladay studied the minimum perceptible brightness difference between a task and its background for a range of different illuminances at the plane of the eye from the dazzle glare source. The dazzle glare source was also presented at a number of different viewing angles.

The results of this part of the study showed that for a fixed viewing angle the minimum perceptible brightness difference, ΔF, increased linearly with increasing illuminance at the eye, E. The sensitivity of the eye to changes in illuminance was greatest at small viewing angles, or eccentricities, with decreasing sensitivity as eccentricity increased.

Holladay argued that the ratio E: ΔF was constant for a fixed viewing angle, D.

ii.   The effect of viewing the dazzle source eccentrically, or non-foveally

To study the effect of viewing the dazzle glare source eccentrically Holladay fixed the glare source and moved the task relative to the glare source; the task was viewed foveally. For each eccentricity, D, of the glare source and for a range of values of E Holladay recorded ΔF. The log ratio of E: ΔF was found to increase linearly with the log of D, thus:

$$E/\Delta F = kD^n$$

iii.   The analogy between dazzle glare and veiling brightness

Holladay observed that there were a number of similarities between what he called veiling brightness and dazzle glare. He carried out an investigation to ascertain whether the two phenomenon were equivalent. To carry out this investigation set up in parallel the two sets of apparatus used to study veiling brightness and dazzle glare. Using the same visual task he measured the minimum perceptible brightness difference, ΔF, to detect the task under conditions of first veiling brightness and then dazzle glare, by switching between the two pieces of apparatus.

The results of the study showed that the effects of the two glare types was very similar, except for a constant multiplier. Holladay concluded that there was an equivalence between veiling brightness and dazzle glare and then went on to show that there was also a mathematical equivalence between the two, thus:

$$\Delta F = \frac{F}{S} + \frac{K_1}{S}\frac{E}{D^2}$$

Where: F = Background luminance of the task

S = Contrast sensitivity

K_1 = A constant having an average value of 4.3 ± 0.5

E = Illuminance at the eye from the glare source

D = Angle between the line of sight and the dazzle glare source

The first term on the right hand side of the equation expresses the task contrast required in the absence of any glare source. The second term is proportional to the illuminance at the eye from the dazzle glare source, and indicates the task contrast required to overcome the effects of dazzle glare. However, Holladay argues that veiling brightness, B_1, can be expressed as:

$$B_1 \propto \frac{E}{D^2}$$

Thus there is an equivalence between veiling brightness and dazzle glare.

iv.   The effect of fixed viewing angle rotated about the dazzle glare source in the vertical plane

Holladay wished to establish if there were any effect on ΔF with changes in the orientation of the dazzle glare source in the vertical plane for a fixed viewing angle; see Figure 2.2.

By noting ΔF for various viewing positions in the vertical plane about the dazzle glare source he established that there was no difference in ΔF between the vertical and horizontal meridians, or at any intermediate meridian.

v.   The additive effects of a number of dazzle glare sources

Using ΔF again as the measure of the effect of the dazzle glare, Holladay found that the presence of a number of glare sources in the field of view were additive. He concluded 'that the obscuring effects of any number of dazzle sources are additive or that the equivalent veiling-brightness B_1 of several dazzle sources in the field of view is the sum of that for each' (Holladay, (1926) p 290, last para).

vi.   The effect of brightness and source size on dazzle glare

Two similar lamps were set up with one placed behind a diffusing screen. Two sets of tasks were set up to receive equal illuminances from the two lamps, and subjects asked to report ΔF for each of the tasks, ΔF measured in the usual way. Holladay found that there were no differences in the values of ΔF for the two sources and concluded that 'the obscuring effect per unit illumination at the eye is , within our experimental error, independent of the brightness of the

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versely as the square of the angle D it makes with the line of vision. It may be noted that both components of ΔF vary inversely as the contrast sensitivity S of the eye, but this is practically constant at ordinary adaptations as has been previously shown.

Influence of Position of Dazzle-Source. This investigation was made for the purpose of determining the relative glare of a dazzle-source at a fixed angle to the line of vision, but the plane containing it, the observer's eye and the test-object varied through 360 degrees.

The arrangement of apparatus employed is shown in Fig. 16, in which L, is the dazzle-source occupying a position in the center of the
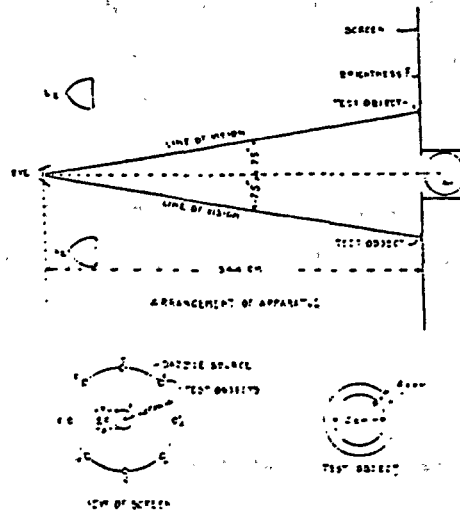
Fig. 16. *Arrangement of apparatus used in studying the effect of relative positions of test-object and dazzle-source.*

screen and located at the level of the eye of the observer. There were 8 test objects each having a reflection factor of 0.56 and of the form shown at C in Fig. 3. These test-objects were placed symmetrically around a circle of 45 cm radius drawn about the center of the dazzle-source. The dazzle-source L, was a gas-filled tungsten lamp in a 10-inch white diffusing ball which gave an illumination E of 31.5 mc at the observer's eye. The results obtained with eight observers are given in Table 1 from which it is evident that the position of the dazzle-source relative to the test-object was without material effect upon its obscuring power so long as the angle D was maintained constant.

Figure 2.2   Diagram of Holladay's apparatus for studying the effect of position of glare source at a fixed viewing angle in the vertical plane; [after Holladay, (1926)]

source and dimensions of the radiating or diffusing surface of the light-source' (Holladay, (1926) p 292).

At the time that Holladay carried out his studies glare was thought to be one unified phenomenon. There were some hints of the distinction to come between the physiological effects, that would become associated with disability glare, and the miscellaneous effects, such as Millar's 'immediate ocular discomfort', which would eventually become associated with the more nebulously defined discomfort glare. That glare was still thought to be a unitary phenomenon can be seen from Holladay's report. However his empirical findings, discussed above under items i, ii, v, vi identified some of the central themes that were to become the subject of glare research later.

He correctly concluded that the phenomenon of glare was dependent on the intensity of the source, which produced an illuminance at the plane of the eye (i.); he correctly concluded that there was an inverse relationship between the effect of the glare source and eccentricity (ii.); he was also correct about the additive effects of glare sources, although the exact nature of the additivity function would be decided some time later cf British Glare Index and VCP models (v.); a more controversial conclusion was that the glare effect was independent of source dimension and brightness.

Holladay gave a theoretical interpretation of the causes of discomfort glare, which included discussion of the various possible locations for the seat of the perceived effect. These included:

      i.   Brain or central nervous system

      ii.   Optic nerve

      iii.   Retina

      iv.   Surface membranes of the eye

      v.   Media of the eye

Holladay argued that dazzle glare could be attributed to Rayleigh scattering in the optic media of the eye, and provided a theoretical analysis to support his proposition; (for a discussion of Rayleigh scattering see, for example, (Hecht (1987)). A brief description of Rayleigh scattering is given in Appendix B. This was of course the entry point for Stiles, who argued that any changes in ΔF could only be partially explained by scattering, and that in any event it was not appropriate to use the model of Rayleigh scattering in the context of Holladay's argument; this point of issue between Stiles and Holladay s discussed in section 2.3.2 above. The debate led directly to Stiles initiating the concept of discomfort glare (see section 2.3.2 above), being those effects of glare that could not be directly attributed to the effects of light scattering and its contingent physiological responses.

2.5.3.2   Holladay's Discussion of the Psychophysical Effects of Light Sources

Towards the end of his 1926 paper Holladay discussed the psychophysical effects of light sources. With the advantage of hindsight it could be argued that this section of his paper was possibly the most significant for subsequent development of glare models, and certainly for the development of the American VCP model. In this section of the paper Holladay discussed the subjective sensations of 'pleasure' or of 'discomfort' that might be initiated by the presence of a light source in the visual field. He investigated the effects of a number of parameters on these sensations, which included:

- Size of the light source

- Brightness of the light source

- Background brightness

Holladay used a screen on which to present his glare sources. In one mode he used two luminance sources, a standard and a test. For a range of values of the standard luminance source the test was adjusted to achieve a range of different sensations relative to the standard source; this provided comparative data on the perceived level of sensation from

the test source. In the second mode of use only the single test lamp was used to make absolute measurements of perceived sensation.

The source luminances could be adjusted, as could their solid angle. Additionally the background luminance provided by the screen against which the luminance sources were presented could be adjusted.

Following the precedent set by Nutting (Nutting, (1916)) Holladay presented the luminance stimuli to his subjects intermittently; no specific details of the presentation sequence are given. Holladay also states that the results from the comparative and absolute methods were comparable, although no statistical analysis is provided.

Holladay deduced from the analysis of his data that the degree of subjective sensation, or shock , caused by the 'momentary exposure' of a light source could be expressed in the form:

$$K = LogB + 0.25LogQ - 0.3LogF$$

Where: K = the level of 'shock or psycho-physiological sensation'
          B = the luminance of the presented glare source
          Q = the solid angle subtended by the source
          F = the luminance of the background screen against which the glare source, or sources, were presented

Using this equation, in conjunction with the data from his study, Holladay proposed a twelve point scale, each value of which was associated with a subjective description, of adjectival rating. The scale and ratings are given, verbatim, below:

1.   0.3   When sensation is scarcely noticeable
2.   0.6   "   "   " most pleasant
3.   0.9   "   "   " still pleasant
4.   1.2   "   "   " at limit of pleasure
5.   1.5   "   "   " very comfortable
6.   1.7   "   "   " still comfortable

7. 1.8 " " " less comfortable

8. 1.9 " " " at boundary between comfort and discomfort

9. 2.2 " " " perceptibly uncomfortable

10. 2.4 " " " uncomfortable

11. 2.6 " " " at boundary between objectionable and intolerable

12. ≥2.8 " " " when sensation is irritating (higher values painful)

With hindsight Holladay might be criticised for ascribing to subjects a very precise ability to scale subjective ratings. However, this type of subjective scaling has found use in many experiments, particularly discomfort glare experiments. A modified form of Holladay's scale was used by Hopkinson in his glare experiments; Hopkinson used a four point, five part scale, discussed in sections 2.3.1, 2.5.2.5 and 2.5.2.6 above. Additionally the criterion attached to the eighth point of Holladay's scale can be seen as the antecedent of the 'Borderline between Comfort and Discomfort' (BCD) criterion much used by American glare researchers, particularly Guth.

In general the equation expressing the magnitude of subjective sensation caused by the presence of a momentarily presented light source can be expressed in a non-logarithmic form, thus:

$$Perceived\ glare\ sensation\ =\ \frac{BQ^{0.25}}{F^{0.3}}$$

In this form the equation can be seen to be an antecedent to the later glare formulae of both the British and of the American systems. Consistent with later developments Holladay's equation showed that the subjective sensation of 'glare' was directly proportional to the source luminance and some measure of the size of the source, and inversely proportional to the background luminance. This equation together with his empirical findings, particularly those about the inverse relationship between glare and viewing angle, and the additivity of individual glare sources, provided a very significant foundation to the ensuing studies of discomfort glare. Comparison with the general form of the discomfort glare function, cited by Boyce and given below (Boyce, (1981), p 306) shows that, although identified in his data, the only parameter missing from Holladay's equation is the angle subtended between the source and the observer.

Glare sensation = $\dfrac{\text{(Luminance of the glare source)}^m \times \text{(Angular subtense of the source)}^n}{\text{(Luminance of the background)}^x \times \text{(Angle between source and observer)}^y}$

Although Holladay did not explicitly collate his findings to form one model of glare perception.

Holladay's studies into glare and visibility were extensive, and the report of the studies influential in the subsequent development of both discomfort and disability glare models. However he collected data from only a very small sample of subjects, in some cases as small as one, and not larger than four subjects. Although the graphs reproduced in the paper show strong trends, no indication is given of the amount of variance in the data. It might be reasonable to assume that the data had substantial variance, particularly as Holladay was in some instances selective in the data he plotted (Holladay, (1926) p 307, para 1). That the glare studies following Holladay's work reported results consistent with his data indicates the robustness of the glare parameters he identified.

2.5.3.3 A Formative Discomfort Glare System

In 1941 Fowler and Crouch (Harrison, (1950)) prepared a report for a sub-committee the IESNA Lighting Practice Committee. The report was based on the work of Holladay, and included a series of glare tables for different types of luminaires. The tables, which can be interpreted as a form of luminance limiting values, used a K value of 1.9, Holladay's BCD criterion, to derive the limiting luminance values.

2.5.3.4 American Post-war Investigations of Discomfort Glare

Similar to discomfort glare investigations in the UK, there were many American glare studies carried out in the late and post-war period. Poulton has observed (Poulton, (1991)) that the extent of the American interest in glare is almost disproportionate, and that this may be attributable to commercial pressures.

2.5.3.4A   Harrison's Glare Factor

In 1945 Harrison and Meaker (Harrison and Meaker, (1947)) published a report of a detailed study into discomfort glare in interior environments. The results reported were derived from both laboratory data and field observations. The results led Harrison to propose the concept of a 'glare factor'. The glare factor was related to the parameters of the luminous environment by the function:

$$Glare\ factor = \frac{AB^2 * (Location\ coefficient)}{H^2 * (Surround\ brightness\ factor)}$$

Where: A = area [of the glare source]

B = brightness [of the glare source]

Location coefficient = a measure of the position of the glare source relative to the observer

H = Height of the glare source

Surround brightness factor = a measure of the background luminance

2.5.3.4B   Harrison and Meaker

Harrison carried out a second study of discomfort glare, working with Meaker. In this study they investigated the change in glare rating with angle of view to the glare source, following a paper published by Lukiesh and Guth (Lukiesh and Guth, (1946)). Harrison and Meaker's study departed from the more usual American study by using presenting the glare source continuously.

Additionally they carried out subjective verification of their empirical glare rating equation. For this verification they used a group of seven experienced lighting engineers, who visited nine installations. The subjective assessments of the level of 'comfortableness' of each of the rank ordered installations was plotted against the calculated Glare Factor; the results are shown in Figure 2.3; the graph shows that the Glare Factor was a reasonable predictor of subjective glare rating. The use of an 'evaluation panel' was an antecedent to the evaluation teams used by Hopkinson and Petherbridge to assess the

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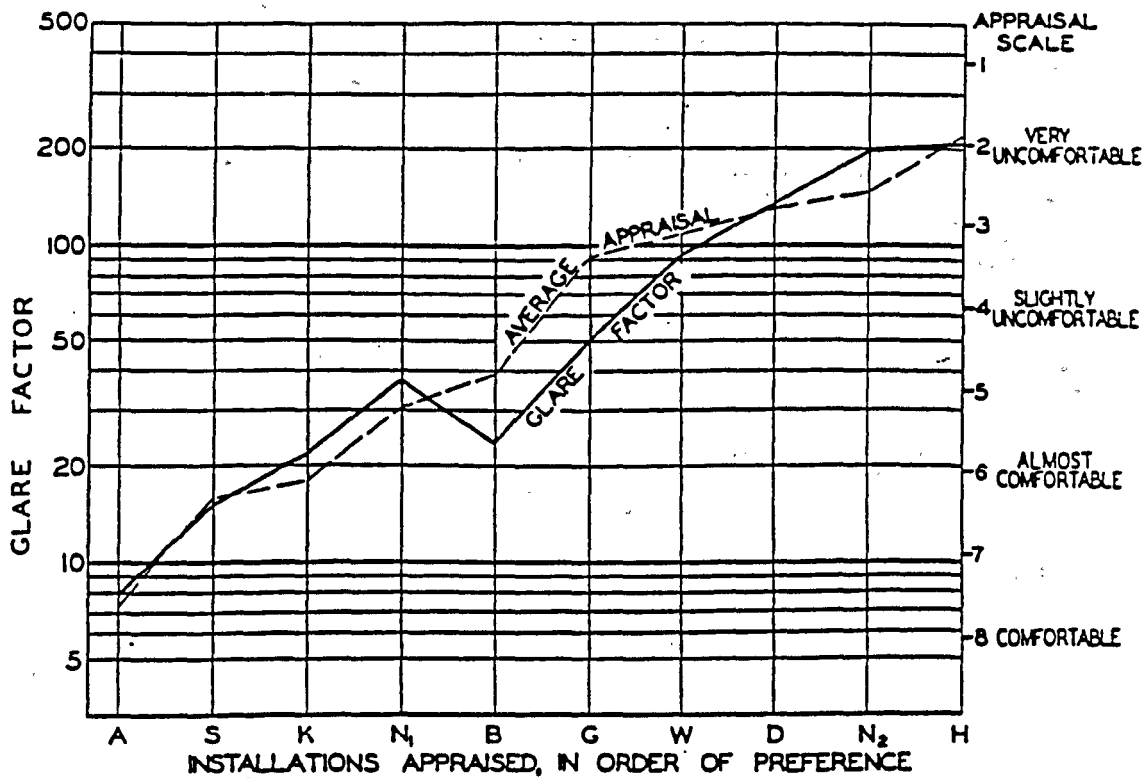
Comparison between calculated glare factors for
ten installations (designated by the letters,
A, S, K, N_1, B, G, W, D, N_2, H) and the aver-
ages of seven individual appraisals for comfort
(office occupancy).

Figure 2.3 Harrison's rank ordering by preference glare of ten installations.

TABLE 3

VISUAL COMFORT INDEX -- 50 FOOTCANDLES

DESCRIPTION OF LUMINAIRE: Ceiling Mounted Direct

Shielding: Enclosed   Shielding Materials
No. of Lamps: 4   Sides: Diffusing Plastic
Lamps: T-12; 430 ma. Bottom: "   "
Efficiency: 57% Down
         3% Up

REMARKS: Relative to luminous ceilings, the area
of these units is small and the brightness is high.
The similarity in brightness and projected area with
crosswise and endwise view gives little preference
for one over the other.
    This table has been computed on a basis of 15%
reflectance for the combined working plane and floor.
If this reflectance is 30%, refer to Table B and ad-
just the values as though for a 40-footcandle basis.
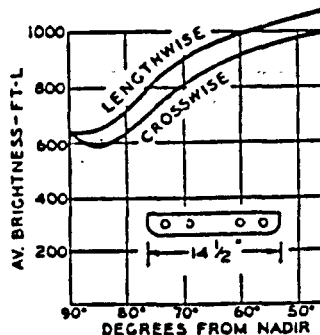
VCI Values for 50 Footcandles. For Other Illumination Levels See Table B									
Room Width	Room Length	Units Viewed Endwise				Units Viewed Crosswise			
		Height Above Floor (Feet)				Height Above Floor (Feet)			
		8-1/2	10	13	16	8-1/2	10	13	16
15	20	5	11	45		5	13	45	
	30	•	6	21		•	8	22	
	40	•	5	14		•	7	16	
	60	•	5	11		•	6	14	
	80	•	•	10		•	6	14	
20	20	•	9	36	67	•	10	39	67
	30	•	•	14	36	•	5	16	36
	40	•	•	9	22	•	•	10	23
	60	•	•	7	14	•	•	9	16
	80	•	•	7	11	•	•	8	14
	100	•	•	6	11	•	•	8	14
30	40	•	•	6	13	•	•	6	14
	60	•	•	•	7	•	•	•	9
	80	•	•	•	6	•	•	•	8
	100	•	•	•	6	•	•	•	7
	150	•	•	•	5	•	•	•	7
40	40	•	•	•	10	•	•	•	10
	60	•	•	•	5	•	•	•	6
	80	•	•	•	•	•	•	•	5
	100	•	•	•	•	•	•	•	•
60	60	•	•	•	•	•	•	•	•

•Probably less than 5%

Figure 2.4 Visual Comfort Probability table

formative British Glare Index system in the early 1960s, discussed in section 2.5.2.6 above.

Poulton observes that the Harrison - Meaker Glare Factor system was the first practical glare evaluation system.

2.5.3.4C   Meaker and Oetting: The Visual Comfort Index

Subsequent to developing the Glare Factor system with Harrison, Meaker co-authored a technical bulletin with Oetting (Meaker and Oetting, (1953)) and issued by the General Electric Company in 1953. The title of the technical bulletin was 'Visual Comfort Index (VCI) Data and Tables - Their Meaning and Use in Lighting Design'. This system combined the Glare Factor system (G) with the BCD criterion that had been developed by Lukiesh and Guth (Lukiesh and Guth, (1949)). The BCD criterion was used to assess how many people would rate a lighting installation as 'comfortable'. The VCI system was thus a precursor to the VCP system. The VCI system was used to produce tables that gave the percentage of the population that would be satisfied with the installation, for a given room dimensions and luminaire layouts; see Figure 2.4.

2.5.3.4D   The IESNA 'Scissors Curve'

The VCI system was adopted by the IESNA when preparing its recommendations for the lighting of offices and schools in 1955. The system included the BCD criterion, which provided estimates of BCD luminance for different angles of view to the glare source for typical fluorescent lighting installations. The BCD luminances were derived using the VCI system of Meaker and Oetting.

The IESNA system was implemented graphically. The ordinate was linearly scaled for brightness, or luminance (in foot-lamberts), while the abscissa was inversely and non-linearly scaled for the 'angle from nadir', the angle of view. Two lines were drawn on the graph, see Figure 2.5. The sloping line provided a sliding limiting luminance which was dependent on the angle of nadir. The horizontal line gave the limit for a 250 foot-lambert
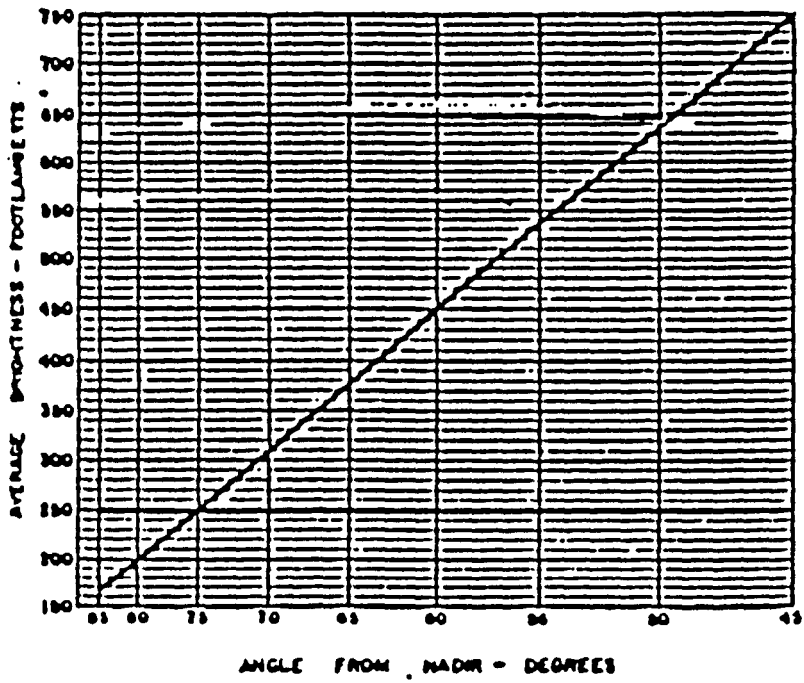
Figure 2.5 Scissors curve

(856.6 cd m^{-2}) uniformly diffusing source. The graph in Figure 2.5 shows the intersecting lines for a range of angles 75° - 45°. Because the intersecting curves resembled the blades of a pair of scissors this graphical representation was awarded the sobriquet 'scissors curve'.

In use, and to satisfy the BCD criterion, the designer had to provide an installation with a distribution of luminances that lay below the sloping upper limit, provided that the luminaires used in the installation were not uniformly diffusing. The horizontal upper limit applied if the installation was comprised uniformly diffusing luminaires. This graphical method was a quick and simple way of estimating the approximate level of glare in a proposed installation. However it was criticised by some members of the IESNA who considered that the method was not as rigorous as the Guth formula.

Fry responded to this criticism by undertaking a comparison of the scissor curve glare values with calculated values from the Guth formula. His hypothesis was that the two methods could be equated. He calculated glare values for forty eight installations and correlated these values with glare values derived from the scissor curve method. The results are plotted in Figure 2.6. There is clearly a strong correlation between the calculated and graphically derived values. Fry concluded that Guth's formula and the scissor curve were related and that the scissors curve method provided that values of glare should not be exceeded.

2.5.3.4E   The BCD Criterion Method

In parallel with the work of Harrison and Meaker, Lukiesh and Guth were developing their single criterion Borderline between Comfort and Discomfort, the so called BCD method. The studies of BCD were, unlike the studies of Harrison and Meaker, carried out exclusively in the laboratory. In their early studies Lukiesh and Guth (Lukiesh and Guth, (1949)), and latterly Guth, asked subjects to fixate the pole of a hemisphere, which provided a uniform luminance background. A small luminance source was presented to the subjects over a range of different positions. The source was presented intermittently in the sequence: three 1 second exposures, each separated by 1 second intervals, at the end of this sequence their was a 5 second rest interval before the whole sequence was repeated. Subjects were asked to set the luminance of the glare source or the background so that the
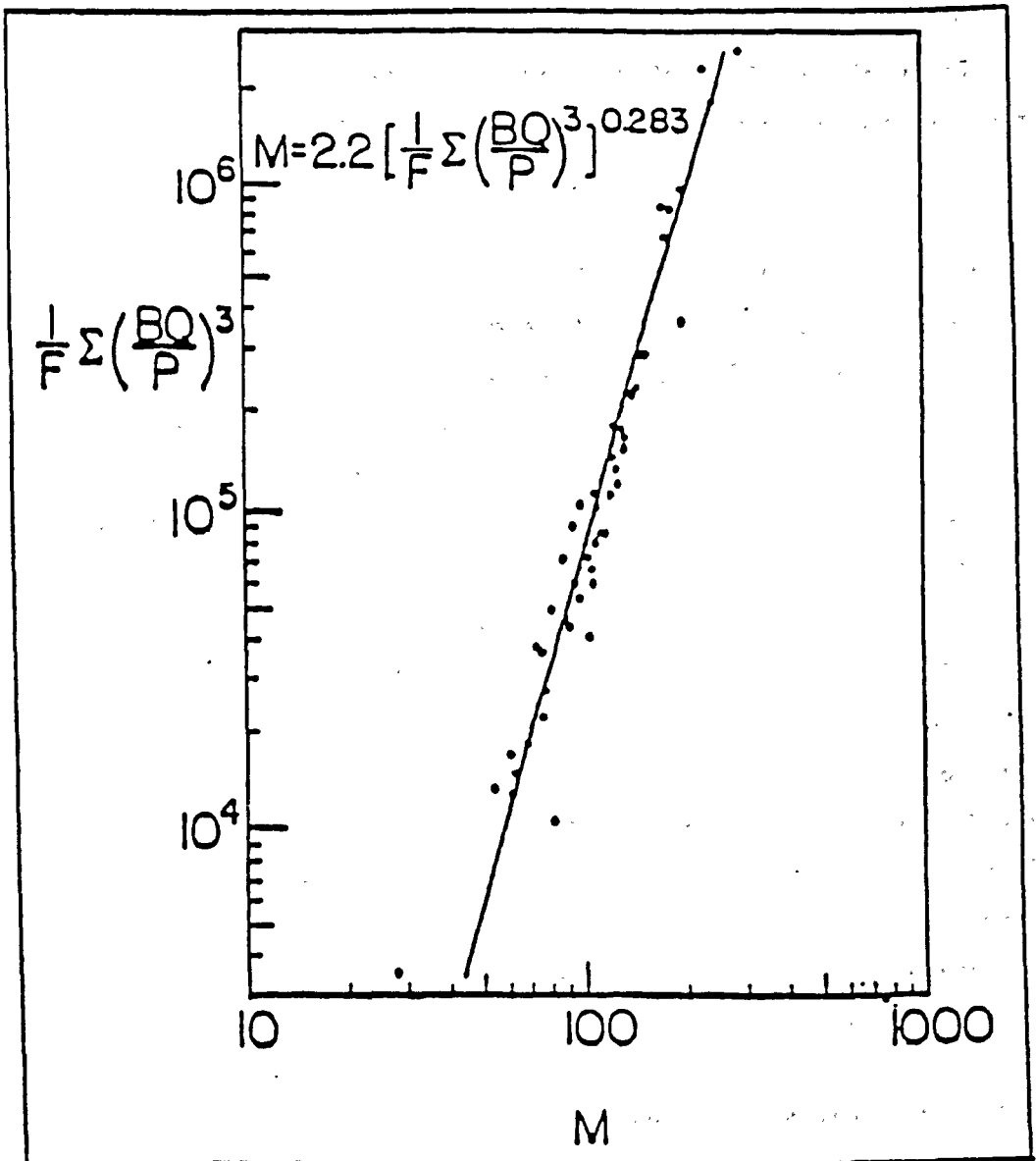
The validity of the modified Guth formula as tested with Guth's 48 different lighting arrangements.

Figure 2.6 Results of Fry's validation study of the scissor curve method.
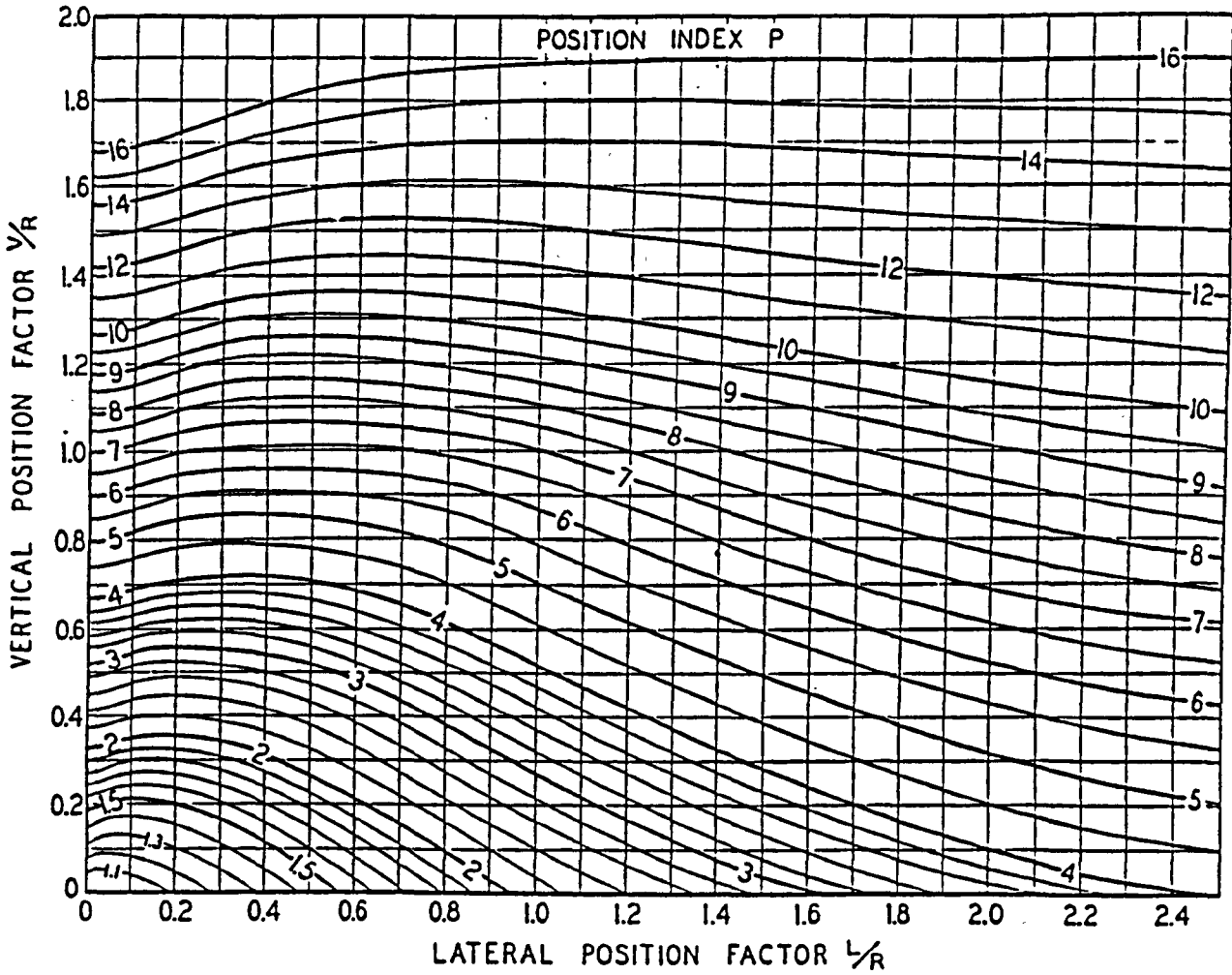
Figure 2.7 Guth Position Index chart

source appeared at the BCD for a range of conditions. Later the experiments were repeated using simulated environments in the form of model rooms.

From the initial studies the empirical equation giving the luminance for BCD was derived:

$$B = 108PF^{0.44}(Q^{-0.21} - 1.28)$$

Where: B = the brightness [luminance] of the source

Q = the angular size of the source

P = the Position Index, a parameter expressing the variation in glare with changes in viewing angle

F = the background brightness [luminance]

This formula was subsequently revised to express the 'index of sensation', M.

$$M = \frac{B}{(PF^{0.44}(Q^{-0.21} - 1.28)}$$

Where the symbols take the same meaning as before. It was at this time that the Position Index table was developed to simplify the calculation of M. An early form of this table is shown in Figure 2.7. The Position Index was included in further developments of the Lukiesh and Guth model, and also in other glare assessment methods eg the British Glare Index system.

Much like the initial form of the British Glare Index model, the glare calculation model of Lukiesh and Guth was too complicated for practising lighting engineers. Also the assumption of additivity for this function was not necessarily valid.

2.5.3.4F   Too Much Choice

By the mid-1950s American lighting practitioners had access to three different glare models. These were:

- Harrison and Meaker's Glare Factor system, G

- Lukiesh and Guth's Index of Sensation, M

- Logan and Lange's Brightness Ratio, B/P (not discussed here)

Fry (Fry, (1956)) reported that all three systems were fundamentally the same, which was in one way comforting. It did nothing to relieve the complexity of carrying out glare calculations. Fry also observed that it would be invaluable to have a glare system which allowed simple additivity of the glare sensations from a number of individual glare sources. It was clearly time to rationalise the glare calculation systems.

2.5.3.4G   The Development of the Discomfort Glare Rating System

The IESNA 'Requirements for Quality and Quantity' Committee reported in 1959 that there were significant differences between calculated values of glare and subjective assessments of the same installations. These comments prompted Guth, working now with McNelis, to undertake development of 'a new approach to computing discomfort glare ratings' (Guth, (1963)).

In an analysis of why additivity did not work for his earlier Index of Sensation system Guth resolved that the problem lay with the exponential given to his size parameter, Q. The exponential led to inconsistency in the final values of M, after addition of individual Ms, when correlated with subjective assessments. Following a report by Einhorn (Einhorn, (1961)) which proposed that the exponent to the size parameter should be unity Guth saw a way to resolve the additivity problems of his glare system.

Guth proposed (Guth, (1963)) that the solution to the additivity problem was change the exponent of the size parameter from -0.21 to 1.0. Additionally he changed the final form of the summation sequence used to obtain the overall value of the index of sensation. Before modification the Index of Sensation, M, was obtained by simple addition of the individual values of M for each glare source considered. Now Guth proposed that the final value of M_t obtained after summation should have an exponent added to give a value M_e, taken as the value of glare sensation for the whole installation. Guth claimed that (Guth,(1963)):

'There was excellent agreement between the experimental and computed values [using the revised equations]. This was encouraging and stimulated further experiments and analyses.'

The revised glare calculation equations were:

$$M_t = M_1 + M_2 + ... + M_n$$
$$M_e = M_t^a$$
$$a = n^{-0.0914}$$

Where: $M_1, M_2, ... , M_n$ = glare sensations of individual sources

M_e = the overall Index of Sensation for an installation

n = the number of individual sources in the installation

The glare sensation for individual sources now became:

$$M = \frac{BQ(\omega)}{PF^{0.44}}$$

Where the symbols have the same meaning as before, excepting Q which now became a function of ω which defined the solid angular dimensions of the source.

$$Q = \frac{(1 - 1.28\omega^{0.21})(0.000034 + \omega^{0.79})}{\omega}$$

Harrison commented that he thought that a better function defining Q would be:

$$Q = 20.4\omega + 1.5\omega^{0.2} - 0.075$$

Guth could apparently find no reasonable grounds for objecting to Harrison's comment and included the suggested alteration into his equation for M. At this stage the Guth model had substantially reached its final form and was to form the principal component of the American VCP model. The final form of the VCP model as defined in the 1981 edition of the IES[NA] Lighting Handbook (Illuminating Engineering Society of North America. IES Lighting Handbook. (USA, 1981)) contains a number of minor changes and additions to the Guth DGR equation, these are:

- The parameter M_s for the final value of the glare sensation is now denoted by Discomfort Glare Rating, DGR
- To account for the change from foot-lamberts to cd m^{-2} the equation for M is multiplied by a factor of 0.5, becoming:

$$M = 0.5 \frac{L_s Q}{PF^{0.44}}$$

Although the correction factor presumably had some other function than just changing the formula expressed in foot-lamberts to cd m^{-2}, as:

$$1 \text{ cd m}^{-2} = 0.29 \text{ foot-lamberts}$$

Additionally, in the expression of the equation there has been a change in the symbol for luminance, B has changed to L_s.

- The background luminance F is obtained from the function:

$$F = \frac{L_w \omega_w + L_f \omega_f + L_c \omega_c + \sum L_s \omega_s}{5}$$

Where: L_w = average luminance of the walls
L_f = average luminance of the floor
L_c = average luminance of the ceiling
L_s = luminance of a source

All luminances in cd m^{-2}

ω_w = solid angle subtended at the observer by the walls
ω_f = solid angle subtended at the observer by the floor
ω_c = solid angle subtended at the observer by the ceiling
ω_s = solid angle subtended at the observer by a source
All solid angles in steradians

The factor of 1/5 is included because it is assumed that the total field of view of the observer is 5 steradians. The value of the Position Indices are obtained either from tables or directly from an analytical function defined in the IES[NA] Lighting Handbook. The Position Index is calculated for each source in the field of view.

In use the DGR is defined in a way such that the design figure quoted gives the percentage of observers in a population that would find the installation comfortable. Thus lower figures denote that less people would find the installation unacceptable. This is the converse to, for example, the British Glare Index system where lower figures denote improved glare conditions. The final design figure arrived at in the American system is the Visual Comfort Probability, VCP, from which the system derives its name.

The conversion from DGR to VCP is obtained either by the use of a graph defined in the IES[NA] Lighting Handbook and shown in Figure 2.8, or analytically from the function:

$$VCP = \frac{100}{\sqrt{2\pi}} \int_{-\infty}^{6.374 - 1.3227 Ln(DGR)} e^{\frac{-t^2}{2}} \, dt$$

The VCP system was published in the IESNA Requirements for Quality and Quantity Committee's report of 1966 (Illuminating Engineering Society of North America. RQQ Report N° 2, (1973)). Although promoted as a 'universal' method for the calculation of glare, there was one significant problem. The system was developed to calculate glare for flat panel recessed troffers, luminous ceilings, and some types of suspended luminaires. These types of luminaire and ceiling did not have luminous side panels. The method did not allow for glare calculations for luminaires with luminous side panels; this seems to have been a deliberate decision by Guth. This is because calculating glare for luminaires with luminous side panels presents a problem comprised two components:

- There is no well defined method for calculating the projected area of the luminaire in a given direction (Poulton, (1991)). Most glare calculations are restricted to the longitudinal and transverse axes of a luminaire because of this problem.

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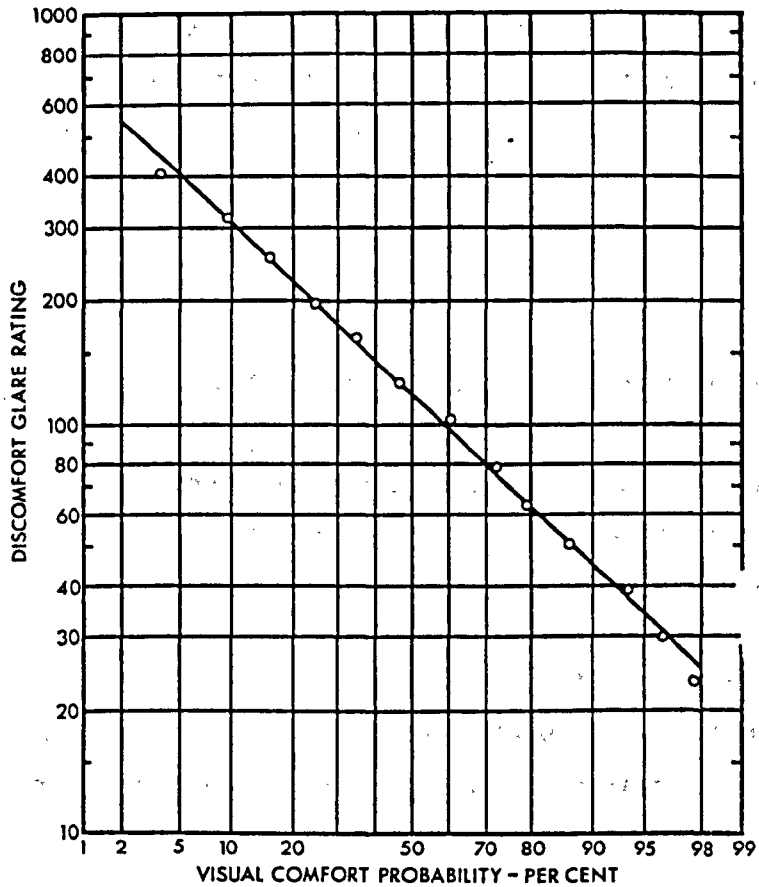
A chart for converting discomfort glare ratings to visual comfort probabilities (VCP) (the per cent of observers who would be expected to judge a lighting condition to be at or more comfortable than the borderline between comfort and discomfort).

Figure 2.8   Chart for converting discomfort glare ratings to visual comfort probabilities; [after Illuminating Engng Soc of North Am, (1981)]

- There is also no well defined method for determining the luminous intensity of a luminaire in a particular direction.

Guth and McGowan reported on these problems (McGowan and Guth, (1969)). They concluded that a way to resolve the two parts of the problem was to use computers. At the time that Guth and McGowan were writing this may have seemed to be an outlandish proposition. At the present time, with access to cheap and powerful desk top computers, it would be entirely practical to make use of computer based programmes for glare calculations, and so resolve problems cited by Guth and McGowan.

2.5.4 The Development of the German Glare Limiting System

By comparison with the British and the American systems the development of the German Glare Limiting, or Luminance Limiting, system started late. One of the early references to a German glare system is by Fischer (Fischer, (1962)), which was published and presented in 1962. In this paper Fischer referred to earlier glare work carried out in Germany by Arndt, Bodmann and Muck with additions by de Boer; although apparently not published until 1966 (Arndt, Bodmann and Muck, (1966); de Boer ibid). In this paper the authors presented an equation for the calculation of G, a measure of glare sensation:

$$G = k \sum \frac{L_s \omega^{0.33}}{L_b P}$$

$$GI = 10 Log\ G$$

Where: k = a constant

L_s = Luminance of the source

ω = the angular size of the source subtended at the observer

L_b = the luminance of the background

P = the Position Index for the source

This glare equation is similar to both the British Glare Index and the American Discomfort Glare Rating equations.

Sollner carried out a major series of glare studies between 1963 and 1965. He used one third scale model offices to simulate real office spaces. The use of model offices allowed a large number of different types of installation to be studied, 750 were investigated in total. Each model installation was viewed by between ten and fifteen subjects; the age range of all subjects was 20 to 50 years. Each subject was asked to report the level of glare sensation perceived in the installation; they gave their ratings on a seven point multiple criterion scale:

- 0 = no glare
- 1 = glare between non-existence and noticeable
- 2 = glare noticeable
- 3 = glare between noticeable and disagreeable
- 4 = glare disagreeable
- 5 = glare between disagreeable and intolerable
- 6 = glare intolerable

The use of the multiple criterion scale is consistent with previous studies, see for example Holladay (Holladay, (1926)), Hopkinson (Hopkinson, (1939)).

Sollner used a range of different types of surface mounted fluorescent luminaires in use at the time that the study was carried out. These included: bare fluorescent lamps, luminaires with plastic diffusers, luminaires with narrow white louvres and luminaires with grey louvres.

The model studies were supplemented with a series of studies of thirty three real installations.

The results of the study indicated that there were four principal parameters that influenced the subjects' glare ratings. These were:

- Luminance of the luminaire

- The length of the room and the mounting height of the luminaire

- The adaptation luminance

- The luminaire, particularly the presence of luminous side panels

Sollner summarised the data from his study in a series of curves: These curves were given for regular arrays of ceiling mounted luminaires, and plotted luminaire luminance as a function of angle between the normal to the central luminaire and the line of sight to the observer, or emission angle. These luminance curves were produced for a range, of what Sollner called, Glare Ratings, which were taken as the median values from the glare sensation data from the experimental study.

The curves, known as luminance limiting curves, were given for end-wise or longitudinal (C0 plane) viewing and for cross-wise (C90 plane) or transverse viewing. The curves for C0 and C90 viewing are shown in Figure 2.9. These curves were derived for an installation producing an illuminance of 1000 lux on the horizontal working plane. To account for installations producing higher or lower horizontal working plane illuminances a correction factor, ΔG, was applied. The polarity of the correction is determined by the value of the installation's working plane illuminance; for values in excess of 1000 lux ΔG is positive, for values less than 1000 lux ΔG is negative.

The value of, ΔG, was calculated from the formula:

$$\Delta G = 1.16 Log \frac{E}{1000}$$

Where: E = actual horizontal illuminance (lux)

In their initial form Sollner's curves (Bodmann and Sollner, (1965); Sollner, (1965)) were not practical for use by engineers. Fischer adopted Sollner's curves to form an approximate glare calculation system, based on the luminance limiting curves. Fischer converted Sollner's curves to cartesian co-ordinates (Fischer, (1972)); these are shown in Figure 2.10. There are two sets of curves, consistent with Sollner's curves,

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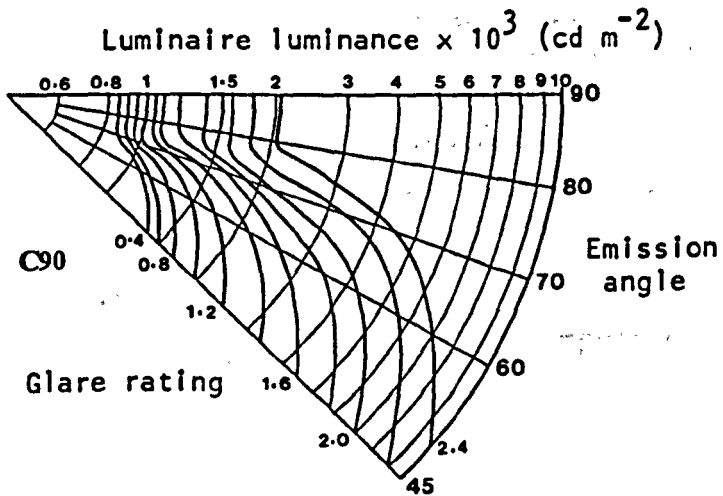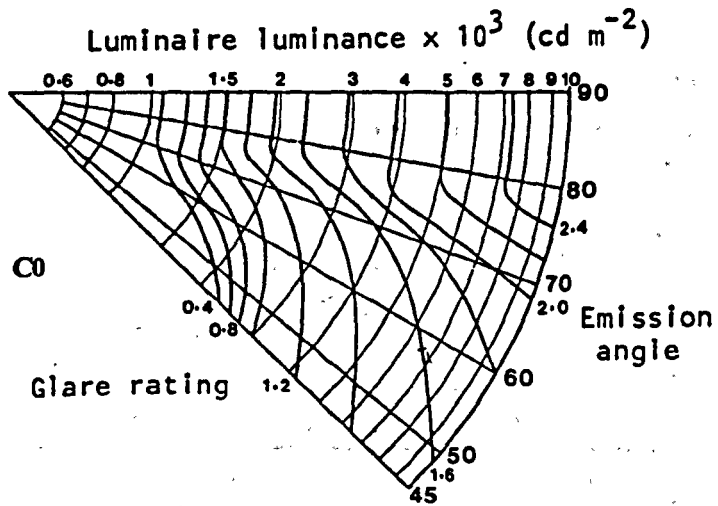
Figure 2.9   Sollner's original glare limiting curve set for C0 (longitudinal viewing) and C90 (transverse viewing); [from Boyce, (1981)]
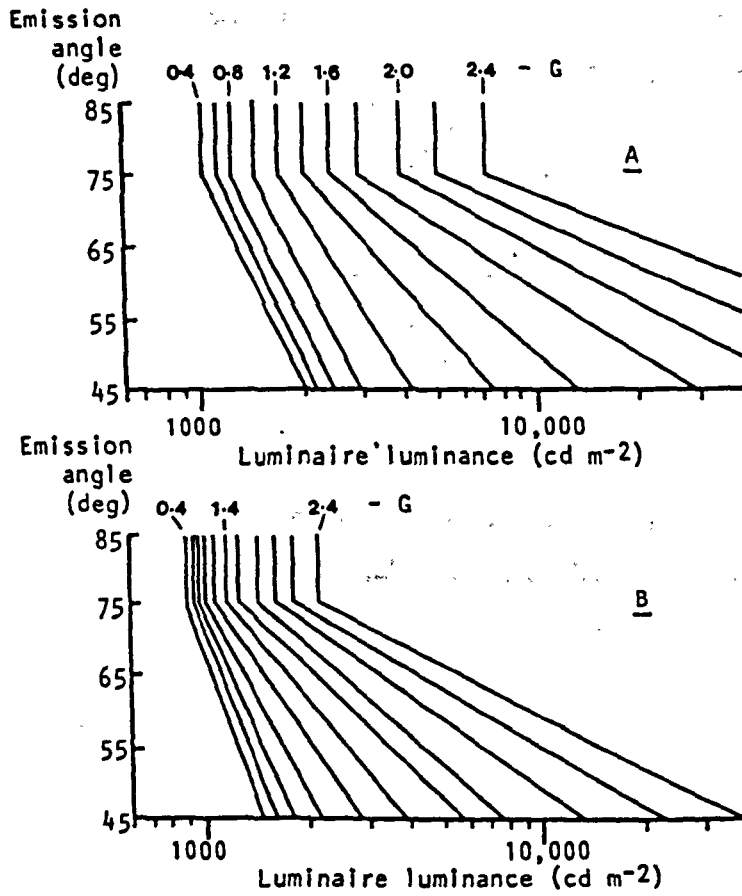
Figure 2.10　　Sollner's glare limiting curves after modification by Fischer

one for parallel (C0) and one for transverse (C90) viewing. Each set of curves is split into two parts, a sloping section and a vertical section, and each individual curve is associated with a particular level of Glare Rating. Fischer also defined the two parts of each curve analytically (Fischer, (1972)):

1. For luminaires without luminous side panels, and for luminaires with luminous side panels:

$$Log(L_{75-90}) = 3.00 + 0.15(G - 1.16Log\frac{E}{1000})^2$$

and:

$$Log(L_{45}) = 3.186 + 0.40(G - 1.16Log\frac{E}{1000})^2$$

2. For all luminaires with luminous side panels viewed cross-ways:

$$Log(L_{75-90}) = 2.93 + 0.07(G - 1.16Log\frac{E}{1000})^2$$

and:

$$Log(L_{45}) = 3.10 + 0.26(G - 1.16Log\frac{E}{1000})^2$$

Where: E = illuminance on working plane
        G = Glare Rating

In practice the lighting designer selects a value of Glare Rating appropriate for the environment which he is designing. The designer uses the photometric specification for the selected lamp and luminaire combination to obtain the luminance distribution. The luminance distribution is compared with the limiting luminance values, derived analytically or from the curves, for the chosen glare criterion. If the luminances of the distribution are lower than the limiting luminances then the lamp and luminaire combination will, at least, satisfy the glare requirements for the installation. If the luminances in the distribution are greater than the limiting luminances then, using this glare system, the designer has no option but to select another lamp and luminaire combination and repeat the process until a combination is found that does satisfy the glare requirements.

The system developed by Sollner and made practicable by Fischer has a number of limitations. One of the more significant of which is the approximation inherent in the system makes most predictions of Glare Rating imprecise. Its one major advantage over the British Glare Index and the American VCP systems is that it is every easy to use. It is plausibly because of this simplicity in use that the German luminance limiting system found application in a number of countries, including Austria, France, Germany, Italy, the Netherlands. Subsequently it also found application in Switzerland and Israel.

By 1975 the system had been incorporated into the CIE Interior Lighting Guide as the so called CIE Safeguard System (CIE Publication N° 29, (1975)). Shortly after the publication of the CIE Interior Lighting Guide Fischer was involved with the publication of three technical reports, issued by the Phillips laboratories in Eindhoven, which discussed the details of the system (Philips Engineering Report N° 5, (1976); Philips Engineering Report N° 6, (1975)). It is about this time that the German Luminance Limiting system acquired the status European Glare Limiting system. This status may have been justified by the relatively wide spread application of the model in preference to the more precise, but fundamentally more complicated, British and American systems.

2.5.5   Development of the CIE Glare System

2.5.5.1   The CIE Glare Committees

Consistent with its status as the international body representing the global lighting community, the CIE (Commission Internationale de l'Eclairage) has had a long standing interest in the development of glare systems.

At the 12th Session of the CIE in Stockholm in 1951 CIE committee E-3.1.1.2: Estimation of Comfort in Lighting was formed under the chairmanship of Mr IW Stewart of Australia. Between 1951 and 1955 this committee prepared a report which was presented to the 13th Session of the CIE, held in Zürich, Switzerland in 1955.

The report suggested that there it would be possible to pursue two avenues of investigation into visual comfort.These were (Stewart Report, (1955)):

- 'to pursue a study of the fundamentals of the aesthetics, psychology and physiological aspects of glare'

- 'to develop a method of evaluation and control which would be internationally acceptable'

The formal conclusion to the report was that (Stewart Report (1955)):

'the CIE should undertake preparation of international tables for the evaluation of direct discomfort glare from lighting fittings.'

Guth was appointed chairman of E-3.1.1.2 at Zürich, after which Poulton (Poulton, (1991)) indicates that the committee became moribund with very little progress made between 1955 and 1972; this was probably attributable to Guth's involvement with developing the American VCP system.

In 1972 Lowson was appointed chairman, and the committee became more active. Also in 1972, because of changes in the administration of the CIE, the committee E-3.1.1.2 was transformed into CIE Technical Committee 3.4, still under Lowson's chairmanship. During the period 1972-1983 TC 3-4 carried out work which led ultimately to the production of CIE Publication N° 55: Discomfort Glare in the Working Environment (CIE Publication N° 55, (1983)). Included in this publication was the Einhorn formula which, in accordance with the briefs given to both E-3.1.1.2 and TC 3.4, was a compromise discomfort glare formula based on the 'best bits' of existing glare formulae (Minutes of CIE TC 3.4 Committee Pre-sessional Meeting, (1975)).

Co-incidental with the publication year of CIE Publication N° 55, TC 3.4 was dissolved and reformed again as TC 3.13, following yet further structural re-organisation of the CIE. Although CIE Publication provided a means of calculating glare using the Einhorn formula, the original objective of providing an integrated system for the calculation of discomfort glare for practical use by lighting practitioners had still to be met. This was to be the task of CIE TC 3.13.

In the CIE Quadrennium 1983-1987 TC 3.13 was relatively inactive, following the almost frenetic pace of work carried out by TC 3.4 between 1972-1983. At the 21st Session of the CIE in Venice in 1987 there was renewed interest shown in the subject of discomfort glare, attributable to reports of problems with the ergonomics of the fast growing use of visual display units (VDUs). Included with the reported problems were visual and glare problems.

Mr K Poulton was appointed as chairman of the newly formed TC 3.13,and the committee charged with proposing (CIE Circular Letter N° 1, (June, 1988)):

> 'a practical CIE glare evaluation system based on generally accepted parameters influencing discomfort.'

At face value the stated objective of CIE TC 3.13 in 1987 had not changed very radically from one of the objectives set for CIE E-3.1.1.2 in 1955; the work of the CIE could not be said to run at a stunning pace!

In the quadrennium 1987-1991 TC 3.13 set to work to fulfil its objective. By the end of the quadrennium at the CIE 22nd Session in Melbourne the committee had completed at least one draft report which discussed the CIE 'Unified Glare Rating' (UGR) system (CIE TC 3.13, (1994)). The report was discussed in detail at a meeting of the committee, at which it was apparent that, although the committee had made very significant progress in the development of a universally acceptable discomfort glare system, there remained a number practical and 'political' problems to be resolved. At the time of writing the report has reached its 5th draft, and some moves have been made to submit the report for approval by the CIE Secretariat, a move that has some controversy attached to it. The controversy is principally focused on the inclusion in the report of a graphical method for deriving glare values, a system based on the German Glare Limiting system. The outcome of the debate has yet to be decided.

However, it is clear that the report of TC 3.13 has brought within reach the prospect of a universal system of discomfort glare calculation based on existing understanding and models. What remains to be resolved is what fundamental mechanisms underlie the empirical models that form the basis of the CIE UGR system? This broader issue is being

addressed by CIE TC 1.25: Fundamentals of Discomfort Glare. It will not of gone unnoticed that the remit of CIE TC 1.25, to identify the underlying causes of discomfort glare, bears remarkable resemblance to the second half of the remit of E-3.1.1.2 in 1955; it remains to be seen how far and how fast the work of

TC 1.25 progresses!

2.5.5.2 The CIE (Einhorn) Glare Formula

In the period from 1955-1972 E-3.1.1.2 seems to have achieved little in the way of developing either a practical, or a fundamentally based, and internationally acceptable discomfort glare system. The first major step towards realising a practical CIE glare system was the development by Einhorn of what was formally called the CIE Glare Index equation (CIE TC 3.13, (1994)). In its initial form the equation was:

$$CGI = 10Log0.1\frac{(1 + E_d /500)}{E_d + E_i} \sum \frac{L^2\omega}{p^2}$$

Where: CGI = CIE Glare Index

E_d = the direct vertical illuminance at the eye due to all sources

E_i = the indirect illuminance at the eye

L = is the luminance of the luminous parts of each luminaire in the direction of the observer's eye; cd m^{-2}

ω = the solid angle of the luminous parts of each luminaire at the observer's eye; steradians

p = the Guth Position Index for each individual luminaire which relates to its displacement from the line of sight

This formula was developed by Einhorn following the brief given to him at the CIE pre-sessional meeting in London in 1975 (Minutes CIE TC 3.4, (1975)):

'of a development of a formula which fits existing data and which can be validated by appraisal.'

In it initial form, with constant values of 10 and 0.1, the CGI scale had a range from 0 to 20. At the CIE 19th Session, Kyoto, Japan in 1979 the value of each of these constants was

modified so that the CGI scale ran from 10 to 30, consistent with the existing British Glare Index scale. Poulton reports that this change was made to accommodate comments by the Scandinavian delegates at the Session and so ensure their support for the new formula (Poulton, (1991)). Thus the constant values changed from 10 and 0.1 to 8 and 2, and the CGI formula took its final form:

$$CGI = 8Log2\frac{(1 + E_d/500)}{E_d + E_l} \sum \frac{L^2\omega}{p^2}$$

The allows for precise calculation of CGI from first principles. The details of how to calculate each of the variables in the glare equation are as follows:

* Calculation of E_d, the Direct Illuminance at the Eye

This variable is usually calculated for regular arrays of luminaires. This allows wall illuminance data to be used, as a room reference position is often assumed near a wall. The direct wall illuminance is then given by:

$$E_d = 0.5 \ Room \ Index(1 - Direct \ Ratio) * F/A$$

Where: F/A = the downward flux per unit floor area and:

$$RoomIndex = \frac{LW}{(L+W)H_m}$$

L = length of the room;
W = width of the room;
H_m = mounting height of the luminaire above the working plane.

* Calculation of E_l, the Indirect Illuminance at the Eye

This variable is usually obtained from inter-reflection calculations for the installation of interest. Additionally, the average luminance of the installation is a reasonable estimate of E_l. This variable is a function of room reflectance, flux fraction ratio, with a lesser

dependence on Room Index; there is little correlation of the variable with luminaire light distribution.

* The Term $(1 + E_d/500)/ (E_d + E_i)$: A Measure of Adaptation and 'Co-variance'

Poulton has discussed the meaning of the term $(1 + E_d / 500)/ (E_d + E_i)$ (Poulton, K, (1991), p 241).

He observes that the denominator includes variables expressing the effects of luminance from both the glare sources and from the background eg luminances from walls, ceilings and floors etc. Thus this term estimates the adaptation luminance. Also this term is equivalent to the variable F in Guth's DGR equation, but has the additional benefit of allowing for variation in luminance with the cosine of the elevation of the angle.

The variable E_i is equivalent to the variable L_b of the British Glare Index system, if L_b is expressed in Apostilbs ie cd m^{-2}/π.

The numerator of the expression is, incorrectly, called 'co-variance', defined in the draft of TC 3.13's Technical Report as:

'the change in glare sensation with change in size or number of luminaires.'

Glare sensation is directly dependent on E_d, therefore E_d is a variate and not a co-variate. A co-variate is defined as a measure of the association between two random variables, X and Y, and is given by (Hoel, (1984)):

$$Cov(X,Y) = E(X - \mu_X)(Y - \mu_Y)$$

Aside from the this technical error, Poulton (Poulton, (1991), p 241) observes that the numerator expressed as a function of E_d has a number of advantages by comparison with the numerator expressed as a function of average horizontal illuminance, these include:

    i.   When calculating E_d there is no need to distinguish between luminaires with and without luminous side panels

ii. There is no anomaly in assessing indirect light ie high flux fraction ratio, as detrimental

iii. The inclusion of E_d in the denominator also overcomes the difficulty of calculating infinite glare in darkened rooms lit by only one small luminance source

* **Calculation of Luminaire Size and Luminance**

The size of the luminous parts of the luminaire are calculated from the geometry of the particular situation. The solid angle of the projected area of a luminaire is given by:

$$\omega = \frac{A_{projected}}{r^2}$$

Where: $A_{projected}$ = the projected area of the luminous parts of the luminaire

r = the distance between the observer and the centre of the luminaire being considered

The luminance of the luminaire would normally be determined from tabulated photometric data, or less often from direct measurement of the luminaire's luminance distribution.

* **Calculation of the Position Index, p**

The calculation of the Position Index is carried out according to the equation derived by Lukiesh and Guth:

$$\frac{1}{p} = \frac{d^2 E}{d^2 + 1.5d + 4.6} + 0.12 (1 - E)$$

$$\textit{Where:} \quad E = e^{(-0.18 \frac{s^2}{d} + 0.011 \frac{s^3}{d})}$$

Also: d= the ratio of the forward perpendicular distance of the source to the height of the luminaire above eye level

s = the ratio of the sideways perpendicular distance of the source to the height of the luminaire above eye level

The Einhorn formula was formally adopted as the CIE Glare Index formula and included in CIE Publication N° 55 in 1983 (CIE Publication N° 55, (Paris, 1983)). However the formula was not received with universal approbation. It received particular criticism from the Britain where it was thought that the calculated values of glare from the formula did not correlate well with Hopkinson's data. Also since its publication the formula has not been adopted as a national standard for glare calculation by any member, or non-member, state of the CIE. This probably reflects the measure of conservatism attached to the use of existing discomfort glare models. This is more likely to be so where commercial use is made of a glare model in the specification of a luminaire and lamp system's glare characteristics.

However, the Einhorn formula did lay significant foundations for the work of TC 3.13 in the committee's developing the CIE UGR system.

2.5.5.3   The Evolution of the CIE Unified Glare Rating System

Although the development by Einhorn of the CIE Glare Index formula was a significant milestone it did not answer the requirement for a practical system of discomfort glare calculation; this was not Einhorn's remit in 1975. The development of a practical CIE system of glare calculation was the charge of TC 3.13, as cited in section 2.5.5.1 above.

The activity of TC 3.13 has been outlined above; a detailed discussion of the development of CIE UGR system is given in chapters 2 and 10 of Poulton (Poulton, (1991)). This section briefly reviews the current draft of the Technical Report produced by the committee. This draft probably represents a very substantial form of the final draft of the Technical Report; the exception to this may be the exclusion of the graphical method for determining glare levels. The graphical method is thought by some members of TC 3.13 to be too inaccurate. There is anecdotal evidence to suggest that even the originators of the graphical method think that, as much of the UGR system assumes the involvement of

computer calculation, the graphical method is redundant. The outcome of this debate remains to be resolved.

A detailed review of the current draft is given in Appendix A.

The main body of the report was divided into three parts. The first part discussed the UGR formula a modified form of the CIE formula:

$$UGR = 8 \, Log \, \frac{0.25}{L_b} \sum \frac{L^2\omega}{p^2}$$

Where: L = The luminance of the luminous parts of each luminaire in the direction of the observer's eyes; cd m^{-2}

ω = The solid angle of the luminous parts of each luminaire at the observer's eyes

p = The Guth Position Index for each individual luminaire, which relates to its displacement from the line of sight

L_b = The background luminance; cd m^{-2}. This parameter is calculated from the equation:

$$L_b = \frac{E_i}{\pi}$$

E_i = The indirect illuminance at the eye of the observer, as defined in the CIE equation.

This part of the report states that glare calculations derived by using the equation are likely to produce the most accurate predictions, so implying that this is the preferred method for calculating discomfort glare. As computers are now common it may not be impractical to expect that a majority of discomfort glare calculations may soon be carried out from first principles using computer-based software. Development of software capable of deriving UGR values using the equation is currently underway.

The second part of the report describes how UGR values are calculated using a tabular method similar in principle to that which is specified in the current CIBSE Technical Memorandum N° 10. The tabular method is based on the use of the UGR glare formula.

The final part of the report gives a brief description of the UGR implementation using a graphical method for deriving glare values, which is based on the use of glare limiting curves and so is analogous to the German Glare Limiting system. There is currently some debate concerning the accuracy of this method, and it may not be included in the final report of the committee.

2.6   Commentary

The review of the major glare systems and their development is now completed. It would have been possible to include further discussion about other glare systems, and other contributions to the development of the glare systems described.

Most notable of the glare systems not included in the review is the Nordic NB system, a development of the British Glare Index system which has figured significantly in the development of the CIE UGR system, (CIE TC 3.13 Report, (Vienna, 1994)).

Of other contributors to the systems described but not mentioned in any detail Lowson figures prominently. He was instrumental in the development of the Australian glare system, which was the only glare system to be incorporated in a national statute. Lowson also contributed significantly to the debate and general development of the CIE Glare Formula over a number years (Poulton, (1991)).

However, for the purpose of the present discussion the review is thought to have covered sufficient ground, in depth and breadth, for the development of the rest of the dissertation.

The principal issue arising from the discussion of Chapter 2, and to be explored in Chapters 3-5 is the distinction made between disability glare and discomfort glare. Chapter 3 begins with a discussion of why it is appropriate now to re-investigate the distinction between the two glare types, initially promulgated by Stiles (Stiles, (1929)), and accepted thereafter by glare modellers.

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Chapter 3   A Re-investigation of the Causal Links Between Light Scatter and Discomfort Glare

3.1   Introduction

The development of contemporary models of discomfort glare can be traced back directly to the work of early researchers, particularly the work of Holladay and of Stiles (Holladay, (1926); Stiles, (1929)). This development of glare models has been discussed in detail in Chapter 2. The conclusions drawn from the early work have carried forward into contemporary models of both types of glare.

One of the principal conclusions from the early work on glare was that disability and discomfort glare were two distinct phenomena. Disability glare was argued to be caused by light scatter, and discomfort glare, argued to be caused by effects other than light scatter; Appendix B provides details of light scattering. As discussed in chapter 2 the distinction between the two glare types can be attributed to the early studies of Holladay and of Stiles (Holladay, (1926); Stiles, (1929)). Since this time very few, if any studies, have investigated possible causal links between light scatter effects and discomfort glare.

Since the early research was carried out there have been very significant changes to experimental techniques, particularly statistical analysis methods and the technology available for running experiments. Perhaps most significantly there has been a very substantial increase in our understanding of the functioning of the visual system, especially the mechanisms of contrast detection.

The development of formal statistical analysis techniques was initiated by RA Fisher in the early 1920s (Fisher, (1922)). From this work, initially developed for use in agricultural experiments, a wide and powerful repertoire of analysis methods has been derived. These methods allow experimenters to carry out reliable analysis of their data, and also allow deeper insights into the interactions between the experimental factors; such analysis was not possible before the work of Fisher.

All forms of experimental technology have progressed since the early glare experiments. In

many present day experiments control of apparatus and logging of data is given over to computers, which potentially allows greater repeatability and precision than was allowed before the advent of computer control.

Perhaps the most potentially significant developments for scientific understanding of discomfort glare were the advances in knowledge of the visual system. The genesis of these developments is, similar to defining the start of contemporary glare research, very difficult to locate. The Kuhnian paradigm shift (Kuhn, (1970)) in our understanding of the visual system was probably initiated by the work of Kuffler in the early 1950s (Kuffler, (1953)). Today our understanding of the visual system is probably the most advanced of all of the sensory mechanisms.

One of the most significant developments in our understanding of the visual system was the publication in 1968 by Robson and Campbell(and Robson, (1968)) of a paper describing the human Contrast Sensitivity Function (CSF). This function shows how the human visual system is sensitive to both contrast, which had been known for a long time before 1968, but also to the size, or spatial scale, of the objects that the visual system views.

The advances in the three different subject areas summarised above do not undermine the scientific value of the earlier glare studies. However, theses advances do present the opportunity for re-investigating some of the underlying assumptions and conclusions of the early studies. The incentive for carrying out such a project is that investigating initial assumptions using modern techniques and understanding may reveal weaknesses in the assumptions. These weaknesses may mask potential routes to increasing our understanding of the phenomenon of discomfort glare.

This chapter describes an experiment carried out to re-investigate the initial assumption that light scatter has no causal link with discomfort glare. This assumption has been built into the development of discomfort glare models since Stiles (Stiles, (1929)) reported that light scatter could only account for 15% of the reported 35% visibility reduction by light scatter reported by Holladay in 1926 (Holladay, (1926)).

If it were possible to confirm the rôle of light scatter as a cause of discomfort glare

perception it would extend our current understanding of discomfort glare. This would be made possible by using the large body of understanding about the physical and geometrical optical mechanisms that underlie light scatter effects. The increase in understanding could lead to improved models of discomfort glare.

3.2 The Use of Spatial Gratings to Assess the Effect of Light Scatter on Visual Task Visibility

In Holladay's experiments (Holladay, (1926)) a variety of visual tasks were used to measure the effect of light scatter on visual task visibility. There are no explicit descriptions of how the tasks were formed. It can be inferred that the different tasks, and their contrasts, were achieved by using the cards of different reflectance values to form either background or task details. It is not clear whether the tasks were achromatic, chromatic, or both.

No description is given in Holladay's paper of how the tasks were presented to the subjects. It is inferred that the presentations were manually controlled, which would have made the process of determining threshold contrast very slow. The very slowness of the process is likely to have biased the results of the experiment, or increased the experimental variance.

In any event the tasks used by Holladay were probably not sufficiently sensitive to allow accurate assessment of changes in threshold contrast brought about by light scatter. The definition of a task suitable for this use was to be developed by Robson and Campbell just over four decades after Holladay reported his results.

The effect of light scatter on the visibility of visual tasks as seen by human eyes, as argued by Stiles (Stiles, (1926)), was extrapolated from light scatter measurements on excised ox eyes. Although the theoretical arguments put forward by Stiles were very convincing, it would be more appropriate to measure the effect of light scatter on task visibility as seen by human subjects. The technique for carrying out these measurements also had to await the results reported by Robson and Campbell.

In 1968 Campbell and Robson (Campbell, and Robson, (1968)) reported an experiment that showed that the human visual system was sensitive, not only to task contrast, but also to the spatial scale of the task. This conclusion was drawn from data which recorded the threshold contrast (C_{th}) of human subjects to one dimensional, sinusoidal luminance patterns of the type shown in Figure 3.1; where, for a given adaptation luminance, C_{th} is that contrast of the task where it is only just visible. This type of luminance pattern is called a spatial grating.

In their experiment Campbell and Robson asked subjects to set C_{th} for a range of spatial frequencies of sinusoidal gratings. The size range was defined in 'cycles per [visual] degree' (cpd); this is the number of complete cycles of the pattern that will fit into one degree of the visual field; see Figure 3.1.

The results of their experiment are shown in Figure 3.2. The graph has contrast sensitivity (the inverse of C_{th}) as the ordinate, and spatial scale measured in cpd as the abscissa. The curve traced by the data in the graph is called the Contrast Sensitivity Function (CSF). The CSF shows a distinct maximum, either side of which contrast sensitivity declines. The maximum occurs in the range 3-4 cpd, the upper cut off in the range 55-60 cpd, while the lower cut off occurs at approximately 1 cpd.

The CSF is important, Robson and Campbell argued, because it is a visual task that is related fundamentally to the contrast detection mechanisms of the human visual system. This argument has been investigated by many other studies since the initial report by Robson and Campbell. The understanding of how the task is related to the operation of the contrast detection mechanisms has advanced, but the CSF is commonly accepted as the principal function defining the contrast sensitivity of the human visual system. For the discussion of this chapter it is appropriate to consider that the CSF defines a very sensitive, and fundamental visual task that can be used in the assessment of visibility changes at C_{th}. It is thus the type of task that could be used to accurately and reliably assess the changes in task visibility caused by light scatter from a glare source.
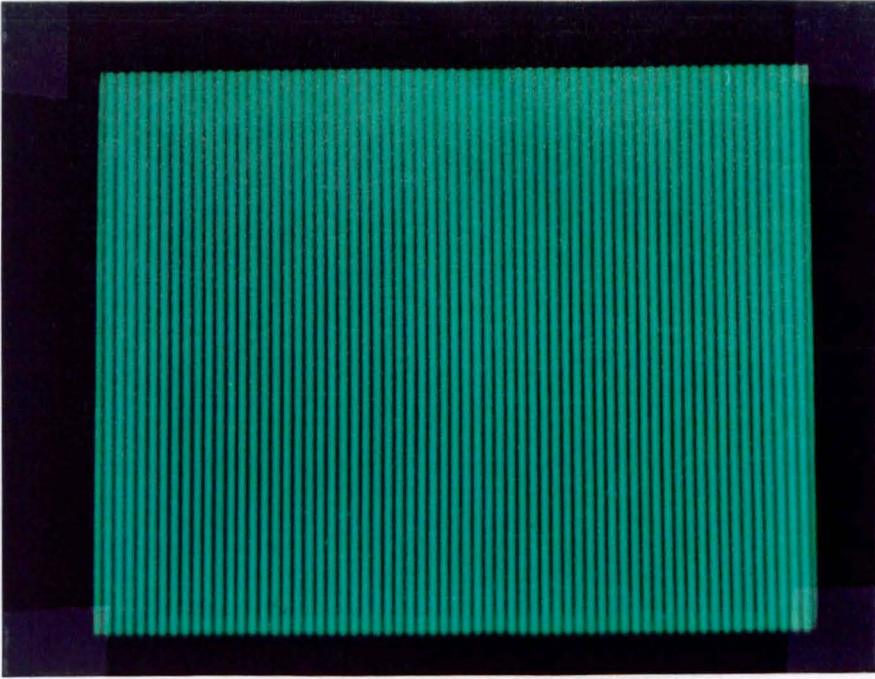
Figure 3.1   Spatial grating similar to that used in the present experiment. The scale used to define this type of pattern is cycles per degree. This is the number of complete cycles of the pattern that can fit into one degree of the visual field.
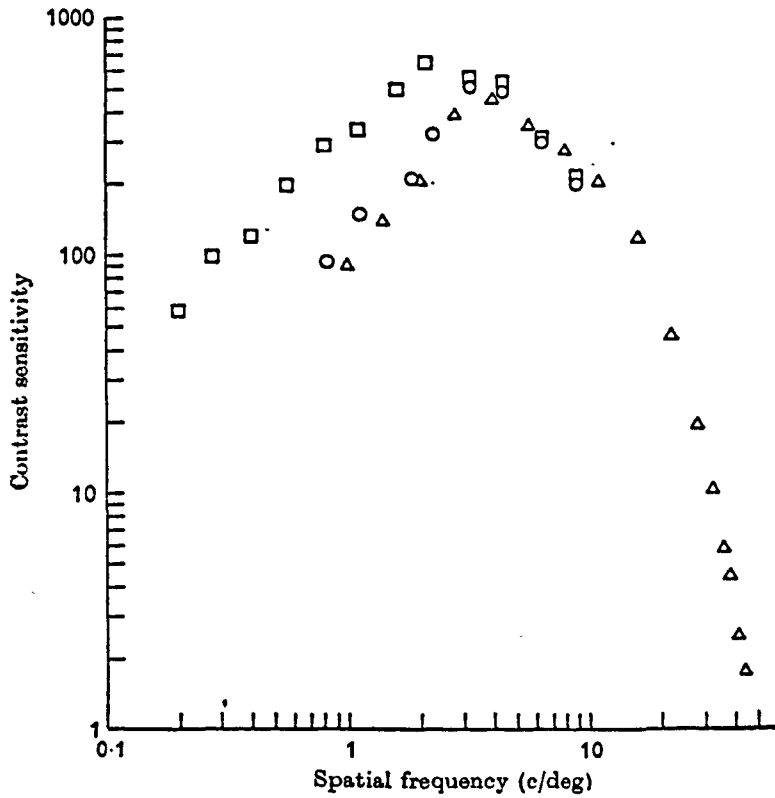
Contrast sensitivity for sine-wave gratings. Subject F.W.C., luminance 500 cd/m². Viewing distance 285 cm and aperture 2° x 2°, △: viewing distance 57 cm, aperture 10° x 10°, □; viewing distance 57 cm, aperture 2° x 2°, O.

Figure 3.2   The results of Campbell and Robson; [after Campbell and Robson, (1968)]

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3.3 The Discomfort Glare Condition for Measuring C_{th}

To test the null hypothesis that there is no causal link-between discomfort glare and light scatter effects it is necessary to establish a glare condition to carry out the test. It would be possible to use many differently defined glare conditions eg Hopkinson's multiple criterion glare conditions. However, these conditions are based on value judgements. Any test of the null hypothesis using these subjectively defined conditions could decrease the reliability of the test. The decrease in reliability would be caused by:

i.   increased variance introduced by subjectively defined conditions, which are prone to large inter-personal differences, and intra-personal variation;

ii.   an increase in the likelihood of bias caused by individually defined subjective conditions.

A discomfort glare condition that is less reliant on value judgement is the Borderline between Comfort and Discomfort (BCD), used in studies of discomfort glare by Guth (Guth, (1963)). This condition is a threshold type measure. Threshold measurements tend to be less susceptible to variance induced by value judgements, because it is possible to more rigorously define a single threshold condition. In this instance the threshold between comfort and discomfort caused by a bright light. If discomfort glare is a meaningful concept to naive subjects then the BCD threshold should more reliably measure subjects' responses than more complex multiple criterion scales.

3.4 The Experimental Null Hypothesis

The null hypothesis which was the basis for the present experiment was formed around the use of the glare condition defined by individually set BCDs. The method for determining BCD was an objective method which used interactive statistical methods. These allowed, as far as is possible, impartial measure of the individual BCDs. Once determined the glare source was set to the subject's BCD, and the subject's C_{th} was measured in the presence of the glare source. The C_{th} was determined using a spatial grating of the type described in section 3.2; the dimensions of this grating were 4 cpd, near the maximum of the human CSF.

There are at least two reasons justifying the use of the BCD glare condition at which to test for changes in C_{th}:

i. As outlined in section 3.3, BCD should be a reproducible condition across subjects, and therefore a reliable individual threshold measure of discomfort glare.

ii. If there were any causal link between light scatter effects on visual task visibility at threshold contrast and perceived discomfort glare the effect would be reasonably expected to become apparent at the threshold of discomfort glare. This is because if task visibility reduction influences perceived discomfort glare then the reduction would presumably become 'just noticeable' at the BCD, or glare threshold, condition.

The C_{th} measured with the glare source present at BCD was compared with a control value of C_{th} measured for the same subject without any glare source present. If the mean of C_{th} under the BCD glare condition were significantly higher than C_{th} measured without glare present then it could be inferred that light scatter was causing a reduction in the visibility of the spatial grating.

It is unlikely that any increase in C_{th} could be attributed to changes in the adaptation state of the visual system. This is because if the glare source had any affect on the adaptation state of the visual system, and hence the adaptation luminance, it would tend to increase the adaptation luminance compared to the no glare condition. An experiment reported by Van Nes and Bouman (Van Nes and Bouman, (1967)) showed that increases in adaptation luminance increased contrast sensitivity, or reduced C_{th}, up to an asymptotic limit.

Adaptation luminance also shifts the peak of the CSF; see Figure 3.3. Thus any increases in adaptation luminance caused by the glare source would be expected to decrease C_{th}, not increase C_{th}.

It is plausible that a range of mechanisms could contribute to the increase in C_{th}. However, it might be reasonably anticipated that one of the major factors influencing any increase in C_{th} would be light scatter, as established by Holladay's study, and in many other studies

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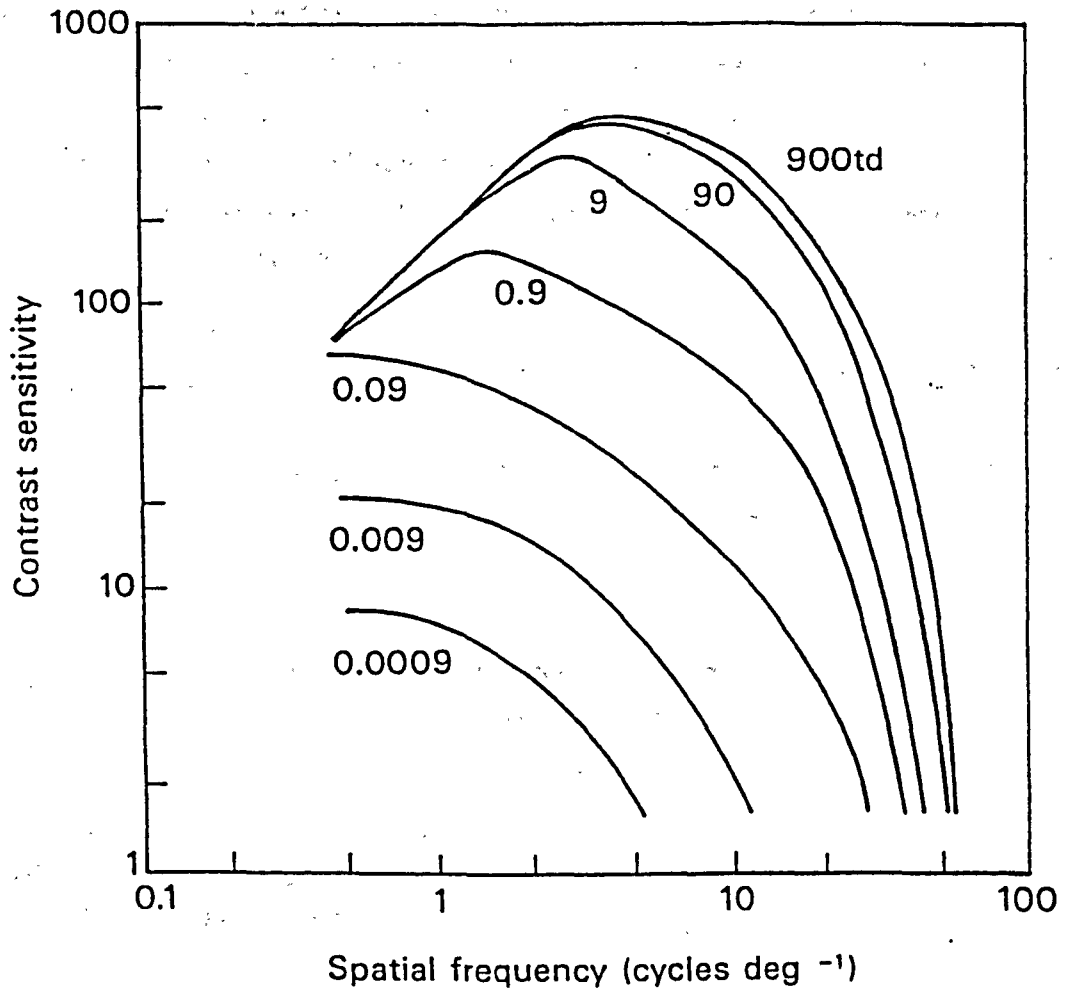
Figure 3.3   The results of Van Nes and Bouman (Van Nes and Bouman, (1967)). The
graph shows the contrast sensitivity function (CSF) for the human visual
system. The CSF is an empirically measured function showing the
sensitivity of the visual system to different sizes of spatial gratings of the
type shown in Figure 3.1. With decreasing adaptation luminance there is a
simultaneous decrease in contrast sensitivity and shift in the peak of
sensitivity function.

since; see for example Finlay and Wilkinson (Finlay and Wilkinson, (1984), Haines (Haines, (1968)). The effects of light scatter on threshold elevation are also discussed in Vos' review (Vos, (1984)).

Conversely if the glare condition C_{th} were significantly lower than the no glare C_{th} then adaptation luminance would have been affected by the presence of the glare source. It would therefore be unlikely that light scatter significantly affected perceived discomfort glare; at least in the sense that reduction in task visibility was directly correlated with increases in perceived discomfort glare. It seems implausible that increases in task visibility would be associated with increases in perceived discomfort glare.

The principal null hypothesis to be tested in the experiment was:

$H_0(1)$: For a fixed background, or adaptation, luminance, there is no difference between the threshold contrast measured under no glare condition and glare condition.

$H_0(2)$: For a fixed background, or adaptation, luminance, there is no significant correlation between subjectively rated discomfort glare at the BCD, and subjects' objectively measured C_{th}.

$H_0(3)$: If the glare source set to the BCD luminance has no influence on C_{th}, then the regression of C_{th} with glare source at BCD on control condition C_{th} should have a gradient of one, and a zero intercept.

The threshold contrast was measured using a measured a monochromatic (green, P31 phosphor) square wave grating with a spatial frequency of 4 cpd. The dimension of the glare source was 2°. The glare condition was BCD luminance, and was set to each individual's BCD luminance; the method used to determine BCD luminance is described in section 3.5.3.2 below.

3.5   The Experiment

3.5.1   Overview

This overview section provides a general description of the experimental set-up and apparatus. Details of the apparatus and experimental design are given in the remaining sections of the chapter.

The objective of the experimental measurements was to determine for a number of subjects the luminance at which a glare source appeared at the Borderline between Comfort and Discomfort, BCD. The measurement was made for each subject at five different horizontal viewing positions. At these measurement positions as soon as a subject had finished their determination of the glare source BCD, the glare source was reset to the BCD level and threshold contrast, C_{th}, measurements made using a square wave grating. C_{th} under glare conditions was compared with C_{th} with no glare present to assess if the threshold was effected by the presence of the glare source.

To carry out the experiment subjects sat facing a nominally uniform luminance background. The glare source was presented over a range of luminances against this background. The luminance of the glare source was interactively controlled by computer programme; the same programme also served to log subjects' responses to the glare source. For a number of calculated glare source luminances the subjects were asked to evaluate whether they thought the source appeared glaring. At the end of a sequence of glare source presentations the programme computed the BCD by using Probit analysis (Finney, (1971)); this process is described in Section 3.5.3.2.

Once a subject's BCD had been determined their threshold contrast was measured with the glare source set to the BCD level just determined. C_{th} was measured using a square wave grating of approximately 4 cpd presented on a high resolution CRT screen. The contrast of the grating was controlled using the same interactive process as used in the evaluation of the glare BCD.

Supplemental data was collected for one additional subject. The experimental method and apparatus and method used for this subject was the same as for the main part of the

experiment. However, the data were collected for the subject in both the horizontal and vertical meridians. In the horizontal meridian the data were collected for each of the five available positions. In the vertical meridian only three positions were available because above an angle of elevation of about 55° - 60° the glare source could not be seen due the cut off caused by the eyebrows.

3.5.2   The Apparatus

3.5.2.1   The Luminous Environment

The uniform background field, against which the glare source was seen, was provided by a 1.22 m radius white perspex hemisphere, or dome, which is shown in Figure 3.4. The interior surface of the dome was sand blasted to produce a matt, non-specular, surface. The outer surface of the dome was covered in an opaque tape to ensure that no spurious light could penetrate through the slightly translucent perspex.

The dome was mounted vertically with the apex of the dome at a height of 1.2 m to coincide with the average eye level of a seated adult (Tutt and Adler, (1979)). When subjects were seated facing the interior of the dome, and their line of sight coincident with the axis passing through the apex, the luminance field covered 2π steradians.

The interior of the dome was illuminated by two 15 volt , 50 watt tungsten-halogen sources powered, via transformers integral with the light fittings, from unfiltered ac mains at a nominal 220 volts, RMS; the sources were mounted into fittings that contained an ac step-down transformer. The sources were mounted onto the frame used to support the dome, and faced outwards. Placed behind the dome was a matt white photographer's umbrella which reflected the light from the tungsten-halogen sources back into the dome. The reflected light was diffuse so did not produce any directional lighting effects within the dome. The integration that occurred within the dome ensured that there were minimal shadows cast.

For the main part of the experiment the interior surface of the dome was set to 24 cd m^{-2} to match the maximum mean luminance achievable on the CRT screen. For the

supplementary ... the interior surface of the dome was ...
10 cd m[?], which ... represents the lower limit of photopic vision ... The
measurement po... with background luminance was a position at ... and
just to one side of ... central aperture of the dome.

The luminance uniformity measured as the ratio of maximum luminance to minimum
luminance along ... horizontal meridian passing through ... apex of the dome was ...
(21.9:25.67 cd m... background of 24 cd m...)

The luminance of ... terior surface of the ... ... is not ways. The
umbrella could be ... independently of ... ... umbrella relatively close
to the dome increase... illumin... ... ... the ... ...
reduced the lumin... ... ...
background lumin...

The second mod... ... input control of ... ...
supply voltage to ... ... tungsten-halogen lamp ... ...
voltage was con... ... by using two vari... ...
sources. Only on... ... ... in back... ... ...
control, as there ... ...

As the backgrou... ... ...
check measurem... ... ...
been completed, ...
percentage of th... ...
and not exclusiv... ...

At the apex of t... ...
CRT screen use... ...
measurement of ... ... a fixed ...
point for single ... ...

Cut into the upper vert... which was covered in copper tape to prevent extraneous light from
which the glare source the dome through the perspex. ... ... 30°, 40°, 50°, 60° and 80°

Figure 3.4 Photographs of the experimental apparatus. 3.4a: The interior of the perspex
dome, and the glare source. 3.4b: An exterior view of the perspex dome,
which was covered in copper tape to prevent extraneous light from entering
the dome through the perspex.

supplementary experiment the interior surface of the dome was additionally set to 10 cd m^{-2}, which currently represents the lower limit of photopic vision. The reference measurement point for both background luminances was a position at about 4 o'clock, and just to one side of the central aperture of the dome.

The luminance uniformity measured as the ratio of minimum luminance to maximum luminance along a horizontal meridian passing through the apex of the dome was 1: 1.17 (21.9:25.67 cd m^{-2}), at a background of 24 cd m^{-2}.

The luminance of the interior surface of the dome was controlled in two ways. The umbrella could be moved independently of the dome; moving the umbrella reflector closer to the dome increased the luminance of the interior surface; moving the umbrella away reduced the luminance. This method of adjustment was used for large changes in background luminance, as it caused no change in colour temperature.

The second mode of luminance control of the dome's surface was by controlling the ac supply voltage to the tungsten-halogen lamps used to illuminate the dome. The supply voltage was controlled by using two variable transformers, one for each of the two sources. Only small adjustments in background luminance were made using voltage control, as there were changes in colour temperature with changes in voltage.

As the background luminance was provided from lamps using unfiltered mains supply check measurements were made both before and after each experimental condition had been completed. In general the variation in background luminance was only a small percentage of the background setting, and was probably attributable to a number of factors, and not exclusively mains variations, eg temperature changes.

At the apex of the dome was cut a 38 mm hole through which the subjects viewed the CRT screen used in the measurement of threshold contrast. When not in use for measurement of C_{th} the CRT screen was reduced to a uniform field and used as a fixation point for subjects while they responded to the glare source to determine their BCD.

Cut into the upper vertical and left hand meridians of the dome were a series of holes at which the glare source could be mounted. The holes were cut at 20°, 40°, 50°, 60° and, 80°

in the horizontal meridian. The holes were located at the same points in the vertical meridian, except no hole was cut at 80°, as there is a visual cut off at about 60° in the vertical meridian (Boff and Lincoln, (1988)) due to the eyebrow structure. When mounted at the holes the glare source subtended an angle of two degrees from the subjects viewing point.

Mounted onto the base of the dome was a chin rest and head restraint used by subjects while they carried out measurements of BCD and, C_{th}. The height of the restraint was adjustable allowing subjects, once seated, to align their eyes with the apex of the dome. Subjects used natural pupils throughout the experiment.

It was not practicable to measure each subjects pupil diameter during the course of the experiment. It was possible to estimate the pupil diameter for one subject, the author, at a background luminance of 24 cd m^{-2} using a photographic technique. Figure 3.5 shows a photograph of the subject resting on the head restraint looking towards the central aperture where normally the CRT screen was mounted. In place of the CRT screen there was mounted a camera, which was used to take the photograph. Included in the frame was a ruler. By visual inspection, and using the ruler scale in the photo, the average pupil diameter from six photographs for the right pupil was estimated to be 3.9 mm, and for the left pupil 3.8 mm.

This compares with a pupil diameter of 3.68 mm calculated using the model of de Groot and Gebhard (de Groot and Gebhard, 1952)).

3.5.2.2   The Glare Source

The source of glare luminance was provided by a modified industrial boroscope normally used for the inspection of inaccessible spaces. The device consisted of a power unit in which was mounted a 150 watt, 15 volt tungsten-halogen source with integral reflector. Mounted at the focus point of the reflector was one end of a liquid optic. (The liquid optic operated in the same way a fibre optic, but was filled with a saline solution having a higher coefficient of transmission than a fibre optic.) The remaining end of the liquid optic was fitted into a recess of a perspex rod which could be fixed at the hole positions cut
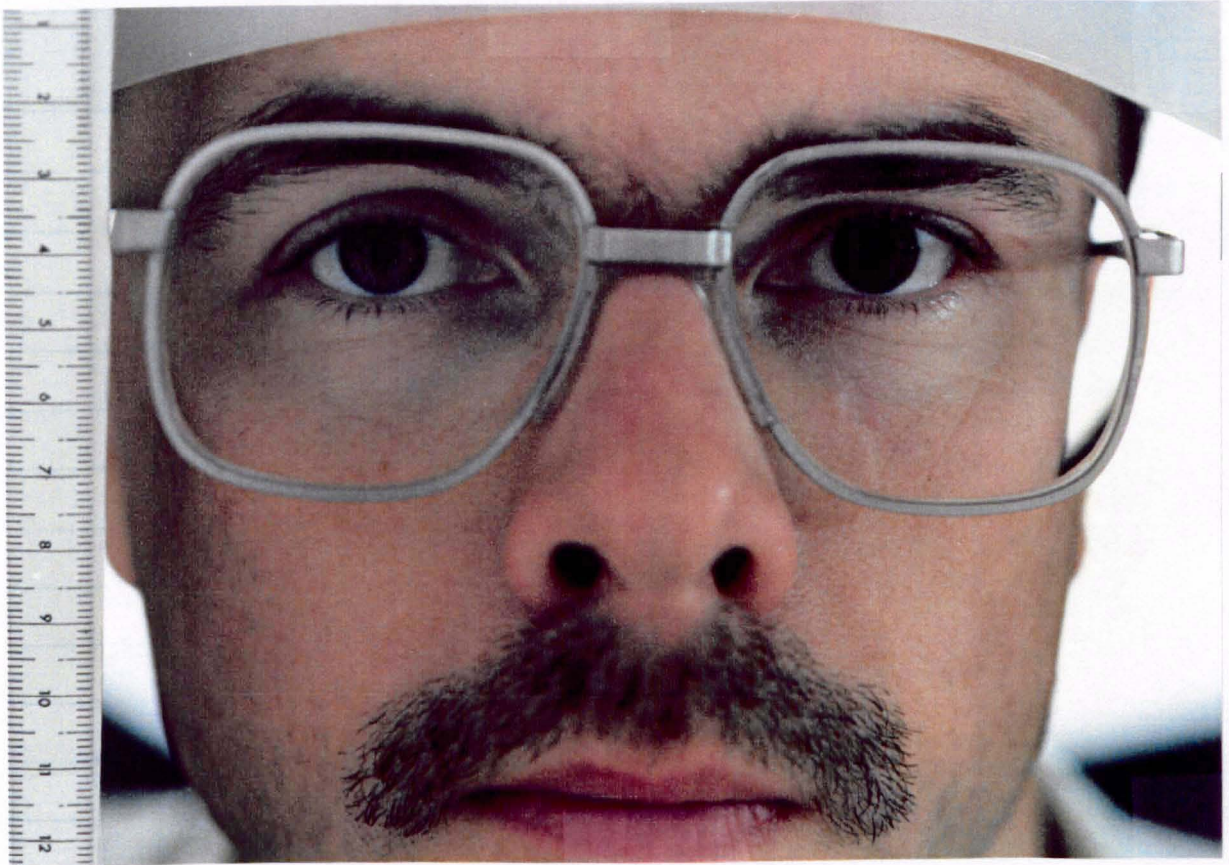
Figure 3.5 Photograph of a subject looking at the central aperture of the glare dome, with the background luminance set at 24 cd m^{-2}. Using the ruler scale in the photo, and averaging across six photos, the diameter of the right pupil was estimated to be 3.9 mm, and the left eye 3.8 mm.

into the dome, as described in Section 3.5.2.1 above. The diameter of the rod subtended 2° when viewed by the subjects. The end of the perspex rod seen by the subjects was abraded to produce an approximate lambertian surface. This reduced any directional effects of viewing the luminance source through the perspex rod.

The face of the perspex rod, which was the glare source, was at a fixed radius from the subjects when they were seated. Additionally, the front face of the glare source was always normal to the radius of the dome at the mounting position, and the subjects always looked at the central fixation point while setting BCD and C_{th}.

Fitted into the boroscope box was a stepper motor which controlled the position of a black anodised aluminium knife edge which could be positioned across the end of the liquid optic. By varying the position of the knife edge the luminance of the glare source could be adjusted. At the position where the knife edge completely occluded the end of the liquid optic no light was transmitted to the perspex rod. The position of the knife edge was controlled by a stepper motor under voltage control.

The glare source was calibrated by measuring its luminance for a range of control values of the stepper motor. The instrument used to measure the luminance was a Spectra Pritchard 1980A photometer.

The calibration data for the glare luminance source as a function of the control value of the stepper motor for 24 cd m^{-2} and 10 cd m^{-2} background luminances are shown in Table C.1 and Table C.2 in Appendix C; the scatter plots and fitted functions for the data are shown in Figure 3.6 and Figure 3.7. The logistic functions fitted to the data were used to quickly obtain interpolated values between the calibration data points for the programme that controlled experimental apparatus.

With full occlusion of the liquid optic the luminance of the perspex rod mounted at the surface of the dome was 3.9 cd m^{-2}, with an interior surface luminance of 24 cd m^{-2}. With the end of the liquid optic fully exposed to the source the end of the perspex rod had a maximum luminance of the order of 60.10^3 cd m^{-2}. The position of the knife edge was controlled interactively by the computer programme used to record the subjects' glare BCD.

$$y = -1189 + 54870/(1+e^{-0.0014165*(x-7646.8)})$$

Fit Standard Error = 913.6; F-Statistic = 7415.6

Degrees of Feedom Adjusted $\tilde{r}$=0.998
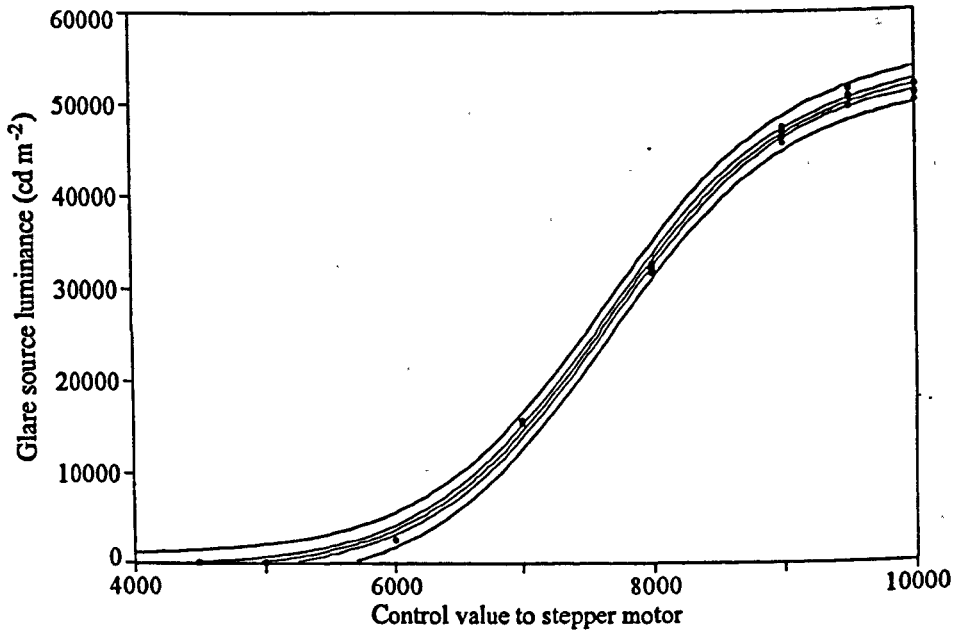
Figure 3.6   Glare source luminance calibration at 24 cd m^{-2} background luminance. The
ordinate shows the luminance of the source, the abscissa shows the control
value to the stepper motor which could be positioned to occlude 0% to
100% of the liquid optic transmitting the glare source luminance; refer to
section 3.5.2.2. The sigmoid shape of the curve is caused by the geometry
of the knife edge revealing progressively more segment area of the circular
liquid optic; the area of a segment of a circle of radius r, as a function of θ
(radians) the angle subtended by the arc, is given by:

$$Area\ of\ segment = \frac{r^2}{2}(\theta - \sin\theta)$$

The inner set of dotted lines, closest to the fitted curve, gives the $\pm$ 95%
confidence intervals of the mean; the outer set of dotted lines gives the
$\pm$ 95% prediction intervals for the fitted function.

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$$y = -1211 + 55865/(1+e^{-0.0014041*(x-7707.0)})$$
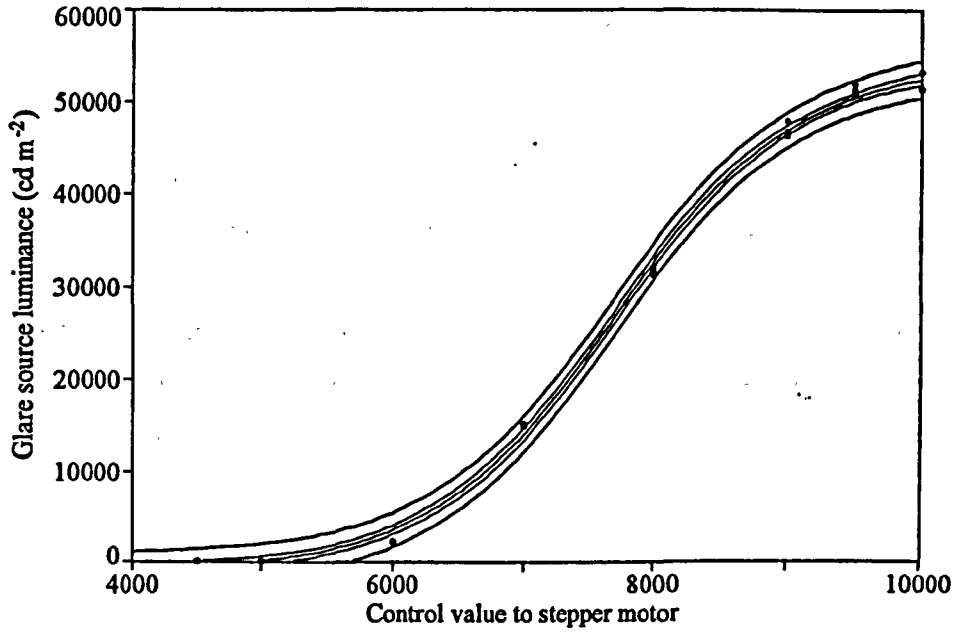
Figure 3.7   Glare source luminance calibration at 10 cd m^{-2}. For explanation of the graph axes and intervals about fitted function see caption to Figure 3.6.

The glare source luminance was calibrated only once at the start of the experiment. However, glare source and background luminances were measured at the start and finish of every experimental run. Thus keeping a running check on the luminance calibration.

As the luminance was controlled via a knife edge there was no variation in colour temperature with changes in luminance.

During an experimental run the glare source was varied across a large proportion of its total range of operation ie from total occlusion up to a maximum luminance of 60.10^3 cd m^{-2}. At the higher luminances of the glare source some integration of the glare luminance took place within the hemisphere, causing small changes in the background luminance. The changes caused by the glare source were small, certainly less than 3%. It was not possible to reduce the main background illumination to compensate for these small changes.

3.5.2.3   The Measurement of Luminance

During the experiment the luminance of the interior of the dome was monitored using a hand held luminance meter, a Minolta LS-110. The measurement aperture on the luminance meter was ⅓°. The luminance of the dome was checked both before and after each subject had completed the measurement of either BCD luminance or C_{th}. The luminance was checked by measuring at a reference point on the interior surface of the dome. The reference point was located, approximately, on the horizontal meridian and just to the right of the aperture cut at the apex of the dome. This reference point was chosen because it appeared close to the centre of the field of view and where the luminance on the surface of the dome was most uniform - and hence small position changes were unimportant.

The luminance of the glare source was initially computed by the control programme in terms of the position of the stepper motor controlling the knife edge. The computed position of the motor was set and then the luminance of the glare source verified by measurement using the Minolta LS-110. The measurement was made so that the aperture of the photometer covered most of the glare source area. The measurement aperture was always contained within the area of the glare source.

3.5.2.4   The CRT Display

The square wave grating used in the measurement of C_{th} was produced on the screen of the CRT which was a Tektronix 608 high resolution CRT. The display of the CRT used a green P31 short persistence phosphor. Other relevant technical specifications are given in Appendix D.

3.5.2.5   The Image Synthesizer

The grating was generated using a Innisfree 'Picasso' Image Synthesizer. The Synthesizer allowed the control of both the spatial frequency (spacing of the bars in the grating), and the contrast of the grating. The spatial frequency could be controlled manually and by computer. For the purposes of measuring C_{th} the these two parameters were controlled by the computer programme. For the measurement of C_{th} the spatial frequency was set at a fixed value of 4 cpd. The contrast of the grating was varied interactively, using the same control algorithm as was used to control the luminance of the glare source in the measurement of BCD luminance.

Technical specifications of the 'Picasso' Image Synthesizer are given in Appendix D.

3.5.2.6   Contrast Calibration of the CRT Spatial Grating

With the square wave grating set at the fixed value of 4 cpd the contrast control voltage from the Image Synthesizer to the CRT screen was varied. The voltage level was controlled from the computer via a 4-bit digital to analogue convertor; the voltage varied over the range $\pm$ 5 volts, and was controlled by the converter to 1 part in 4096 ie 2.4 millivolts, 12 bits.

For a given control value of the convertor the contrast between the light and dark bars of the square wave grating was measured using a Spectra Pritchard Tele-photometer model 1980A, using a measurement aperture of 2'. Contrast for the experiment was defined by the formula normally used for grating contrast (Campbell and Robson, (1968)):

$$Contrast = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

For each value of control voltage the luminance of the light and dark bars was measured five times. Between each measurement the control voltage was changed to another value to measure a different contrast. Thus the five contrast measurements were made by returning to the control value to provide an estimate of the reliability of the converter, and of the voltage control circuits in the Image Synthesizer. The calibration data of contrast as a function of control value are given in Table C.3 and Table C.4. The data and fitted functions are plotted in Figure 3.8 and Figure 3.9.

The calibration data file was subsequently used to derive the control voltage to the contrast module on the Image Synthesizer when the apparatus was under computer control during experimental runs.

3.5.2.7   Variation of Contrast Calibration in Presence of the Glare Source

A check was carried out to assess if the contrast calibration of the phosphor coating was in any way effected by the presence of the glare source. To carry out this check a test set of contrast calibration data were measured without the glare source, and with the glare source set to a value of 44 000 cd m^{-2}. For the test measurements the inside surface of the hemisphere was set to a value of 24 cd m^{-2}, and the spatial grating was set to a spatial frequency of 4 cycles per degree.

An analysis of variance (ANOVA) was carried out on the data to assess if the calibration was significantly affected by the presence of the glare source. The factors included in the ANOVA were:

    i.   Control value, the numerical value given to the computer control programme to set the value of the contrast. The value of control value were set to: 1 000, 750, 500, 250, 100 for both glare luminance conditions.

$$y = 0.0018334 + 0.000051285*x$$

Fit Standard Error = 0.0069; F-Statistic = 227.9

Degrees of Freedom Adjusted R^2=0.862
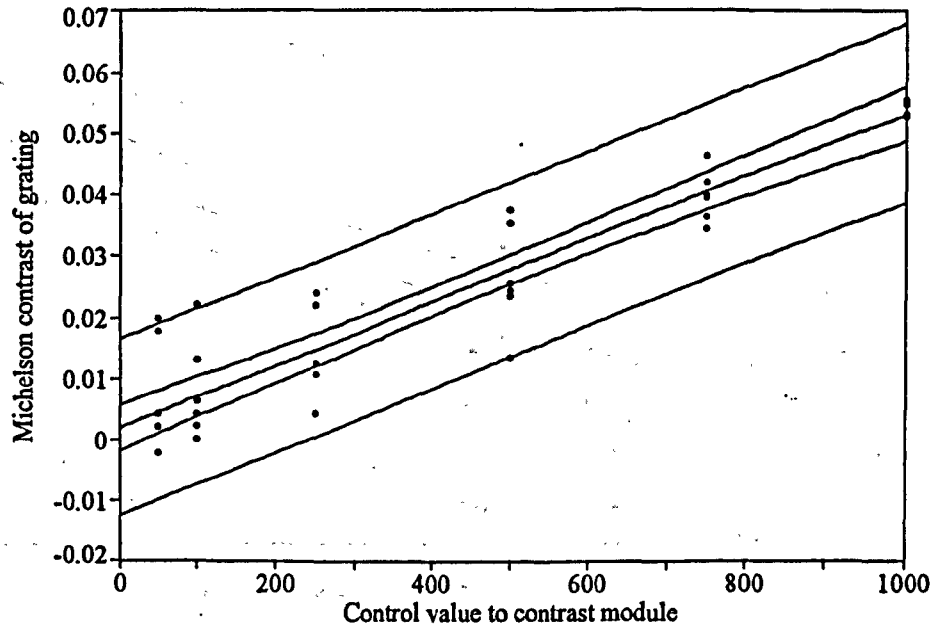
Figure 3.8 Spatial grating contrast calibration at 24 cd m^{-2} background luminance. The ordinate gives the Michelson contrast of the grating, and the abscissa gives the control value of the contrast module on the Innisfree image synthesizer; refer to section 3.5.2.6. The inner set of intervals gives the ± 95% confidence intervals on the mean, and the outer intervals give the ± 95% prediction confidence intervals.

$$y = 0.0058395 + 0.000045455*x$$

Fit Standard Error = 0.0154; F-Statistic = 39.7

Degrees of Freedom Adjusted $\hat{r}$=0.556
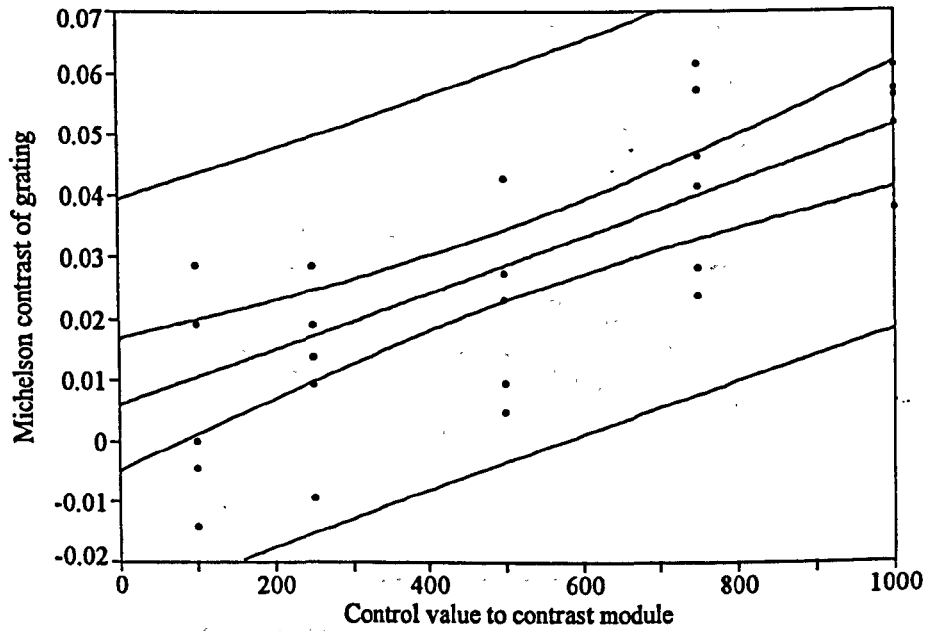
Figure 3.9   Spatial grating contrast calibration at 10 cd m^{-2} background luminance. Refer to the caption on Figure 3.8 for an explanation of the axes and intervals about fitted function.

ii. Glare luminance, the glare luminance was either off or set to a value of 44 000 cd m^{-2}.

The ANOVA for the data is given in Table 3.1 below.

The factor 'control value' is significant to at least 0.1%
($F_{4, 40, 0.001} = 12.61$; $F_{4, 60, 0.001} = 11.97$). This is a very high level of significance and would be anticipated intuitively.

The factor 'glare luminance' is not significant, even at the 10% significance level
($F_{1, 40, 0.10} = 2.835$; $F_{1, 60, 0.10} = 2.791$). This confirms that there is no change in the contrast calibration for the CRT screen in the presence of the glare source. This analysis meant that, at one background luminance, the same contrast calibration curve could be used by the control programme for both glare and non-glare conditions.

3.5.3 The Experimental Measurements

The independent, or experimental, variables in the experiment were:

i. Background luminance; 24 cd m^{-2}; additionally 10 cd m^{-2} for the supplementary data for the single subject.

ii. Angle of view; for all subjects: 20^0, 40^0, 50^0, 60^0, 80^0 in azimuth, additionally 20^0, 40^0, 50^0 in elevation for the supplementary experiment.

Other independent experimental factors were:

iii. Spectacle use; 'spectacles' or 'no spectacles'; categorical, or nominal variable. For the main experiment the subjects were balanced for spectacle and non-spectacle use. The supplemental subject did wear glasses.

iv. Subject age; years. Subject ages varied from 21 - 51 years.

Factor	Sums of Squares	%'age Variance	Degrees of Freedom	Mean Square	Variance Ratio
Control value	.01686	74.1	4	.00422	38.36
Glare luminance	.00009	.4	1	.00009	.8182
Residual	.00581	25.5	54	.00011	
Total	.02276	100.0	59		

Table 3.1   Glare source ANOVA

The stimulus variables were:

v. The glare source luminance; up to a maximum of 60.10^3 cd m^{-2}.

vi. The contrast of the spatial grating; Michelson contrast, defined in section 3.5.2.6. The range of Michelson contrasts used in the experiment was from 0.002 - 0.0209 at 24 cd m^{-2}, and from 0.006 - 0.025 at 10 cd m^{-2}.

The dependent, or response, variables were:

vii. The subjective rating of the Borderline between Comfort and Discomfort, BCD, for the glare luminance; cd m^{-2}.

viii. The objective assessment of the Michelson threshold contrast, C_{th}, of the spatial grating.

The independent variables i., background luminance, and ii., angle of view, were manually set and static for any particular experimental condition. The independent variable glare luminance was varied by the experimental control programme. The response variables BCD and C_{th} were logged, and final values calculated, by the control programme.

3.5.3.1   The Experimental Control Programme

The control programme worked so that the stimuli, the glare source luminance or the contrast of the spatial grating, was interactively controlled by the responses given by the subject for a sequence of presentations of the glare source or grating contrast. Also, not only was the level of the stimuli controlled, but the range within the maximum allowed by the apparatus. The core of the programme was based upon an Adaptive Probit Estimation (APE) method described by Watt and Andrews (Watt and Andrews, (1981)), which is itself a derivative of traditional Probit techniques; see for example (Finney, (1971))

A brief descriptive account of the Probit technique is given here; for a more technical account of APE refer to Watt and Andrews (Watt and Andrews, (1981)).

3.5.3.2   The Measurement of Threshold Values Using Probit Analysis

The measurement of threshold values in different types of experiments can be achieved by the use of a variety methods. One method is Probit analysis (Finney, (1971)). To measure, say, a value of threshold contrast for a visual task the task is presented to an subject over a range of fixed values of contrast. The values would range from sub-threshold to supra-threshold. The task is presented to the subject at each contrast for a certain number of times; the greater the number of presentations at each contrast, the greater the reliability of the final measure of threshold contrast. At each contrast the probability of, in this instance seeing the task, is calculated from the relative frequency count of the number of occasions that the subject saw the task.

The probability of seeing the task is plotted against the values of contrast used, to produce a probability of seeing curve. Such a curve could look like the example shown in Figure 3.10, which actually shows the probability of a light source being perceived as glaring. In this type of experiment it is traditional to take the value of the stimulus at 50% probability of seeing as the threshold value of contrast.

In practice the Probit method of determining 'threshold values' is reliable, more reliable than some of the more commonly used methods such as the 'Method of Adjustment'; see for example Laming (Laming, (1986)). The Probit method does have some drawbacks however. It is necessary for the experimenter to carry out pilot studies to determine the likely range of stimuli within which the threshold value will fall. This process is time consuming, and therefore costly. Even when the pilot studies have been carried out there is no guarantee that each subject used in the study will have their threshold value falling in the range of contrasts used in the pilot studies. A number of different situations can arise which can reduce the efficiency of the Probit method. These are summarised in Figure 3.11.

Watt and Andrews (Watt and Andrews, (1981) developed an adaptive, or recursive, Probit method to overcome the short comings of the traditional method of measuring the Probit response curve. The method is called 'Adaptive Probit Estimation', or APE. To measure a Probit curve using APE a range of stimuli values are used, the range being sufficiently wide so as to include the threshold value of interest. At the start of an APE run all of the

Probability of source perceived as glaring
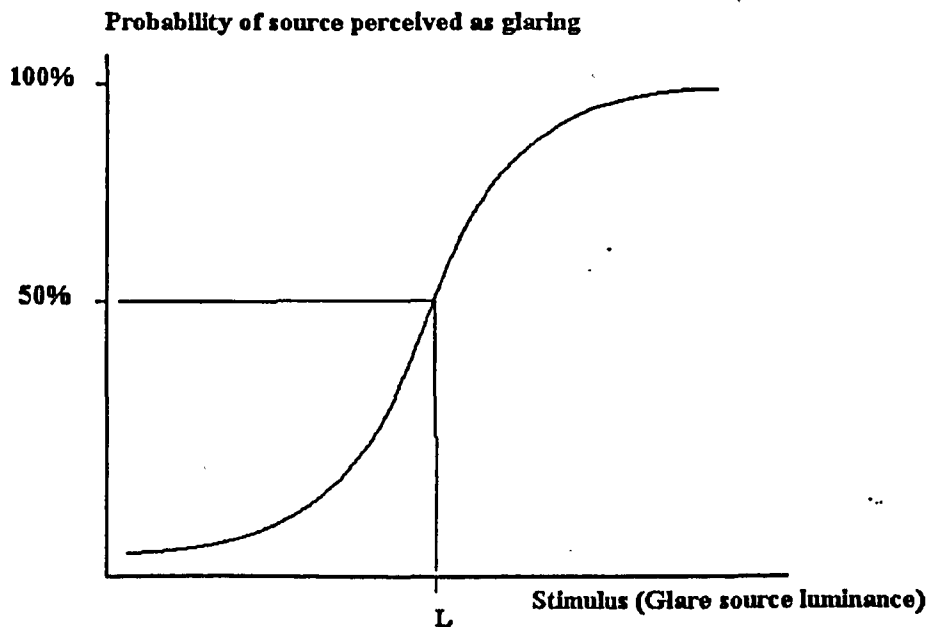
Figure 3.10 The graph shows an idealised Probit curve. The x-axis represents the stimulus magnitude, which in this study was glare source luminance. The y-axis represents the probability of a certain class of response from the subject; for the glare study the y-axis measures the probability that a subject would find the source glaring. The threshold value is taken to be where the 50% probability point intersects the stimulus axis. In the present glare study the threshold value represents the 'Borderline between Comfort and Discomfort', or BCD. The slope of the linear portion of the curve estimates the standard deviation of the data.
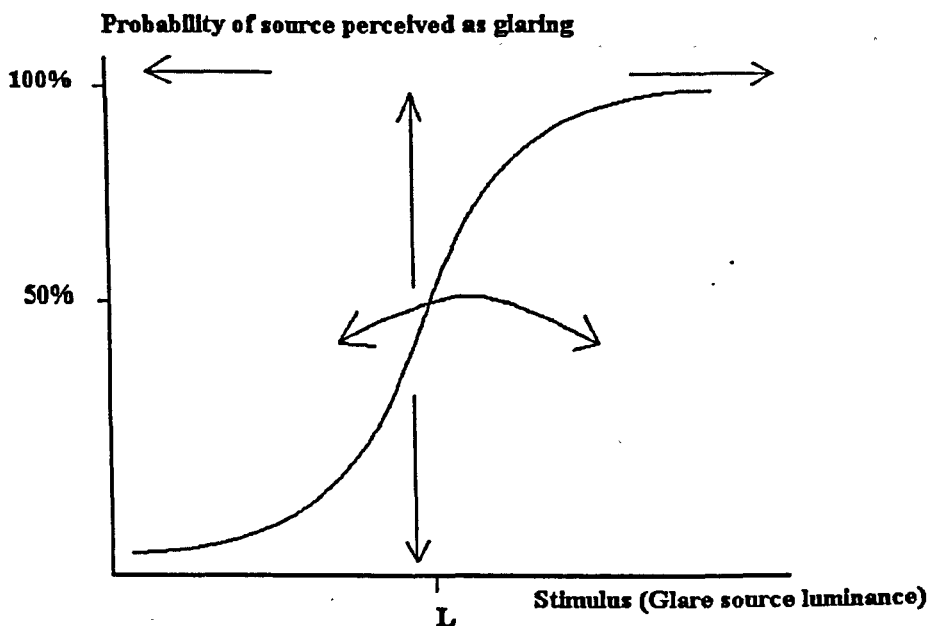
Figure 3.11 The arrows on the graph show ways in which movement in the probit curve can influence the efficiency with which a fixed stimulus range is able to model a probit curve. Vertical movement in the curve has no effect on the efficiency of the stimulus range. Provided that the stimulus range contains the threshold, probit curve rotation will have little effect on the efficiency. The movement in the curve that has greatest effect is horizontal movement. This type of movement can result in all of the stimulus range contained in the upper or lower asymptotes. This will provide very little information about the linear portion of the curve, the part of the curve that is of greatest interest. Use of adaptive, or recursive, methods that ensure that the stimulus range always covers the linear portion of the curve ensure maximum efficiency in the estimation of the Probit curve; Watt and Andrews' APE Probit estimation programme uses adaptive methods.

stimulus values are used. During the course of the run the current position of the subject's threshold is calculated, along with its associated standard deviation. This recursive calculation is used to continuously adjust the stimulus range. By the end of a run, about sixty four presentations, the stimulus range should have been reduced to a small sub-set of the full range. The threshold will be contained within this sub-set. The APE process is shown schematically in Figure 3.12.

3.5.3.3 The Measurement of the Borderline Between Comfort and Discomfort, BCD

The subjective glare ratings were measured using the control programme, which controlled the luminance of the glare source seen by the subjects. The programme controlled a stepper motor driving a knife edge placed in front of the liquid optic in each of the boroscope light boxes. The light passing down the liquid optic was attenuated by driving the knife edge across the face of the liquid optic. A presentation of the glare source consisted of the control programme selecting a glare luminance from a fixed repertoire of luminances, carried on the programme's calibration file. The glare source luminance selected was presented until the subject responded. At any one presentation the value of glare luminance seen by the subject was computed from the previous sixteen responses. There were 64 presentations for any particular experimental condition. The experimental subject responded to any one glare luminance presentation by stating whether they thought the luminance was 'glaring' or 'not glaring'. The subjects made their response by pressing one of two switches, which were connected to the computer. The programme recorded the response data and calculated the probabilities of a 'glaring' response, P(Glare), for each of the glare luminance levels used during the course of an experimental run. The values of P(Glare) were plotted against the values of luminance level used during an experimental condition and the best fit curve, or Probit curve, calculated. The value of luminance at the 50% point of the probability curve was taken as representing the glare luminance value at the 'Borderline between Comfort and Discomfort', or BCD.

3.5.3.4 The Measurement of Threshold Contrast, C_{th}

The measurement of C_{th} was made at both a no glare condition, the control measurement

Stimulus range

Number of presentations of stimulus

Final estimate
of threshold value
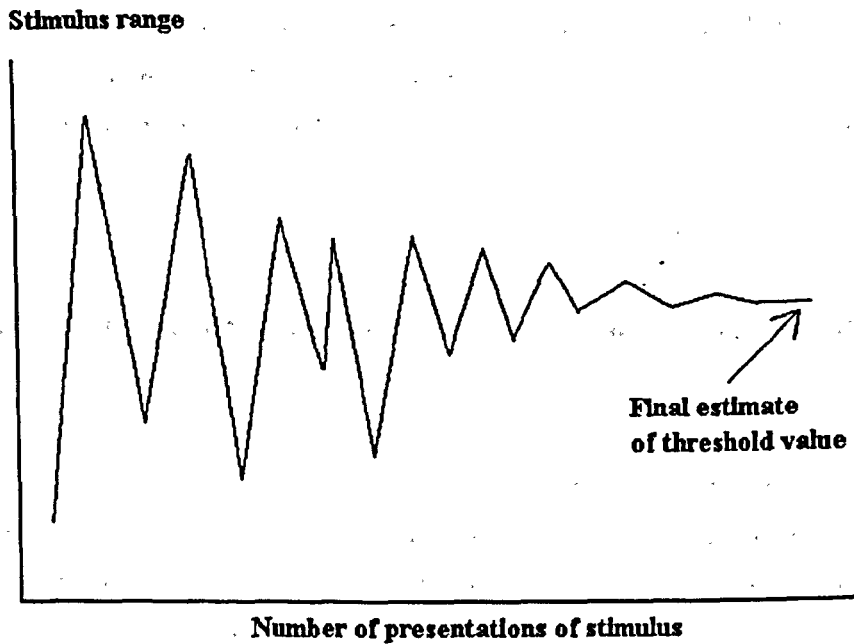
Figure 3.12 The figure shows that at the start of an APE run the stimulus range covers most of the available range. As the run progresses the experimental subject begins to home in on the 'threshold' value; the stimulus range used by APE is gradually reduced. By the end of the run the subject has, in principle, reached a stage where most of his responses are centred around the threshold value; at this stage APE is selecting the stimuli from a very reduced stimulus range.

of C_{th}, and under the condition of glare at BCD. The measurement of C_{th} under glare and no glare conditions was made using the same Probit method as used for the measurement of subjective glare ratings. In the measurement of C_{th} the control programme set the contrast of the grating on the CRT screen. The subject responded to a grating presentation by saying whether they could, or could not, see the grating. For the repertoire of contrasts used during an experimental run the probabilities of seeing the grating were calculated. The best fit curve to the probability of seeing data was calculated, and the value of contrast at 50% probability of seeing was taken as C_{th}, using the principle described in Figure 3.10.

3.5.3.5   The Subjects' Task

The subjects were seated on a chair facing the interior of the dome. Fixed to the floor of the dome was a chin rest. The subjects were asked to adjust the height of the chair and the chin rest so that they were comfortable and their line of sight was approximately aligned with the aperture cut at the apex of the dome.

Each subject was given a verbal description of the objectives of the experiment ie that they were to establish their BCD for a particular condition; once a BCD level had been established a measurement of C_{th} would be made at the BCD luminance. The same verbal description was given to all subjects. The subjects were then introduced to the method they would use to make the glare ratings and measurements of C_{th}. A trial run of the control programme followed the verbal introduction.

Thus all subjects were fully informed of the purpose of the measurement session before data collection started. It would have been difficult, if not impractical, to have asked the subjects to carry out the measurement session without being aware of what was required of them.

Once the subjects had been familiarised with the objectives of the experiment and had completed the trial run data collection began. The subjects were instructed to fixate the CRT screen seen through the aperture cut at the apex of the dome. While fixating the CRT screen they were asked to rate the appearance of the glare source luminance using the

switches in front of them. Consistent with the definition used by Petherbridge and Hopkinson (Petherbridge and Hopkinson, (1950)), the subjects were told to rate the source luminance as glaring if:

'They thought that the light source appeared irritating, distracting, uncomfortable or, glaring'

If the light source did not conform to any of these criteria then they were to give a not glaring rating. Once it had been established that the subjects understood what was required of them the collection of glare response data began. For any one experimental condition 64 responses were collected, which took approximately 5 minutes.

Once the glare rating data had been collected for a particular experimental condition the glare source luminance was set to the value calculated for the BCD derived from the Probit curve. The subjects C_{th} was then measured in the presence of the glare source. The measurement of C_{th} under no glare condition was recorded using the Probit method in an experimental session arranged at some time following the recording of the glare data. For many subjects this measurement was on the same day as the collection of glare data, in a few cases the measurement of C_{th} with no glare source was unavoidably delayed by some days.

Glare rating data were recorded for each subject at five horizontal positions, 20°, 40°, 50°, 60° and, 80°. All data were recorded at one background luminance of 24 cd m^{-2}. This luminance being set to match the maximum mean luminance of the CRT screen. For the supplementary data for the single subject additional data were collected at a background luminance of 10 cd m^{-2}, and at each of the two backgrounds BCD and C_{th} data were collected for three vertical positions, 20°, 40°, and 50°.

Additionally, each subject was tested for visual anomalies using a Keystone Visual Screener and a Visitec Contrast Sensitivity screen test. The visual screening test was carried out for all subjects after they had completed the measurement session. Any subject found to have significant visual anomalies relative to the norm indicated by the screening tests was not used in the experiment. It was thought at the start of the experiment that it might be possible to quantify the visual screening data for use as a categorical

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variable. This was not found to be viable in practice.

3.5.3.6   Summary of the Experimental Design for the Main Experiment

The statistical experimental design for the main experiment was:

*   Single background: 24 cd m^{-2}

*   Spectacle use at two levels: 'spectacles' and 'non-spectacles'

*   Azimuthal position at five levels: 20^0, 40^0, 50^0, 60^0, 80^0

*   Age as a continuous variable across twelve subjects: 21, 23, 24, 25, 26, 26.7, 36, 39, 41, 44, 45, 51 years

Spectacle users and non-spectacle users were balanced across the age range. For each experimental condition each subject ie each age level, repeated the measurement of both BCD and glare condition C_{th} two times. The sequence of azimuthal positions was randomised across all subjects. Threshold contrast for the no glare, or control, condition was measured three times for each subject.

3.5.3.7   The Experimental Design for the Supplemental Experiment

A different experimental design was used for the supplemental experiment with the single subject:

*   Two backgrounds: 24 cd m^{-2} and 10 cd m^{-2}

*   Azimuthal position at five levels: 20^0, 40^0, 50^0, 60^0, 80^0

*   Elevation at three levels: 20^0, 40^0, 50^0

The single subject repeated each measurement of BCD and glare condition C_{th} three times.

The sequence of measurements was balanced for background and, azimuth and elevation; the sequence of angles at each meridian was randomised. The single subject's no glare C_{th} was measured ten times at each background level.

This subject was also tested for visual anomalies using the Keystone and Visitec screeners.

Chapter 4   The Analysis of the Experimental Results

4.1   Introduction

The analysis of the experimental results was carried out in two stages. The data were first investigated, using Analysis of Variance (ANOVA). This analysis was used to identify the main, or principal, effects of the independent variables (age, position, spectacle use) on the two response variables (BCD, $C_{th\,(glare)}$).

The common logarithm of the response variable BCD, the luminance of the glare source set by the subject, was used in all analyses of the response variable. The logarithmic transformation of the data was justified because it is well established that the physiological response of the visual system to luminance signals is logarithmic; see for example (Cornsweet, (1970)).

The ANOVA was used to guide the second stage of the analysis, in which the response variables, Log (BCD) and C_{th}, were regressed on the independent variable position of the glare source. Also, the response variables were correlated with the independent variable: age.

One of the principal tests of H_0 was carried out correlating $C_{th\,(glare)}$ with $C_{th\,(no\,glare)}$. It would be expected that if there were no effect of the glare source on C_{th} then there would be a linear relationship between the two variables, with a gradient of 1, and passing through the origin at zero. If there were an effect of the glare source on the value of C_{th} this would be unlikely to be the case.

A further important relationship was investigated correlating Log (BCD) with $C_{th\,(glare)}$. Additionally, Log (BCD) was correlated with $C_{th\,(no\,glare)}$; and $C_{th\,(no\,glare)}$ was correlated with age.

The ANOVA, regression and correlation analyses were all used in the assessment of the of the null hypothesis H_0, defined in Chapter 3, Section 3.4.

In the following discussion about the data analysis a low value of Log BCD corresponds to a high sensitivity to discomfort glare, and conversely.

4.2   Analysis of Variance

Analysis of variance is an established method for analysing experimental results. The method is used in experiments where multiple comparisons have to be made of different parts of the same data set. It is not valid to use the Students t-test for multiple comparisons. This is because if a single t-test is carried out at a significance level of $(1-\alpha)$ then at the nth comparison, in a multiple comparison, this significance level is degraded to $(1-\alpha)^n$. For example, an initial significance level of $\alpha=5\%$, gives $(1-\alpha) = 95\%$. This would be degraded after the third t-test comparison to $(1-0.05)^3 = 0.86$, or 86% (Dixon and Massey, (1983))

To bypass this problem Fisher developed the technique of analysis of variance (Fisher, (1926)). The method partitions the variance in the response data between the experimental factors, also called the independent variables. The variance remaining after partitioning is called the residual variance, and is taken as an estimate of the underlying experimental variance. The values of the variance attributable to the independent variables, and the residual variance are used to calculate variance ratios, the so called F-test. The variances from the independent variables are used as the numerators, with the single value of the residual variance used as the denominator.

Theory states that if the variance ratio exceeds a certain value for the degrees of freedom of the numerator and denominator, and for the chosen significance level, then the two variances are likely to come from different populations. Thus, if the tabulated value of the F-test is exceeded an experimental factor is deemed to have a significant effect upon the response variable. For detailed discussion see for example (Dixon and Massey, (1983)).

The experimental factors and response variables used in the present experiment were defined in Chapter 3, Section 3.5.3.6. They are summarised here for convenience:

Experimental factors:	-	Azimuthal position of the glare source
(independent variables)	-	Age of the subjects
	-	Spectacle use
Response variables:	-	Log (BCD)
	-	C_{th} measured with glare source present

Also, threshold contrast, C_{th}, was measured for all subjects without the glare source present. This measurement of C_{th} represented the control condition. The control C_{th} was measured three times for each subject.

4.2.1 The Analysis of Variance of the BCD Data: Main Experiment

The ANOVAs for the subjectively rated BCD luminance for the main experiment are given in Table 4.1 and Table 4.2.

4.2.1.1 Pooling of Variances

In the first ANOVA, Table 4.1a, of the response variable Log BCD, all three experimental factors ie azimuthal angle, age and spectacle use, were included. This analysis showed that the factor 'spectacle use' had no significant effect upon the response variable Log BCD. Thus, the variance attributable to this data could be pooled with the residual variance to provide a more precise F-test for the remaining independent variables. This analysis is given in Table 4.1b.

Analysis of variance of response variate Log BCD luminance, including factor spectacles

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Spectacle use	1	0.007	0.007	0.17	0.683
Age (years)	11	24.822	2.257	53.18	<0.001
Azimuth position (degrees)	4	2.437	0.609	14.36	<0.001
Spectacle Position interaction	4	0.063	0.016	0.37	0.827
Age Position interaction	44	5.161	0.117	2.76	<0.001
Residual	55	2.334	0.042		
Total	119	34.825			

Table 4.1a

Analysis of variance of response variate Log BCD luminance, excluding factor spectacles

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age (years)	11	24.829	2.257	58.03	<.001
Azimuthal position (degrees)	4	2.437	0.609	15.67	<.001
Age Position interaction	44	5.225	0.119	3.05	<.001
Residual	60	2.334	0.039		
Total	119	34.825			

Table 4.1b

Analysis of variance of response variate threshold contrast, C_{th}, measured with glare source present

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F pr.
Spectacle use	1	3.05E-05	3.05E-05	24.82	<.001
Age (years)	11	2.39E-04	2.18E-05	17.69	<.001
Azimuthal position (degrees)	4	1.04E-06	2.60E-07	0.21	0.931
Spectacle position interaction	4	1.10E-05	2.74E-06	2.23	0.079
Age Position interaction	43(1)	7.56E-05	1.76E-06	1.43	0.111
Residual	50(5)	6.15E-05	1.23E-06		
Total	113(6)	3.87E-04			

Table 4.2

4.2.1.2   Aliased Terms

The first ANOVA analysis, shown in Table 4.1a, also indicated that there were two aliased interaction terms. That is interactions that are inseparable from other interactions because the experimental factors involved are not independent of each other. The aliased interactions were:

i.   spectacle use and age;

ii.   spectacle use, age and position.

It is intuitively reasonable that the interaction spectacle use and age should be aliased because spectacle use and age are both correlated with individuals, and so are dependent on each other. The three factor interaction spectacle use, age and position is again aliased because of its dependency on the interaction of spectacle use and age.

4.2.1.3   Significant Terms

Both ANOVAs of the response variable Log BCD showed that azimuthal position of the glare source, and the age of the subjects had a statistically very significant influence on the measured values of Log BCD. The probability of the variance ratio being exceeded for each of these factors was less than 0.001, ie less than 0.1%. There was also a very significant interaction between the two factors age and position, the probability of the variance ratio being exceeded for the interaction was 0.001 (0.1%).

4.2.1.4   Proportion 'Explained' by Each Term

The 'sums of squares' (ss) column in the ANOVA tables can be used to estimate the percentage of the total variance attributable to each factor and interaction. Thus, from Table 4.1b it can be estimated that the each factor and interaction contributed the following proportion to the total variance:

i.   age - 71.3%;

ii.   position - 7.0%;

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iii.   age, position interaction - 15.0%

iv.   residual variance - 6.7%.

It can be seen from these estimates that by far the greatest proportion of the variance is attributable to the factor age. This result is discussed below in section 4.5.

4.2.1.5   The Trends from the ANOVAs of Log (BCD)

The tables of means from the analyses show that Log BCD increases with increases in the azimuth of the glare source; mean Log BCD values are plotted against azimuth angles in Figure 4.1. An increase in Log BCD ie a decrease in sensitivity to discomfort glare with increase in azimuth, agrees with intuition, and with previously reported studies (eg Petherbridge and Hopkinson, (1950)). If light scatter effects are the dominant cause of discomfort glare, subjects are likely to be less sensitive to the effect in their peripheral vision, compared to their sensitivity near to the line of sight.

It is possible that the increase in Log BCD with azimuth could be attributed to the decrease in captured flux at the pupil plane with increasing eccentricity of the glare source. (No correction was applied in the experiment for the decrease in flux capture with eccentricity).

However, the roll-off in flux capture with azimuthal angle of the glare source is countered by the increase in scattering effect at the edge of the pupil. This effect is enhanced by both an increased variation in pupil size with age, and by an increase in forward scattered light in the eye with age.

The association between increasing Log BCD with azimuthal angle of the glare source, decreasing flux capture at the pupil plane, and the countering effects of increasing scatter effects at the pupil edge, pupil size increase with age, and the increase in forward scattered light with age would benefit from further investigation.

The analyses also showed that Log BCD decreased with increase in age; mean Log BCD values are plotted against age in Figure 4.2. The decrease in Log BCD, or increase in sensitivity to discomfort glare, with age is most plausibly correlated with age related

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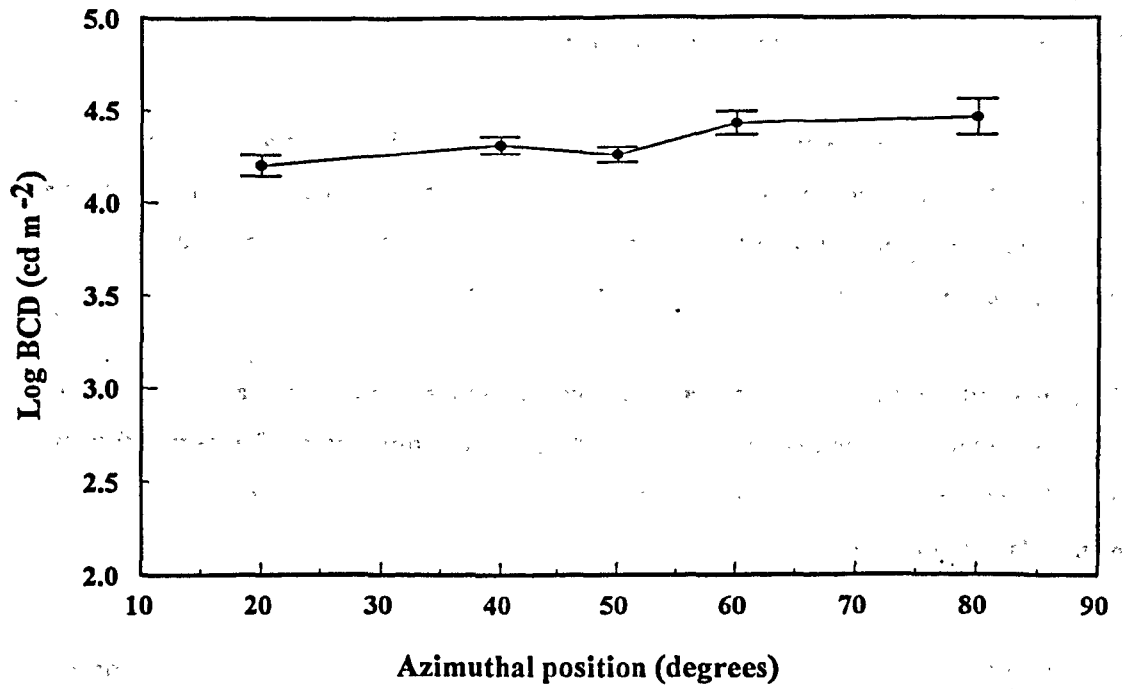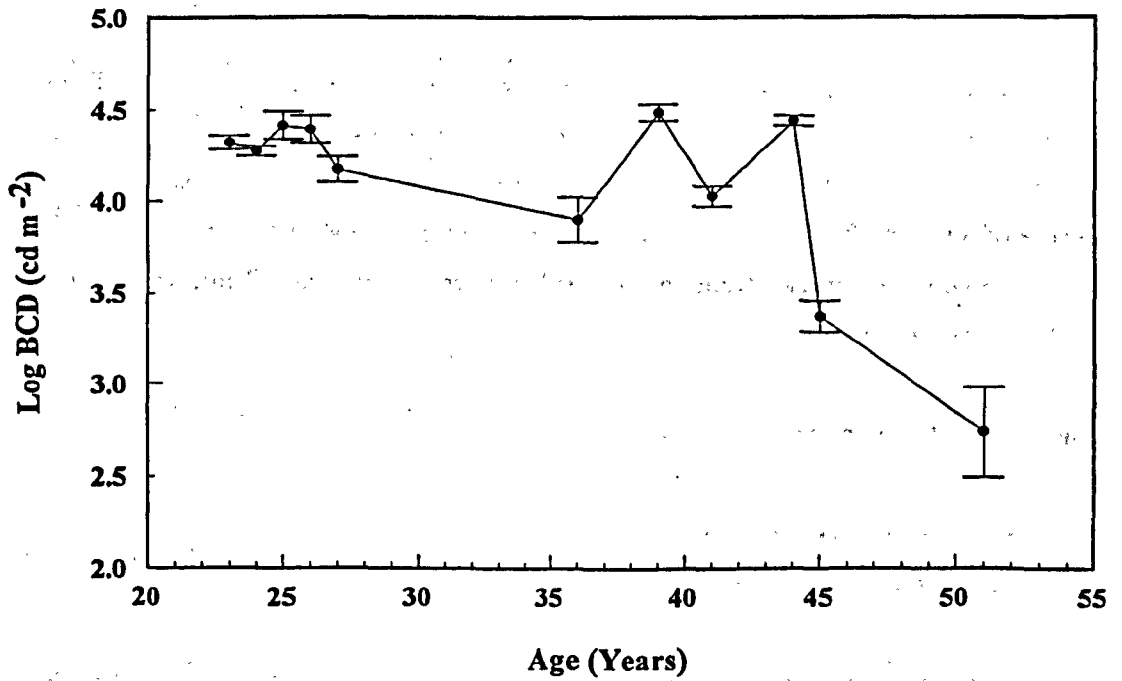
Figure 4.1

Figure 4.2

changes in the optic media, and other sites of scattering in the visual system eg the retina. This matter is discussed in more detail in Chapter 5.

The explanation of the interaction between position and age is also very likely correlated with age related changes in the optic media. If degradation in the optic media does play a rôle in increasing sensitivity to discomfort glare, then positional geometry would plausibly influence scattering effects, so causing the noted interaction.

Also, as cited above, it is known that pupil size variations increase with age, and that there is more scatter in the periphery of the pupil than in the central region. These two factors may also contribute to an explanation of the noted interaction between azimuthal position of the glare source and age.

4.2.2   The Analysis of Variance of the C_{th} Data: Main Experiment

4.2.2.1   Aliasing and Pooling of Terms

The ANOVA for the C_{th} data (C_{th} measured with glare source present) is shown in Table 4.2. All three experimental factors were included in this analysis, which revealed that the azimuthal position of the glare source had no effect on the values of C_{th}. However, because of aliasing effects in the data caused by the experimental factors it was not possible to pool the variance from position with the residual variance. Thus, only a single ANOVA was carried out on the C_{th} data.

Other aliased terms in the analysis were:

      i.   spectacle use and age;

     ii.   spectacle use, age and position.

These aliased terms are consistent with those from the ANOVA for the response variate Log (BCD) discussed in section 4.2.1.

4.2.2.2   Significant Terms and Trends

The analysis showed that there was a significant difference in the mean values of C_{th} for spectacle users and non-users; the significance, or probability of this occurring, was less than 0.1%. The mean value of C_{th} for spectacle users was lower than that for non-users; the mean values are plotted in Figure 4.3. This indicates that for the sample of subjects used in the experiment spectacle users had better acuity and greater contrast sensitivity than non-spectacle users.

This result may be interpreted to mean that, for this sample, spectacle users were better corrected for refractive error than non-users. This result may also be true in the wider population.

In general , people who need refractive correction are more likely to attend their optician routinely than non-spectacle users. For spectacle users a typical period between eye tests is of the order of two years. As a consequence spectacle users are more likely to be better corrected for refractive errors, compared to a person who has never attended an optician, and so has had no objective check on the performance of their eyesight. The difference between spectacle users and non-users is also likely to increase with age, until a stage is reached where non-users become aware of the deficiencies in their acuity eg with the onset of presbyopia.

There was also a significant change in C_{th} with age; the probability of the F-ratio being exceeded was less than 0.1%. In general, younger subjects had a lower C_{th} than older subjects; mean values of C_{th} are plotted against age in Figure 4.4. Although this is not universally true for the data collected from this sample.

It is well established in the literature that age related changes in the visual system cause a significant increase in C_{th} for older subjects, see for example (Blackwell and Blackwell, (1971)). This increase in C_{th} with age is attributable to degradation in the optic media of the eye, the retina, and the visual mechanism beyond the retina. More detailed discussion of the effects of ageing on the visual system, and the consequences for C_{th}, is given in Chapter 5.
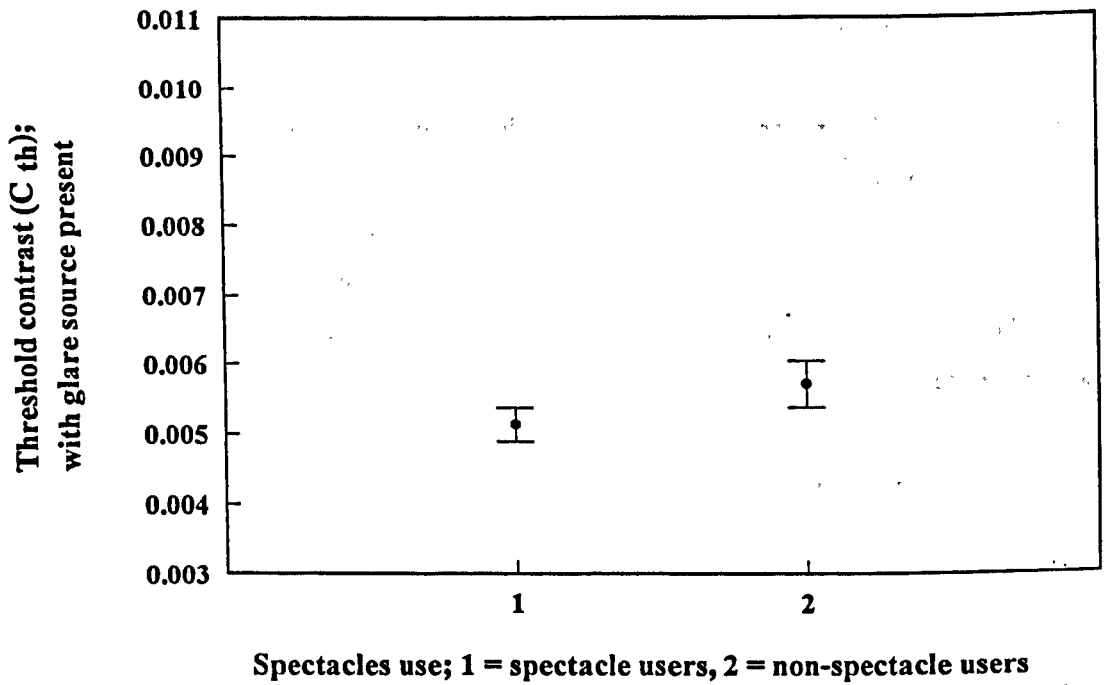
Figure 4.3
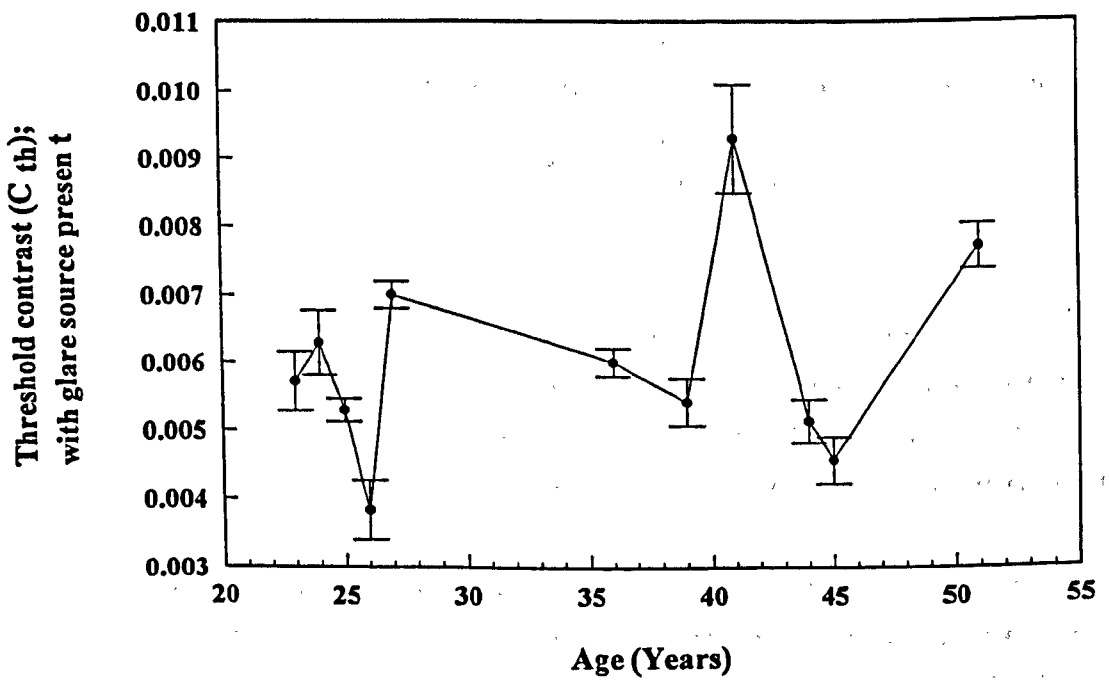
Figure 4.4

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There were no significant interactions between the main effects influencing the value of C_{th}.

4.2.2.3 Proportion 'Explained' by Each Term

Using the 'sums of squares' column the following estimates for proportion variance attributable to each factor were obtained:

    i.   spectacle use - 7.9%;

    ii.   age - 61.8%;

    iii.   position - 0.3%

    iv.   spectacle use and position - 2.8%

    v.   age and position - 19.5%

    vi.   residual variance - 15.9%

The data set for C_{th} contained six missing values. Estimates were made by the ANOVA of these values. In any ANOVA the estimates are very unlikely to be exact. So there is an error produced which is reflected in the percentage variance estimates. Thus the total percentage for the values given above is 108.2%, the 8.2% excess indicating the error produced in the analysis by the missing values.

Also, even though a factor may not have a significant effect on the response variable, it will still have a proportion of the variance associated with it. Hence the reason, that if no significant effect is found, the variance can be pooled with the existing residual variance, aliasing effects permitting.

4.3   The Correlation of Log (BCD) on Age

There is a distinction between correlation and regression. When data is correlated the independent variable, the abscissa in the data plot, takes on random values. This is because it has not been possible to control the values of the independent variable in the data collection. In the present experiment, for example, it was not possible to control the age of the subjects.

If it is possible to control the values of the independent variable during data collection then the dependent variable is regressed on the independent variable. Thus the Log (BCD) data is regressed on position of the glare source because position was controlled by the experimenter.

4.3.1   The Magnitude of the Age Effect on Discomfort Glare Sensitivity

The ANOVAs showed that in the present experiment, age explained the greatest proportion of the variance in both response variables, Log (BCD) and C_{th}. In the case of Log (BCD) 71.3% of the variance was attributable to the factor age, and for C_{th} 61.8%.

It is possible to argue that, for Log (BCD), the variable age is confounded with individual criteria applied to assessing Log (BCD). However, the data plot of Figure 4.5a shows that there is a systematic change in Log (BCD) with age. This indicates that there is a true age related effect.

However, the large scatter in the data may also indicate that there possibly remains a large proportion of the variance in the data that might be attributable to individual criteria. The present experiment did not set out to systematically investigate the influence of individual criteria on discomfort glare perception.

In Figure 4.5a the fitted curve shows that there is an accelerating sensitivity to discomfort glare with age. The gradient of the curve being close to zero up to the age band beginning at 35 - 40. After this the curve gradient becomes quite steep. The increase in gradient may

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$$y=a+bx^c; \; a = 4.45, \; b= -1.02*10^{-9}, \; c=5.33$$

DF Adj r^2=0.4816 F-statistic=54.49
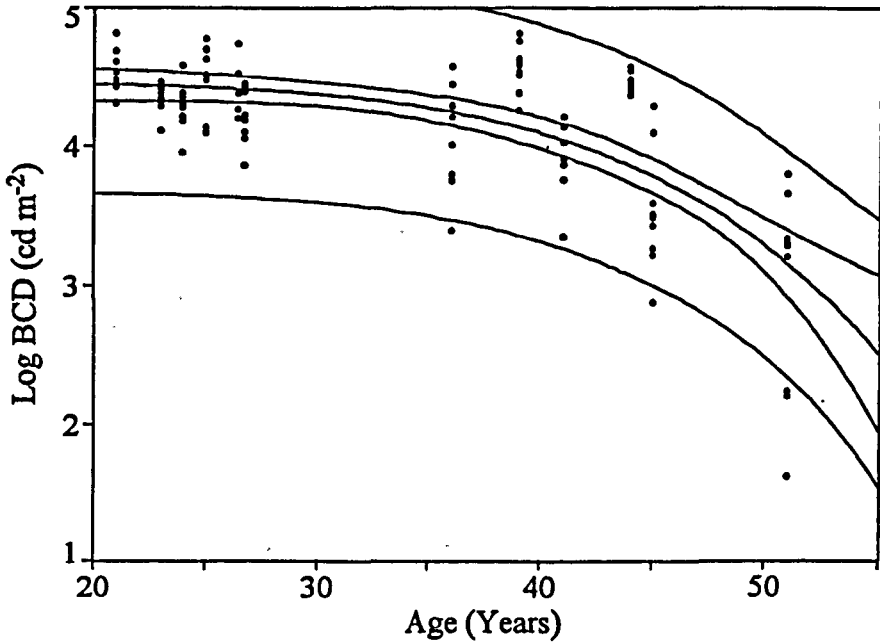
Figure 4.5a The inner pair of intervals show the $\pm$ 95% confidence limits, and the outer intervals are the $\pm$ 95% prediction intervals. All fitted curves in Chapter 4 follow this convention.

$y=a+bx^c$

r^2 (Coeff of Det)	DF Adj r^2		Fit Std Err	F-value
0.4954	0.4816		0.3923	54.49

Parameter	Value	Std Error	t-value	95% Confidence Limits
a	4.448	0.0651	68.34	4.319 / 4.577
b	-1.02E-09	4.39E-09	-0.233	-9.73E-09 / 7.69E-09
c	5.332	1.097	4.860	3.158 / 7.506

Source	Sum of Squares	DF	Mean Square	F
Regression	16.774	2	8.387	54.49
Error	17.085	111	0.154	
Total	33.859	113		

Table 4.3a

$$y = a + bx^3; a = 4.581, b = 9.22 * 10^{-6}$$

D of F Adj r^2 = 0.4182; F-statistic = 83.97
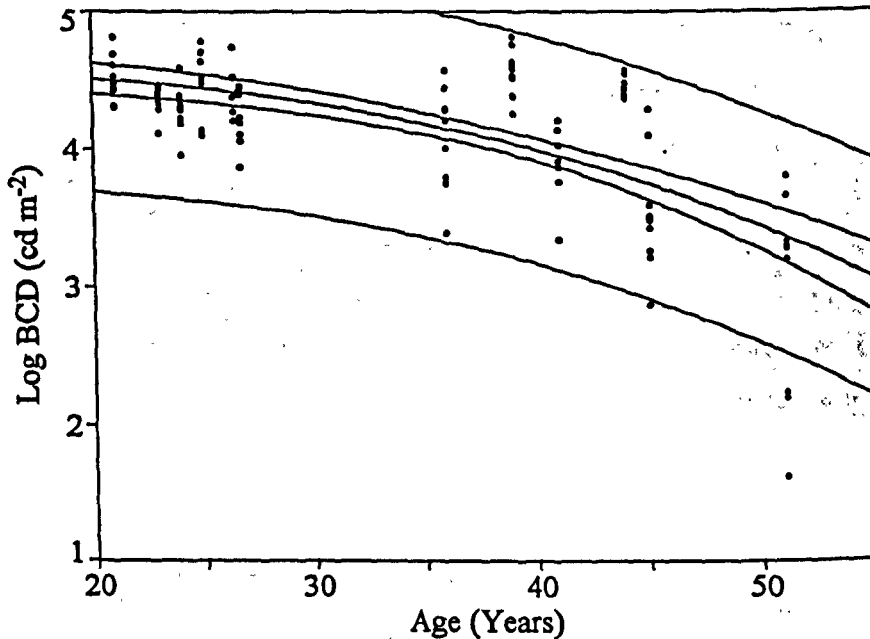
Figure 4.5b

$y = a + bx^3$

r^2 (Coef of Det)	DF Adj r^2		Fit Std Err	F-value
0.4284	0.4181		0.4156	83,97
Parameter	Value	Std Error	t-value	95% Confidence Limits
a	4.581	0.0626	73.15	4.456 / 4.705
b	-9.22E-06	1.006E-06	-9.16	-1.122E-05 / -7.231E-06
Source	Sum of Squares	DF	Mean Square	F
Regression	14.509	1	14.509	83.97
Error	19.351	112	0.172	
Total	33.859	113		

Table 4.3b

well correlate with changes in the visual system that occur with aging. The increasing sensitivity with age may also reflect increasing intolerance to discomfort glare, which may also rely on aging effects on the visual system. The possible causes of the age dependency of discomfort glare sensitivity are discussed in Chapter 5.

4.3.1.1 Justification for Selecting the Power Curve Regression

Section 4.3.2 below discusses why the selection of fitted function for the data is an arbitrary process. There is some justification for selecting the power function for the regression of Log (BCD) on age, as it is well established that progressive, and accelerating, degradation of the human visual system occurs with aging. This is reasonably characterised by the power function, although it would also be possible to use other functions to characterise the data.

4.3.2 Choosing a Function to Fit the Data

The fitted curves shown in Figure 4.5a and 4.5b, and the numeric summaries of the regression fits given in Table 4.3a and Table 4.3b reveal that a large amount of variance remains after the function has been fitted. The statistic r^2, or the coefficient of determination, is a measure of the goodness-of-fit of the function. The statistic is also an estimate of the proportion of the data 'explained' by the function fit. For the power function fitted to the data, Table 4.3b, $r^2 = 0.495$; thus approximately 50% of the data variance is explained by the curve fit. 50% of the variance is attributable to other causes.

Table 4.4 lists 105 functions that can be fitted to the data, and in this table the functions are ranked according to r^2. The ranking indicates that for the set of functions fitted to the data the power function, $y = a + bx^c$, has the highest r^2 statistic.

Table 4.5 shows the same set of functions ranked by their F-statistic. Some re-ordering has occurred, the power function is now ranked 30th in the table. Using tabulated values of the F-statistic it is possible to identify the range of functions that have a statistically significant fit to the data. The F-statistic, for 2 degrees of freedom for the numerator and 113 degrees of freedom for the denominator, has the following approximate values for significance levels of 5%, 2.5%, 1% and 0.1%:

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Rank	DOF Adj r2	FP	Eq#	Eqn
1	0.4816395958	30	8010	$y=a+bx^c$
2	0.4181946284	4	7	$y=a+bx^3$
3	0.4146812244	17	8	$y=a+be^x$
4	0.4082380694	18	71	$y^{0.5}=a+be^x$
5	0.4001628851	5	70	$y^{0.5}=a+bx^3$
6	0.3984797866	7	6	$y=a+bx^{2.5}$
7	0.3931941554	25	29	$lny=a+be^x$
8	0.3878750185	13	5	$y=a+bx^2lnx$
9	0.3819669358	7	91	$y^2=a+bx^3$
10	0.3801708003	8	69	$y^{0.5}=a+bx^{2.5}$
11	0.3777573178	3	4	$y=a+bx^2$
12	0.3726576890	19	92	$y^2=a+be^x$
13	0.3695096496	14	68	$y^{0.5}=a+bx^2lnx$
14	0.3683237457	13	28	$lny=a+bx^3$
15	0.3593820717	4	67	$y^{0.5}=a+bx^2$
16	0.3570555473	9	90	$y^2=a+bx^{2.5}$
17	0.3565263168	5	3	$y=a+bx^{1.5}$
18	0.3544475915	18	50	$1/y=a+be^x$
19	0.3475238037	15	27	$lny=a+bx^{2.5}$
20	0.3444700581	12	2	$y=a+bxlnx$
21	0.3431942478	15	89	$y^2=a+bx^2lnx$
22	0.3382646267	6	66	$y^{0.5}=a+bx^{1.5}$
23	0.3365428116	22	26	$lny=a+bx^2lnx$
24	0.3352879529	2	1	$y=a+bx$
25	0.3297317832	5	88	$y^2=a+bx^2$
26	0.3292450608	18	8002	$y=a+bexp(-x/c)$
27	0.3281275014	12	11	$y=a+bx/lnx$
28	0.3263392601	13	65	$y^{0.5}=a+bxlnx$
29	0.3261707249	12	25	$lny=a+bx^2$
30	0.3218488415	14	9	$y=a+bx^{0.5}lnx$
31	0.3172782879	3	64	$y^{0.5}=a+bx$
32	0.3144979221	4	12	$y=a+bx^{0.5}$
33	0.3102271432	13	74	$y^{0.5}=a+bx/lnx$
34	0.3055537615	12	10	$y=a+b(lnx)^2$
35	0.3047297039	14	24	$lny=a+bx^{1.5}$
36	0.3040550034	15	72	$y^{0.5}=a+bx^{0.5}lnx$
37	0.3008012007	7	87	$y^2=a+bx^{1.5}$
38	0.2968336837	5	75	$y^{0.5}=a+bx^{0.5}$
39	0.2945288715	11	13	$y=a+blnx$
40	0.2927226055	21	23	$lny=a+bxlnx$
41	0.2880652861	13	73	$y^{0.5}=a+b(lnx)^2$
42	0.2840504085	14	86	$y^2=a+bxlnx$
43	0.2836414578	11	22	$lny=a+bx$
44	0.2831017406	6	49	$1/y=a+bx^3$
45	0.2772605530	12	76	$y^{0.5}=a+blnx$
46	0.2766006401	21	32	$lny=a+bx/lnx$
47	0.2756486021	6	15	$y=a+b/x^{0.5}$
48	0.2733765462	12	14	$y=a+b/lnx$
49	0.2717274948	12	16	$y=a+blnx/x$
50	0.2712040954	4	85	$y^2=a+bx$
51	0.2704560483	23	30	$lny=a+bx^{0.5}lnx$
52	0.2632846375	13	33	$lny=a+bx^{0.5}$
53	0.2611332944	15	95	$y^2=a+bx/lnx$
54	0.2607029671	8	48	$1/y=a+bx^{2.5}$
55	0.2587902312	7	78	$y^{0.5}=a+b/x^{0.5}$
56	0.2580154219	3	17	$y=a+b/x$
57	0.2565571355	13	77	$y^{0.5}=a+b/lnx$
58	0.2549681561	13	79	$y^{0.5}=a+blnx/x$
59	0.2546072570	21	31	$lny=a+b(lnx)^2$
60	0.2522681577	17	93	$y^2=a+bx^{0.5}lnx$
61	0.2491473887	15	47	$1/y=a+bx^2lnx$
62	0.2439493757	20	34	$lny=a+blnx$
63	0.2418973370	7	96	$y^2=a+bx^{0.5}$
64	0.2416880931	6	18	$y=a+b/x^{1.5}$
65	0.2415533234	5	80	$y^{0.5}=a+b/x$
66	0.2383843883	5	46	$1/y=a+bx^2$
67	0.2364923968	13	19	$y=a+blnx/x^2$
68	0.2292379655	14	94	$y^2=a+b(lnx)^2$
69	0.2266454951	5	20	$y=a+b/x^2$
70	0.2258254219	15.	36	$lny=a+b/x^{0.5}$
71	0.2255901962	.7	81	$y^{0.5}=a+b/x^{1.5}$
72	0.2236372169	21	35	$lny=a+b/lnx$
73	0.2220923992	21	37	$lny=a+blnx/x$
74	0.2205173836	15	82	$y^{0.5}=a+blnx/x^2$
75	0.2165862306	6	45	$1/y=a+bx^{1.5}$
76	0.2137348578	13	97	$y^2=a+blnx$
77	0.2108699007	6	83	$y^{0.5}=a+b/x^2$
78	0.2090046395	12	38	$lny=a+b/x$
79	0.2046233611	13	44	$1/y=a+bxlnx$
80	0.1956843186	3	43	$1/y=a+bx$
81	0.1934947499	15	39	$lny=a+b/x^{1.5}$
82	0.1888151039	14	53	$1/y=a+bx/lnx$
83	0.1885811569	22	40	$lny=a+blnx/x^2$
84	0.1873763489	8	99	$y^2=a+b/x^{0.5}$
85	0.1843211060	15	98	$y^2=a+b/lnx$
86	0.1828626418	16	51	$1/y=a+bx^{0.5}lnx$
87	0.1818764680	15	100	$y^2=a+blnx/x$
88	0.1792397732	13	41	$lny=a+b/x^2$
89	0.1759647930	6	54	$1/y=a+bx^{0.5}$
90	0.1676829861	13	52	$1/y=a+b(lnx)^2$
91	0.1632420087	6	101	$y^2=a+b/x$
92	0.1576125314	12	55	$1/y=a+blnx$
93	0.1415145603	8	102	$y^2=a+b/x^{1.5}$
94	0.1407131129	7	57	$1/y=a+b/x^{0.5}$
95	0.1386974353	14	56	$1/y=a+b/lnx$
96	0.1372595697	14	58	$1/y=a+blnx/x$
97	0.1346750065	16	103	$y^2=a+blnx/x^2$
98	0.1252655931	5	59	$1/y=a+b/x$
99	0.1221765417	7	104	$y^2=a+b/x^2$
100	0.1112020397	7	60	$1/y=a+b/x^{1.5}$
101	0.1067751927	15	61	$1/y=a+blnx/x^2$
102	0.0984096670	6	62	$1/y=a+b/x^2$
103	0.0368799823	17	21	$y=a+be^{-x}$
104	0.0253354609	18	84	$y^{0.5}=a+be^{-x}$
105	0.0014033884	25	42	$lny=a+be^{-x}$

Table 4.4   Shows 105 functions that can be fitted to the Log BCD luminance vs Age data, ranked according to Degrees of Freedom Adjusted r^2

Rank	F-statistic	FP	Eq#	Eqn
1	83.972783321	4	7	$y=a+bx^3$
2	82.796447298	17	8	$y=a+be^x$
3	80.675486746	18	71	$y^{0.5}=a+be^x$
4	78.081632467	5	70	$y^{0.5}=a+bx^3$
5	77.549769862	7	6	$y=a+bx^{2.5}$
6	75.898681335	25	29	$lny=a+be^x$
7	74.265912141	13	5	$y=a+bx^2lnx$
8	72.485304452	7	91	$y^2=a+bx^3$
9	71.950704598	8	69	$y^{0.5}=a+bx^{2.5}$
10	71.237218027	3	4	$y=a+bx^2$
11	69.747693437	19	92	$y^2=a+be^x$
12	68.840226882	14	68	$y^{0.5}=a+bx^2lnx$
13	68.500718899	13	28	$lny=a+bx^3$
14	65.981309891	4	67	$y^{0.5}=a+bx^2$
15	65.337276255	9	90	$y^2=a+bx^{2.5}$
16	65.191423655	5	3	$y=a+bx^{1.5}$
17	64.620854501	18	50	$1/y=a+be^x$
18	62.746632389	15	27	$lny=a+bx^{2.5}$
19	61.932586031	12	2	$y=a+bxlnx$
20	61.594731233	15	89	$y^2=a+bx^2lnx$
21	60.301531116	6	66	$y^{0.5}=a+bx^{1.5}$
22	59.854371328	22	26	$lny=a+bx^2lnx$
23	59.529940694	2	1	$y=a+bx$
24	58.108048035	5	88	$y^2=a+bx^2$
25	57.701867925	12	11	$y=a+bx/lnx$
26	57.251392070	13	65	$y^{0.5}=a+bxlnx$
27	57.209059658	12	25	$lny=a+bx^2$
28	56.130683833	14	9	$y=a+bx^{0.5}lnx$
29	55.005114970	3	64	$y^{0.5}=a+bx$
30	54.488409424	30	8010	$y=a+bx^c$
31	54.327749683	4	12	$y=a+bx^{0.5}$
32	53.297919302	13	74	$y^{0.5}=a+bx/lnx$
33	52.185521779	12	10	$y=a+b(lnx)^2$
34	51.990923615	14	24	$lny=a+bx^{1.5}$
35	51.831938688	15	72	$y^{0.5}=a+bx^{0.5}lnx$
36	51.069527777	7	87	$y^2=a+bx^{1.5}$
37	50.149430894	5	75	$y^{0.5}=a+bx^{0.5}$
38	49.619679982	11	13	$y=a+blnx$
39	49.206930835	21	23	$lny=a+bxlnx$
40	48.152350764	13	73	$y^{0.5}=a+b(lnx)^2$
41	47.254253885	14	86	$y^2=a+bxlnx$
42	47.163339718	11	22	$lny=a+bx$
43	47.043513527	6	49	$1/y=a+bx^3$
44	45.758122218	12	76	$y^{0.5}=a+blnx$
45	45.614209152	21	32	$lny=a+bx/lnx$
46	45.407051801	6	15	$y=a+b/x^{0.5}$
47	44.914860682	12	14	$y=a+b/lnx$
48	44.559553191	12	16	$y=a+blnx/x$
49	44.447116808	4	85	$y^2=a+bx$
50	44.286701780	23	30	$lny=a+bx^{0.5}lnx$
51	42.765359622	13	33	$lny=a+bx^{0.5}$
52	42.314732490	15	95	$y^2=a+bx/lnx$
53	42.224909533	8	48	$1/y=a+bx^{2.5}$
54	41.826922980	7	78	$y^{0.5}=a+b/x^{0.5}$
55	41.666290891	3	17	$y=a+b/x$
56	41.364869668	13	77	$y^{0.5}=a+b/lnx$
57	41.037778425	13	79	$y^{0.5}=a+blnx/x$
58	40.963681351	21	31	$lny=a+b(lnx)^2$
59	40.485171247	17	93	$y^2=a+bx^{0.5}lnx$
60	39.851397076	15	47	$1/y=a+bx^2lnx$
61	38.807385582	20	34	$lny=a+blnx$
62	38.399178884	7	96	$y^2=a+bx^{0.5}$
63	38.357678655	6	18	$y=a+b/x^{1.5}$
64	38.330961336	5	80	$y^{0.5}=a+b/x$
65	37.705463319	5	46	$1/y=a+bx^2$
66	37.334489320	13	19	$y=a+blnx/x^2$
67	35.928949413	14	94	$y^2=a+b(lnx)^2$
68	35.433055982	5	20	$y=a+b/x^2$
69	35.276882038	15	36	$lny=a+b/x^{0.5}$
70	35.232146924	7	81	$y^{0.5}=a+b/x^{1.5}$
71	34.861777116	21	35	$lny=a+b/lnx$
72	34.570129793	21	37	$lny=a+blnx/x$
73	34.273971506	15	82	$y^{0.5}=a+blnx/x^2$
74	33.539971942	6	45	$1/y=a+bx^{1.5}$
75	33.012174520	13	97	$y^2=a+blnx$
76	32.485704091	6	83	$y^{0.5}=a+b/x^2$
77	32.144989602	12	38	$lny=a+b/x$
78	31.350976689	13	44	$1/y=a+bxlnx$
79	29.757795670	3	43	$1/y=a+bx$
80	29.499204675	18	8002	$y=a+bexp(-x/c)$
81	29.372939616	15	39	$lny=a+b/x^{1.5}$
82	28.557373007	14	53	$1/y=a+bx/lnx$
83	28.516847727	22	40	$lny=a+blnx/x^2$
84	28.308515346	8	99	$y^2=a+b/x^{0.5}$
85	27.782969561	15	98	$y^2=a+b/lnx$
86	27.533478522	16	51	$1/y=a+bx^{0.5}lnx$
87	27.365283558	15	100	$y^2=a+blnx/x$
88	26.917572135	13	41	$lny=a+b/x^2$
89	26.365469158	6	54	$1/y=a+bx^{0.5}$
90	24.988690746	13	52	$1/y=a+b(lnx)^2$
91	24.261642195	6	101	$y^2=a+b/x$
92	23.351037698	12	55	$1/y=a+blnx$
93	20.812989877	8	102	$y^2=a+b/x^{1.5}$
94	20.689116667	7	57	$1/y=a+b/x^{0.5}$
95	20.378588773	14	56	$1/y=a+b/lnx$
96	20.157963172	14	58	$1/y=a+blnx/x$
97	19.763232173	16	103	$y^2=a+blnx/x^2$
98	18.345870840	5	59	$1/y=a+b/x$
99	17.887185112	7	104	$y^2=a+b/x^2$
100	16.283392974	7	60	$1/y=a+b/x^{1.5}$ — Cut-off threshold for $\alpha=0.1\%$
101	15.647616906	15	61	$1/y=a+blnx/x^2$
102	14.463221532	6	62	$1/y=a+b/x^2$ ←
103	6.3840185272	17	21	$y=a+be^{-x}$ ←
104	4.9818059858	18	84	$y^{0.5}=a+be^{-x}$ — Cut-off threshold for $\alpha=1\%, 2.5\%$ and 5%
105	2.1782544556	25	42	$lny=a+be^{-x}$

Table 4.5 The same 105 functions as shown in Table 4.4, but ranked according to the F-statistic. Also shown are the cut-off points for 0.1%, 1%, 2.5% and 5% significance. There must either be some *a priori* justification for selecting a particular function, or an arbitrary selection made according to the practical application of the model.

i. 5% - 3.07

ii. 2.5% - 3.80

iii. 1% - 4.79

iv. 0.1% - 7.32

These values have been used to eliminate those functions from Table 4.5 that are not a significant fit for significance levels greater than 5%.

Referring to Table 4.5, for significance levels of 5%, 2.5%, 1% and 0.1% all but the last function fit the data; so 104 functions are deemed to fit the data for each of these significance levels. For a significance level of 0.1% all but the last three functions fit the data, so 102 functions are deemed to fit. A significance level of 5% is normally taken as an appropriate value. There is now a fundamental dilemma. If a large number of functions are deemed to fit the data, what criterion, or criteria, should be applied in selecting one function?

4.3.2.1   Function Selection Criteria

With the large amount of variance in the data, it is clearly not valid to select, *a priori*, one function or another. If statistics are used, then what statistic, or statistics, should be used? It is possible to use at least four statistics:

i. Coefficient of Determination, r^2;

ii. degrees of freedom adjusted r^2;

iii. fitted standard error;

iv. the F-statistic.

There is no one statistic which can be deemed to have over riding precedence. For

example, should the function be selected to maximise the value of the statistical significance of the fit ie by using the F-statistic? Or should the standard error about the fitted function be minimised?

For empirically modelled data, such as collected in the present experiment, the selection criteria will be based on the application of the model. Discomfort glare models are used to assist the selection of a designed luminous environment that minimises discomfort glare for the largest possible proportion of the wider population. Given this end use, there is some justification for using the fitted standard error to select the best model function. However, the case is not clear cut, and equally persuasive arguments could be put forward for using other selection criteria.

These arguments apply equally to discomfort glare data sets, other than the present data. For example, Hopkinson noted that there was a wide variance in the glare settings from his subjects. To keep the variance as low as possible he eliminated subjects from his experiment who showed more than a certain percentage of variance in their glare settings (Petherbridge and Hopkinson, (1950)). The selection of subjects based on their experimental variance runs the risk of biasing the data set, a criticism that was directed at Hopkinson's experimental data (Markus, (1974)). It is of course another arbitrary selection procedure which can be added to the repertoire of selection procedures listed above.

4.3.2.2 The Use of Theoretical Understanding of the Visual System to Develop Visual Discomfort Models

The use of empirical selection procedures does not invalidate the application of the model, provided the selection procedure is appropriate to the end use of the model. It is also unlikely in the near future that a discomfort glare model will be developed which can statistically account for the greater majority of the observed experimental variance.

However, the development of empirically based discomfort glare models has been carried out since as early as 1929, and Stiles' experiments. It might be appropriate to seek alternative methods of developing discomfort glare models, such as using theoretical

understanding of the visual system to initiate the development of broader based visual discomfort models, and which incorporate discomfort glare. Chapter 6 of this dissertation reports an investigation that uses theoretical understanding of the visual system to propose the first stage in the development of a theoretically based model of visual discomfort.

4.4   The Regression of Log (BCD) on Position

The scatter plot and regression line of Log (BCD) against azimuthal position of the glare source is shown in Figure 4.6. A numeric summary of the linear regression plot is given in Table 4.6. The scatter plot and regression line clearly show that there is an increase in Log (BCD) with increasing angle of the glare source; this is consistent with the results of the ANOVA showing that the position of the glare source had a significant effect on the Log (BCD) value. The increase in Log (BCD) is equivalent to a decrease in sensitivity to discomfort glare.

However, as can be seen in the plot there is a very large amount of scatter in the data about the regression line. The arguments discussed in section 4.3.2 about the absence of any *a priori* selection criteria for choosing the fitted function also applies to the regression of Log (BCD) on position. In the absence of any *a priori* section criteria the linear regression fit was taken as representative, being the simplest fit.

The F-statistic for the regression has a value of 7.53, and this is significant at less than 1%. So despite the small amount of variance explained by the regression line, the fit is statistically significant.

The result showing that Log (BCD) increases with azimuthal position of the glare source is consistent with previous results, particularly those of Guth(Guth, (1963)) who was responsible for developing the Position Index used in the Glare Index and Visual Comfort Probability discomfort glare models. Possible causes of the decrease in glare sensitivity with azimuthal position are discussed in Chapter 5.

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$$y = a + bx; \quad a = 3.789; \quad b = 0.0069$$

D of F Adj r^2 = 0.04611; F-statistic = 7.53
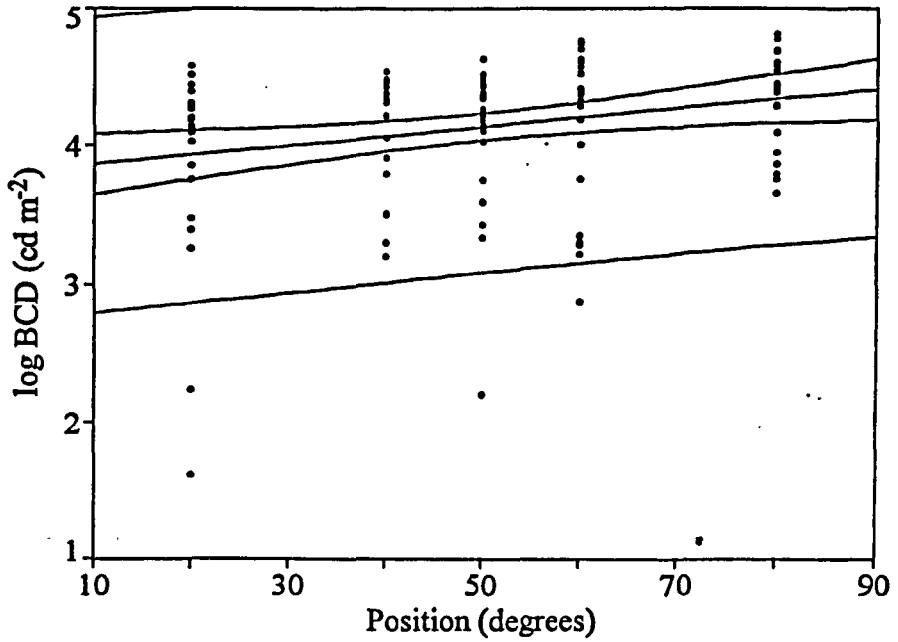
Figure 4.6

ANOVA

	df	SS	MS	F	F Prob
Regression	1	2.1330	2.1330	7.5298	0.0071
Residual	112	31.7267	0.2833		
Total	113	33.8597			

Parameter Estimates

	Coeffs	Std Err	t Stat	P-value	Lower 95%	Upper 95%
Intercept (a)	3.7892	0.1343	28.2087	1.04E-52	3.5231	4.0554
X Variable (b)	0.0069	0.0025	2.7441	0.0071	0.0019	0.0118

Table 4.6

$$y=a+bx; \quad a = 0.0023; \quad b = 0.00015$$

$$D \text{ of } F \text{ Adj } r^2 = 0.2872; \quad F\text{-statistic} = 15.79$$
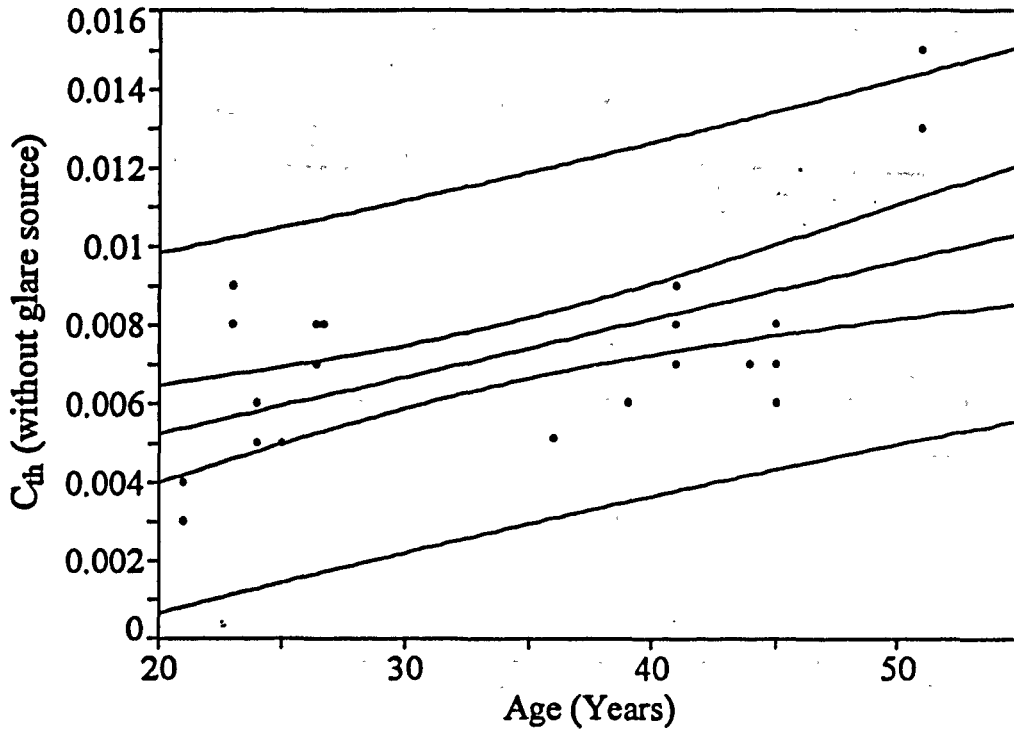
Figure 4.7

ANOVA

	df	SS	MS	F	F Prob
Regression	1	7.40E-05	7.40E-05	15.7924	0.0004
Residual	32	0.0001	4.68E-06		
Total	33	0.0002			

Parameter Estimates

	Coeffs	Std Err	t Stat	P-value	Lower 95%	Upper 95%
Intercept(a)	0.0023	0.0013	1.7940	0.0823	- 0.0003	0.0049
Xvariable(b)	0.0001	0.0000	3.9740	0.0004	7.10E-05	0.0002

Table 4.7

4.5 The Correlation of C_{th} with Age

4.5.1 Correlation of C_{th} (No Glare) with Age

Figure 4.7 shows the data plot, and trend line, of C_{th} measured (no glare) against age. The regression analysis for the trend line is given in Table 4.7. Consistent with many other reports C_{th} increases with age, eg Blackwell and Blackwell, (1971). There is some scatter about the trend line as age is not the only factor with causes a decrease in visual performance. For example, a young person with myopia could plausibly have a poorer visual performance than someone much older who was not a myope.

However, the subject sample used in the present experiment show that there is a general decrease in visual performance with age , as measured by C_{th}. This is consistent with the wider population, thus the sample is not atypical of the wider population.

4.5.2 Correlation of C_{th} (With Glare) with Age

The same characteristic of increasing C_{th} with age was measured with the glare source present; the data and trend line are plotted in Figure 4.8. The regression analyses is given in Table 4.8. Although in the case of C_{th} measured with the glare source present the gradient of the linear trend line is only about one third of the gradient of the trend line for C_{th} measured with no glare source present.

No immediate explanation is available for the difference in gradient. From comparison of the gradients and intercepts it may be that the differences are attributable to variance in the measurement of C_{th} between occasions. Also, a larger number of measurements were made of each subjects C_{th} with glare present, than for the control C_{th}, and so may be a more representative data set.

$$y = a + bx; \quad a = 0.0043; \quad b = 4.91 * 10^{-5}$$

D of F Adj $r^2 = 0.0531$; F-statistic $= 8.41$
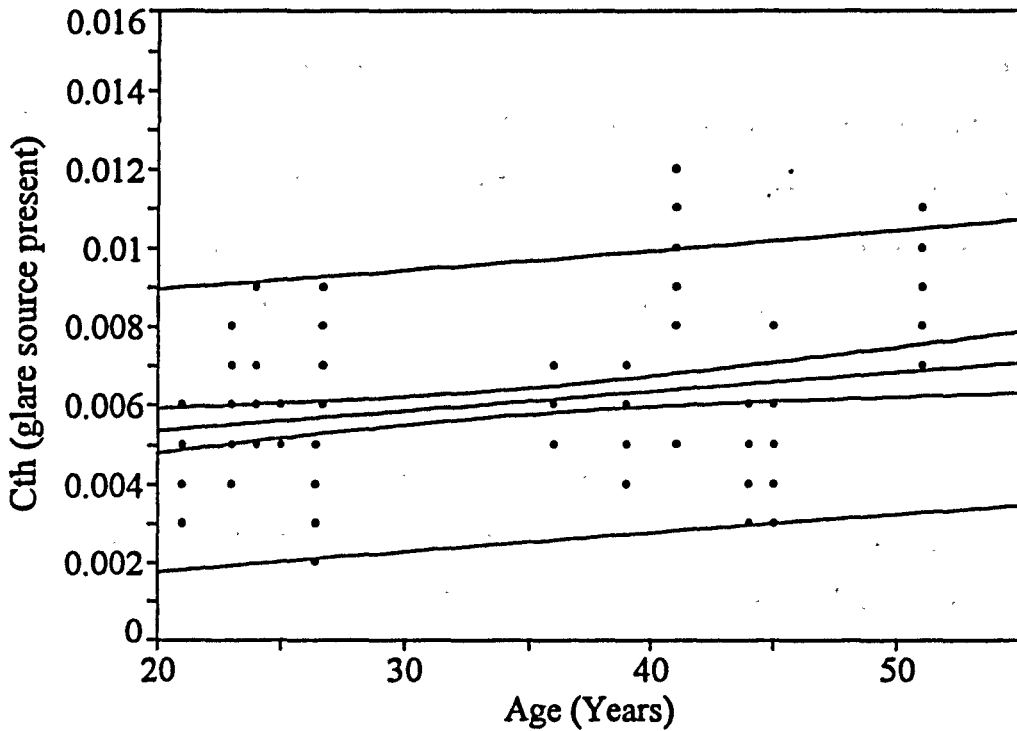
Figure 4.8

ANOVA

	df	SS	MS	F	F Prob
Regression	1	2.70E-05	2.70E-05	8.4083	0.0045
Residual	112	0.0004	3.21E-06		
Total	113	0.0004			

Parameter Estimates

	Coeffs	Std Err	t Stat	P-value	Lower 95%	Upper 95%
Intercept(a)	0.0043	0.0006	7.2924	4.63E-11	0.0032	0.0055
Xvariable(b)	4.91E-05	1.69E-05	2.8997	0.0045	1.56E-05	8.27E-05

Table 4.8
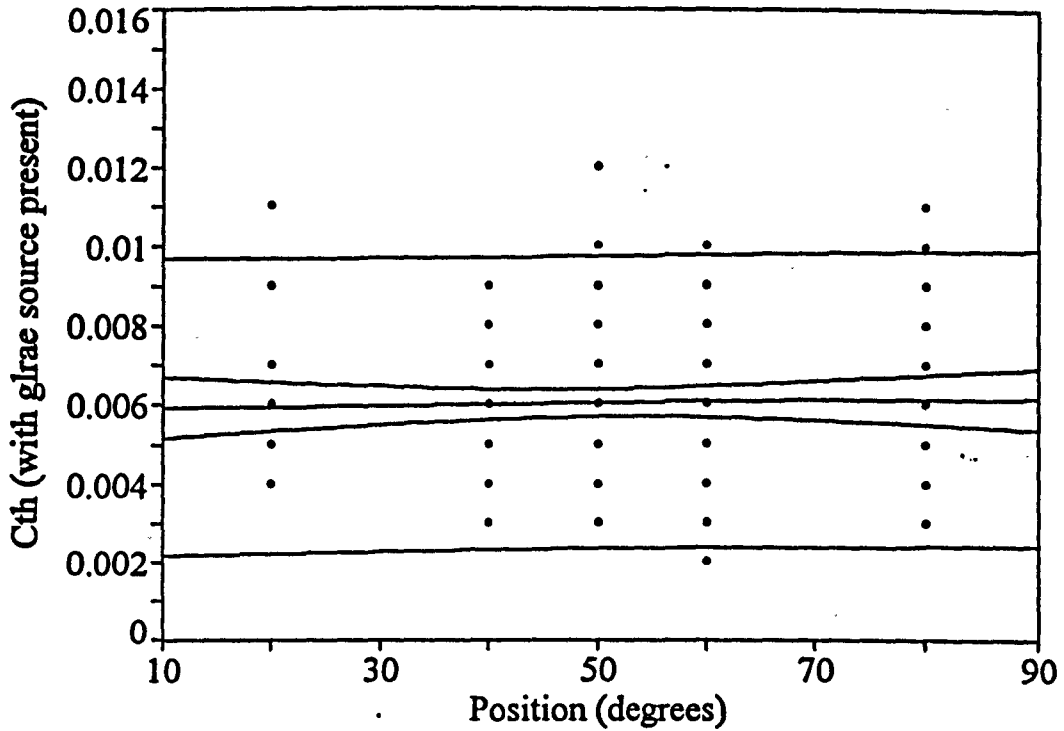
Figure 4.9

ANOVA

	df	SS	MS	F	F Prob
Regression	1	3.75E-07	3.75E-07	0.1086	0.7423
Residual	112	0.0004	3.45E-06		
Total	113	0.0004			

Parameter

	Coeffs	Std Err	t Stat	P-value	Lower 95%	Upper 95%
Intercept(a)	0.0059	0.0005	12.5081	5.38E-23	0.0049	0.0068
Xvariable(b)	2.88E-06	8.74E-06	0.3296	0.7423	-1.44E-05	2.02E-05

Table 4.9

$$y = a + bx; \ a = 0.011, \ b = -0.0012$$

D of F Adj $r^2 = 0.1003$; F-statistic = 14.73
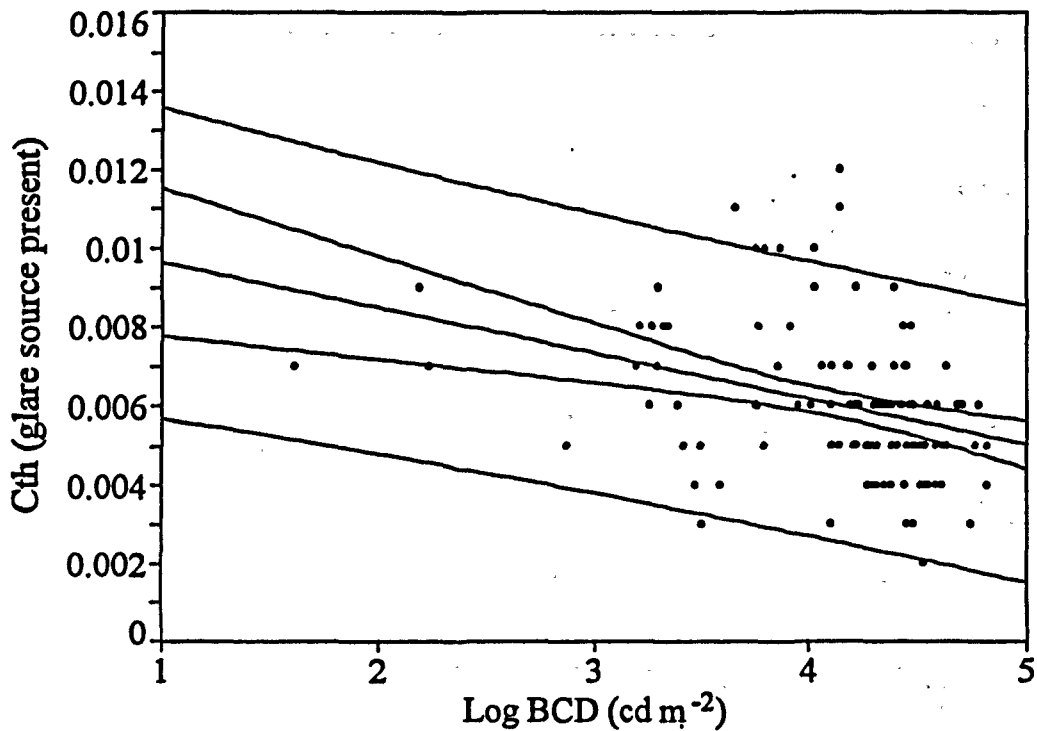
Figure 4.10 As there was no significant scatter from the glare source over the display screen, the correlation between C_{th} and Log BCD shown here is attributable to the amount of scattered light in the eye. This proposition is consistent with, and supports, the principal conclusion of this dissertation.

ANOVA

	df	SS	MS	F	F Prob
Regression	1	4.50E-05	4.50E-05	14.7305	0.0002
Residual	112	0.0003	3.05E-06		
Total	113	0.0004			

Parameter Estimates

	Coeffs	Std Err	t Stat	P-value	Lower 95%	Upper 95%
Intercept(a)	0.0108	0.0013	8.6064	5.31E-14	0.0083	0.0133
Xvariable(b)	-0.0012	0.0003	- 3.8380	0.0002	-1.75E-03	- 0.0006

Table 4.10

4.6 The Regression of C_{th} on Position of Glare Source

The ANOVA of the C_{th} data showed that there was no significant effect of the position of the glare source, when set at each subjects BCD , on C_{th}. The data and trend line are shown in Figure 4.9; the regression analysis is given in Table 4.9. The regression analysis gives an F-value of 0.11, which is non-significant for the degrees of freedom in the sample. This is consistent with the ANOVA result.

4.7 The Effect of Glare on C_{th}

4.7.1 The Correlation of C_{th} (With Glare) with Log (BCD)

One of the objectives of the experiment was to assess if there were any influence of glare source luminance on C_{th}. This was achieved by measuring C_{th} with the luminance set at the subject's BCD luminance.

Figure 4.10 shows the data plot of C_{th} (with glare) against Log (BCD), and the linear trend line fitted to the data. Although there is a great amount of scatter in the data, there is a statistically significant inverse relationship between the two variables. Table 4.10 provides a summary of the linear regression analysis for the data. The F-value for the regression is statistically significant to less than 0.1% ($F_{0.001, 1, 120} = 11.38$).

The trend line indicates that as the luminance of the glare source increases, C_{th} decreases. This result can be interpreted to mean that the glare source luminance influences the adaptation luminance. With increases in glare source luminance there is an increase in adaptation luminance for the subject. This reduces the C_{th}, and agrees with the results of Van Nes and Bouman (Van Nes and Bouman, (1967)) whose results showed that adaptation luminance profoundly influenced the contrast sensitivity of sine wave gratings, similar to those used in the present experiment. More particularly, as adaptation luminance decreased contrast sensitivity also decreased. But the converse argument necessarily holds.

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$$y=a+bx; \quad a = 0.0036; \quad b = 0.335$$

$$\text{D of F Adj } r^2 = 0.1984; \quad \text{F-statistic} = 30.23$$
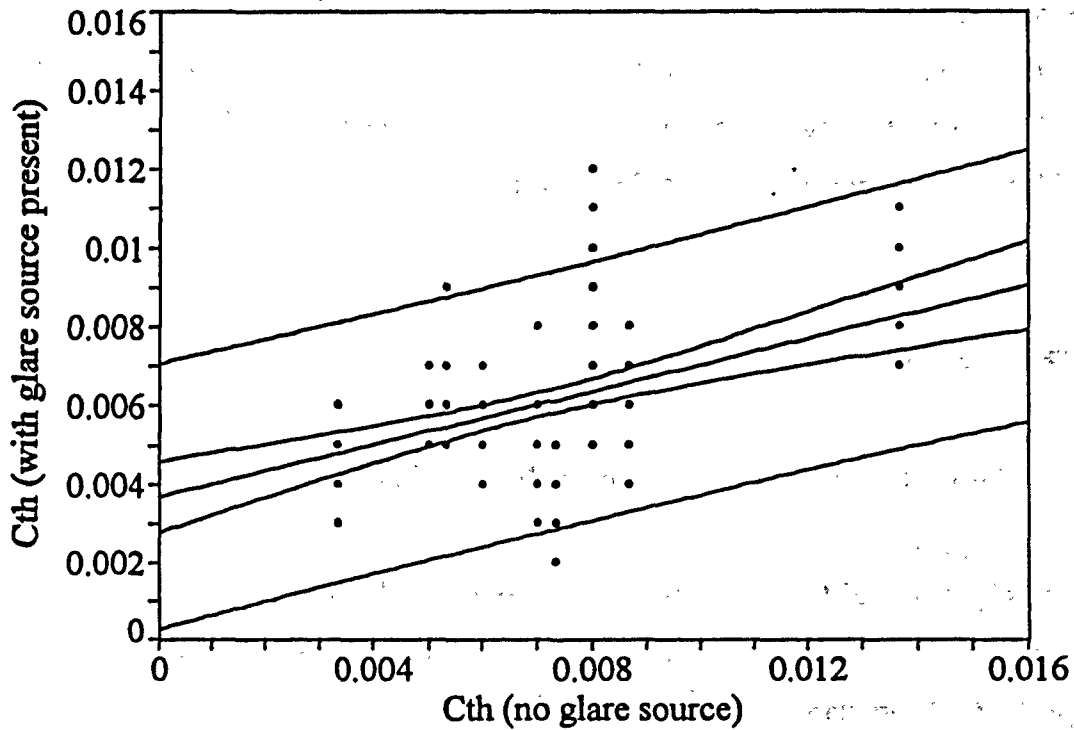
Figure 4.11   The results shown in this graph are thought to be due to improvement in retinal image quality caused by the glare source driving the pupil to a smaller diameter.

ANOVA

	df	SS	MS	F	F Prob
Regression	1	8.23E-05	8.23E-05	30.2338	2.44E-07
Residual	112	0.0003	2.72E-06		
Total	113	0.0004			

Parameter Estimates

	Coeffs	Std Err	t Stat	P-value	Lower 95%	Upper 95%
Intercept(a)	0.0036	0.0005	7.9776	1.40E-12	0.0027	0.0045
Xvariable(b)	0.3353	0.0610	5.4985	2.44E-07	0.2145	0.4562

Table 4.11

The influence of the glare source on C_{th} was, however, small, as indicated by the gradient of the trend line. This was because the glare source area was only a very small proportion of the total visual field.

4.7.2 The Correlation of C_{th} (With Glare) with C_{th} (No Glare)

Further support for the results discussed in section 4.7.1 comes from the data plot and linear trend line for C_{th} (with glare) versus C_{th} (no glare), as shown in Figure 4.11, and Table 4.11 gives the regression analysis. If there were no influence of glare source luminance on C_{th} (no glare) then the trend line would have a gradient of one and would pass through the origin.

The regression analysis shows that the neither of these conditions is satisfied. The gradient is significantly less than unity, as indicated in the analysis summary given on Table 4.11. If the glare source were adversely influencing C_{th} then the gradient would be greater than unity. A gradient less than unity indicates that, consistent with the argument of 4.7.1, with the glare source present C_{th} is lowered relative to the no glare situation. This indicates an increase in adaptation luminance for the subjects with the glare source present.

An alternative explanation of this result is that the glare source has driven the pupil diameter to a smaller diameter. This caused an improvement in retinal image quality, and the consequent reduction in C_{th}.

4.8 The Relationship Between Subjective Glare Setting and C_{th} (No Glare)

The argument proposed in sections 4.7.1 and 4.7.2 is further complemented by considering the correlation of Log (BCD) and C_{th} (no glare). The data plot and fitted regression line are given in Figure 4.12. The regression analysis is given in Table 4.12.

$$y = a + bx^3; \ a = 4.41; \ b = -548268.$$

D of F Adj $r^2 = 0.4308$; F-statistic $= 88.33$
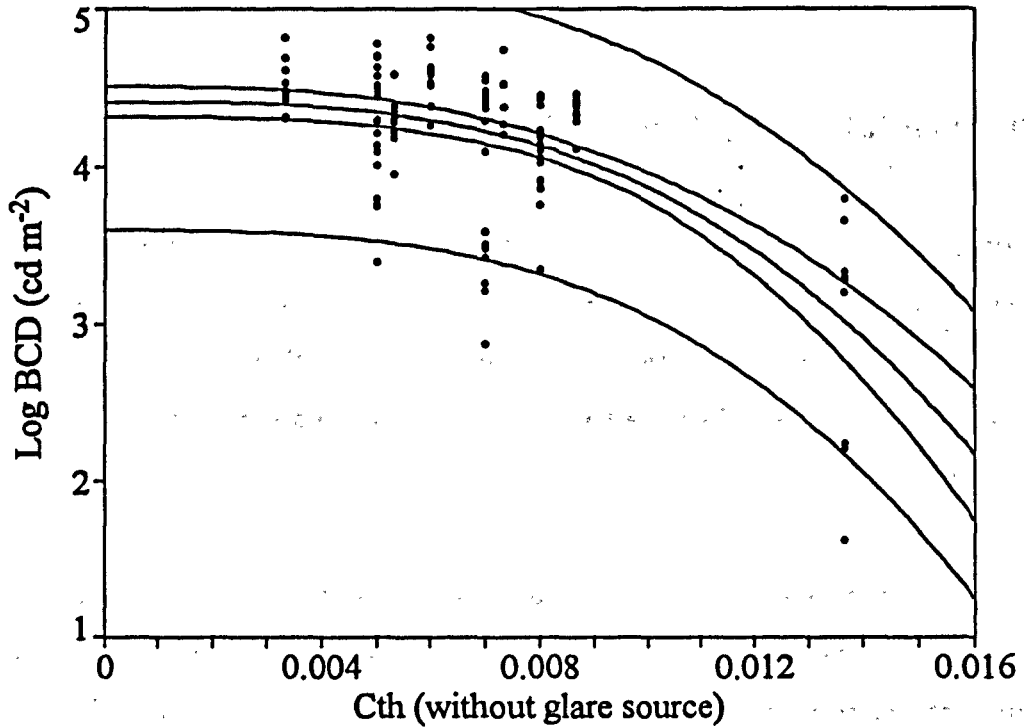
Figure 4.12

$y = a + bx^3$

r^2 (Coeff of Det)		DF Adj r^2		Fit Std Err		F-value	
0.4409		0.4308		0.4111		88.32	
Parameter	**Value**	**Std Error**		**t-value**		**95% Confidence Limits**	
a	4.408	0.04851		90.87		4.313 / 4.505	
b	-548268.	58337.		-9.39		-663859.787/-432676.788	
Source	**Sum of Squares**		**DF**	**Mean Square**	**F**		
Regr	14.93		1	14.93		88.32	
Error	18.93		112	0.169			
Total	33.86		113				

Table 4.12

The regression plot shows very clearly the systematic decrease in Log (BCD) [increase in sensitivity to discomfort glare] with C_{th} (no glare). The regression line is very similar to that fitted to the data of Figure 4.5a, where Log (BCD) was plotted against age. This is no coincidence because there is also a strong correlation between C_{th} (no glare) and age. Thus the present data indicate that both subjects' C_{th} settings, and age are parameters that significantly influence the perception of discomfort glare. The implications of these results are discussed in detail in Chapter 5 below.

4.9   Analysis of the Data from the Single Subject Experiment

In addition to the main experiment, the analysis of which has been discussed in sections 4.2 - 4.8 above, a supplementary experiment was run using a single subject. The data for this subject were collected in more detail; for each experimental condition the subject recorded 5 values of BCD, C_{th} (with glare).

Also, the experimental conditions included vertical and horizontal meridians, not just the single horizontal meridian used in the main experiment. In the horizontal meridian the glare source was positioned at the same azimuthal angles as for the main experiment ie 20°, 40°, 50°, 60° and 80°. In the vertical meridian elevation angles of 20°, 40°, 50° and 60° were used; it was not possible to position the glare source at 80° because of physical restrictions caused by the apparatus. It was also unnecessary, as the eyebrow structure cuts off vision at about 60° above the horizontal.

Finally, all experimental conditions were recorded at two background luminances, 10 cd m⁻² and 24 cd m⁻². The background of 10 cd m⁻² was chosen because this is normally taken as the lower bound of photopic vision, before mesopic vision starts. The higher background luminance was limited to 24 cd m⁻² because of the need to match the background luminance in the hemisphere with the mean luminance of the CRT screen used for measuring C_{th}. The highest mean screen luminance available was 24 cd m⁻².

4.9.1 The Analysis of Variance of the BCD Data: Single Subject Experiment

The ANOVA table for Log (BCD) is given in Tables 4.13a and 4.13b

4.9.1.1 The Effect of Position of Glare Source on BCD Setting

Consistent with the results of the main experiment, the single subject data showed that there was a significant effect (α= 0.003) of the position of the glare source on the setting of BCD. This was true for both horizontal and vertical meridians.

4.9.1.2 The Effect of Meridian on BCD Setting

The ANOVA for the data showed that there was no effect of meridian on BCD setting, for the range of angles used in the experiment. This result may have been different if angles of elevation greater than 60° were available in the vertical meridian. This is because above 60° the forehead and eyebrows start to shade and attenuate the luminance of the glare source.

However, over the range of angles used, and for the single subject data recorded there was no significant difference in the sensitivity to glare between the vertical and horizontal meridians.

4.9.1.3 The Effect of Background Luminance

There was also no difference in the BCD settings between the two background luminances used in the experiment. This result most probably indicates that the two backgrounds used were not sufficiently different to produce any difference in sensitivity.

It would have been possible to have used a background of less than 10 cd m^{-2}, and so produce a much greater difference between the two backgrounds. This option was discounted because this would have necessitated the use of mesopic, and possibly scotopic vision. Although of wider interest, data on glare sensitivity under mesopic and scotopic vision were not of interest in the present experiment, which was concerned with

Analysis of variance of variate: Log BCD Luminance

Table 4.13a

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F Prob
Background	1	0.0072	0.0072	0.14	0.710
Axis	1	0.0169	0.0169	0.33	0.569
Residual	31(2)	1.5925	0.0514		
Total	33(2)	1.6154			

Table 4.13b

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F Prob
Position	3	0.5998	0.1999	5.73	0.003
Residual	30(2)	1.0460	0.0349		
Total	33(2)	1.6159			

Tables 4.13a and 4.13b ANOVA for response variate Log BCD luminance setting for the single subject experiment

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Analysis of variance of variate: C_{th}, with glare source present

Table 4.13c

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F Prob
Background	1	0.138E-03	0.138E-03	117.54	<.001
Axis	1	0.280E-06	0.280E-06	0.24	0.628
Residual	31(2)	0.363E-04	0.117E-05		
Total	33(2)	0.166E-03			

Table 4.13d

Source of variation	d.f.(m.v.)	s.s.	m.s.	v.r.	F Prob.
Position	3	0.244E-05	0.814E-06	0.15	0.929
Residual	30(2)	0.164E-03	0.546E-05		
Total	33(2)	0.166E-03			

Tables 4.13c and 4.13d   ANOVA for response variate C_{th} (with glare source present) for the single subject experiment

elucidating some of the principal causes of glare under photopic conditions.

4.9.2 The Analysis of Variance of the C_{th} Data: Single Subject Experiment

The ANOVA for the C_{th} data is given in Table 4.13c and 4.13d.

4.9.2.1 The Effect of Position of the Glare Source and Meridian on C_{th} (With Glare)

There was no effect of the glare source position, in either meridian, on the value of C_{th}. For the horizontal meridian this result was consistent with the results from the main experiment. For the range of elevation angles used in the vertical meridian the same results was obtained, and is not intuitively unreasonable, given the result for the horizontal meridian.

4.9.2.2 The Effect of Background Luminance on C_{th}

There was a statistically significant difference in the values of C_{th} measured at the two backgrounds used in the experiment. This result is consistent with the findings of Van Nes and Bouman (Van Nes and Bouman, (1967)).

The description and discussion of the analysis of all results is now complete. The interpretation of the analysis, and the conclusions are given below in Chapter 5.

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Chapter 5   Discussion and Conclusions from the Analysis of the Data

5.1   Preliminary Interpretation of the Data

One of the principal results that emerges from the analysis of the data is that there is a very significant effect of age on Log (BCD), a result which is consistent with those reported by Bennett (Bennett, (1977)). This result is independently supported by the correlation between Log (BCD) and C_{th} (no glare), as C_{th} (no glare) was also correlated with age. So, an increase in glare sensitivity, as measured by the decrease in Log(BCD), is correlated with an increase in C_{th} (no glare).

This is likely to be attributable to two, inter-related, reasons:

i.   It is well established that with ageing the performance of the visual system suffers degradation. This is true for all parts of the visual system, but particularly the optical components eg the cornea and lens system. For example, the lenses of a person aged around sixty-five can attenuate the passage of light by up to two log units more than the lenses of a person aged around twenty (Cook and Koretz et al, (1994); Koretz and Cook at al, (1994)).

ii.   The overall degradation in the performance of the visual system can be objectively assessed by measuring the contrast sensitivity function, or CSF. Thus, it is no coincidence that there is a significant correlation found between Log (BCD) and both age and C_{th} (no glare).

C_{th} in older people is higher than for younger people because the optical system will not be able to form as sharp an image for a number of reasons. The eye's range of accommodation decreases markedly with age (Reading, (1988)). Thus, the retinal image suffers more blur in older people than in younger people.

Also, and more significantly for the present results, the optical components of the ageing eye tend to scatter and attenuate the light significantly more than the eye of a healthy

young emmetrope. Attenuation by the optical components reduces the retinal illuminance at the retina, requiring objects to have a higher luminance to achieve the same retinal illuminance as in the young eye. Light scatter causes a reduction in contrast, further degrading the image. The requirement to increase task illuminance to overcome attenuation can conflict with contrast reduction caused by increased light scatter at higher task luminances.

It is potentially the light scattering effects which are underlying the correlation between Log (BCD) with both age and C_{th} (no glare) in the present results. This chapter explores these arguments, and draws conclusions about the relationship between discomfort glare and light scatter.

5.2   What C_{th} Measures

Any optical system, including that of the human eye, is susceptible to limits of performance. In a perfect optical system the upper bound of performance will be constrained by the diffraction limit of the system. This is the resolution limit of the optical system and may be measured by, for example, the ability of the optical system to distinctly resolve two points in an image as they are brought closer and closer together, see for example (Hecht, (1987)).

Most optical systems are susceptible to other limitations in performance, and which operate before the diffraction limit is reached. These limits on performance include spherical and chromatic abberation, coma, astigmatism, field curvature and distortion. The effect of these abberations is to degrade the image of an object, compared to the diffraction limited image, which is not itself a perfect image.

The limits of performance of an optical system can be measured using transfer functions. The contrast sensitivity function, CSF, of Campbell and Robson (Campbell and Robson, (1968)) discussed in Chapter 3, section 3.2 is a transfer function that measures the ability of the human visual system to resolve spatial information at threshold. The CSF provides the upper and lower cut-off frequencies of the human visual system, and also allows
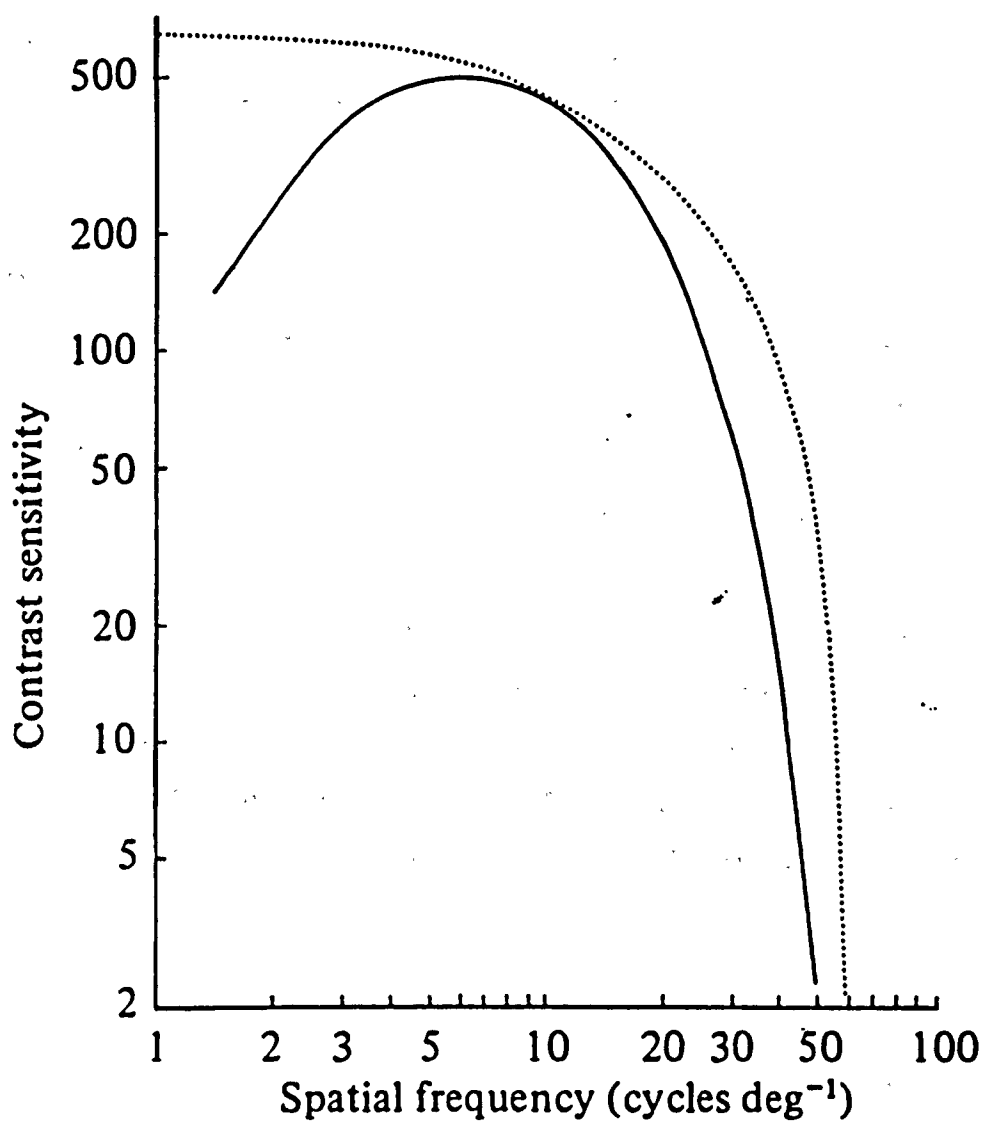
Figure 5.1 The Contrast Sensitivity Function, CSF, for the human visual system with a pupil of 2.5 mm and at a high photopic luminance. The dotted line shows the CSF expected if the optics of the eye were diffraction limited. [Source: Barlow and Mollon, (1982)]

comparison of the performance of the healthy human optical system against a simple one lens, diffraction limited optical system. The CSF and diffraction limiting curve are shown in Figure 5.1.

In general the human CSF peaks in the spatial frequency range 2 - 8 cycles per degree (cpd). Any reduction in contrast sensitivity caused by light scatter is likely have an effect on the CSF particularly in the spatial frequency range 2 - 8 cpd. It was not practical in the present experiment to measure the whole CSF for each subject, so a single representative point was selected in the peak range of the CSF at 4 cpd.

There is an intimate connection between the CSF and the point spread function, or PSF. The PSF is a parameter which has been used extensively in studies of the effect of light scatter on the human visual system. The function used to assess the degree of light scatter in the human visual system, the stray light function, is based on the PSF. The relationship between the PSF as a parameter of light scatter, and age is of relevance to the present investigation.

5.3   The Point Spread Function

The response of an optical system to a point source is called the impulse response. Because of the limitations in performance of all optical systems the impulse response always produces an image of the point source which is smeared over a finite area. In a well corrected optical system, the PSF is the Airy disk (Hecht, (1987)). The form of the PSF is shown in Figure 5.2.

It can be shown by use of Fourier techniques, that there is an equivalence between the PSF and the optical transfer function, OTF. It is the OTF which, as cited in section 5.2 above, is the function which measures the performance of a lens system. Thus, in the case of the human visual system, the optical performance is estimated by the PSF. The PSF for the human eye was extensively investigated and reported by Campbell and Gubisch. (Campbell and Gubisch, (1966))
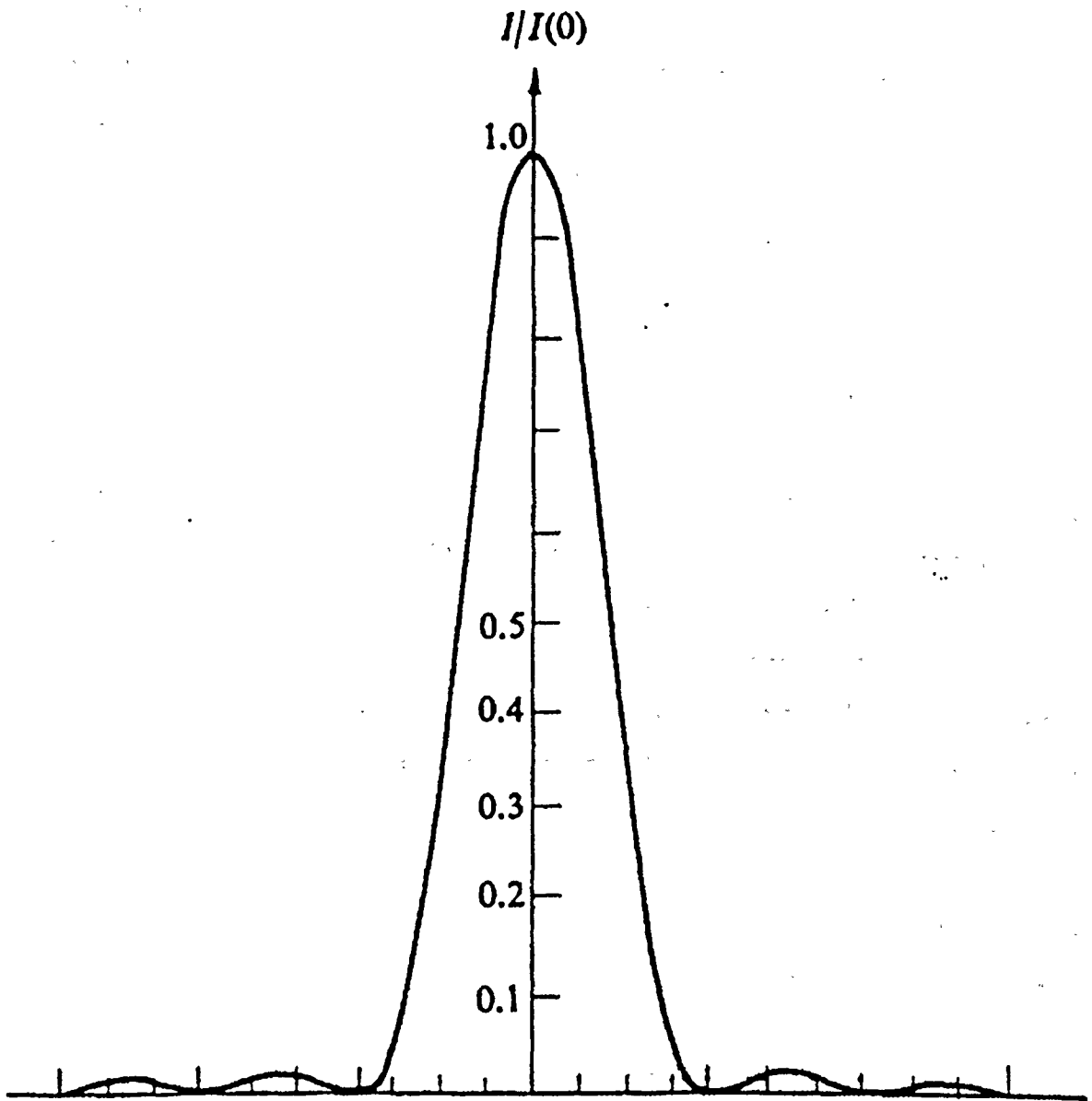
Figure 5.2 The Point Spread Function (PSF) shown in one dimension. The PSF is the 'impulse response' of an optical system to a point source located in object space. After passing through the optical system the focused image of the point source object is smeared because of diffraction limiting effects and optical imperfections in the system, resulting in the PSF.[Source: Hecht, (1987)]

The PSF is generally comprised a central peak, the primary component of the image of the point source, around which is distributed, symmetrically in two dimensions, a much larger area of lower amplitude signal. The surround to the central peak of the PSF is a measure of the effect of light scatter on the point image, and is taken to measure the stray light function, or SLF (Vos, (1984)). It is this function which is of principal interest in interpreting the present results.

5.3.1 Vos's Conclusions

The review and analysis carried out by Vos (Vos, (1984)) investigated the argument that disability glare might be caused by both light scatter within the optical media and neuronal effects. In the review it was argued that light scatter occurred principally at three sites: the cornea, the lens, and the retina, with only a small percentage of scatter occurring in the other optic media eg the vitreous humour. There was an approximately equal amount scatter at each of these locations, and that scatter accounted for almost all of the effects of disability glare.

As discussed in Chapter 2, section 2.4, disability glare is estimated by equivalent veiling luminance, L_v, and is given by the formula:

$$L_v = k\frac{E_G}{\theta_G^n}$$

Where: L_v = Equivalent veiling luminance
  E_G = Equivalent retinal illuminance due to the glare source
  θ_G = Angle subtended by the glare source to the line of sight
  k, n = constants

The stray light function is estimated by:

$$f(\theta) = \frac{10}{\theta^2}$$

Where θ has the meaning defined above. This function is known as the Stiles-Holladay formula, and has been broadly accepted as the principal function for estimating light scatter in the human eye over the range of visual angles, or eccentricity, 1° - 90° (Ipsjeert et al, (1990)).

Vos also concluded that there were a number of unresolved issues of light scatter in the human visual system. One of the major issues was to establish how the light scatter function, or stray light function, changed with age.

5.3.2 The Effects of Age on the Stray Light Function

An alternative form of the stray light function is given by Ijspeert et al (Ijspeert et al, (1990), which uses the PSF.

$$PSF(\theta) \approx \frac{10}{\theta^2}$$

As described above in section 5.3, the stray light function is generally regarded as the surround to the peak of the PSF, where $\theta > 1°$. Ipsjeert et al (Ipsjeert et al, (1990)) have recently reported a study carried out to investigate how the stray light function changed with age, scatter angle, and iris pigmentation. Of principal concern here is the results they reported on the change of the stray light function with age.

Because the PSF as an estimate of the stray light function approximately follows an inverse square law with respect to θ, Ipsjeert et al redefined the function to be:

$$sm(\theta) = Log(\frac{L_v(\theta)\theta^2}{E_G(\theta)})$$

Where: sm = the stray light measure.

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In their study they used effective scatter angles of 3.5°, 7.0°, 13.6° and 25.4°. They found that, with respect to age, the same function could be fitted to the data across all scatter angles, using different values for the parameter sm(θ, 0). Thus:

$$sm(\theta, a) = sm(\theta, 0) + Log(1 + (a/c)^4)$$

Where: a = age in years;

c = 68.7 ± 0.4 years

sm(3.5°, 0) = 0.838 ± 0.005

sm(7.0°, 0) = 0.752 ± 0.003

sm(13.6°, 0) = 0.846 ± 0.003

sm(25.4°, 0) = 1.096 ± 0.006

The present study used visual angles of 20°, 40°, 50°, 60° and 80°. So the result reported by Ipsjeert et al of primary relevance to the present study is that for a scatter angle of 25.4°.

5.3.2   The Test of H_0

5.3.2.1   Fitting of the Stray Light Function to the Log (BCD) vs Age Data

The function of Ipsjeert et al shows how stray light increases with age. If there is an association between stray light and reported discomfort glare, measured by Log (BCD), then the Log (BCD) scale is inverted with respect to sm. This is because Log (BCD) is a measurement of sensitivity. Thus, the stray light function needs to be inverted to allow it to be fitted to the Log (BCD) vs age data.

$r^2 = 0.4228$; D of F Adj $r^2 = 0.4124$; Fstat=82.03

$a = 0.2215$; $b = 78.34$
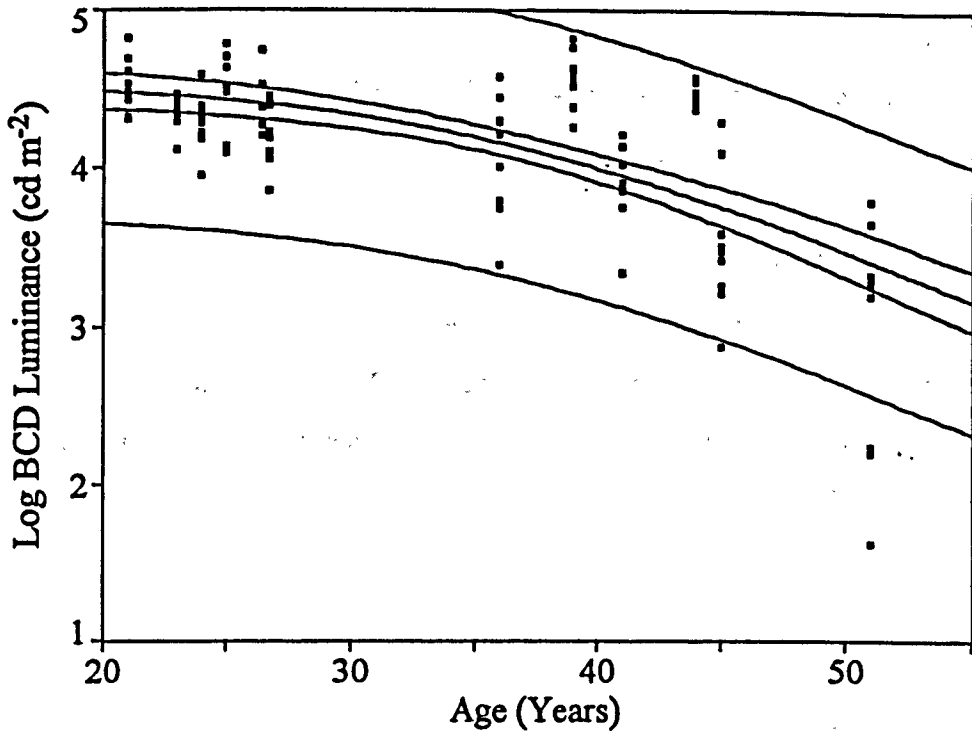
Figure 5.3 The stray light function of Ijspeert et al fitted to the subjectively set Log BCD luminance vs age data. The inner pair of intervals about the fitted function are the $\pm$ 95% confidence intervals, and the outer pair are the $\pm$ 95% prediction intervals. The form of the function fitted to the data was:

$$\text{Log BCD luminance} = (0.2215 + \text{Log}(1 + ((\frac{age}{78.34}))))^{-1}$$

DF Adj r^2	F-value
0.4123	82.03

Parameter	Value	Std Error	t-value	95% Confidence Limits
a	0.2215	0.0031	72.46	0.2155 / 0.2276
b	78.34	2.64	29.69	73.12 / 83.58

Source	Sum of Squares	DF	Mean Square	F
Regression	14.31	1	14.31	82.03
Error	19.55	112	0.174	
Total	33.86	113		

Table 5.1 Regression analysis for the inverted stray light function fitted in Figure 5.3

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The regression line of the inverted stray light function fitted to the Log (BCD) vs age data is shown in Figure 5.3, and the numerical summary in Table 5.1. The regression line is a very good fit to the data, as indicated by the F-statistic, this has a value of 82.0264 ($F_{0.1\%, 1, 120} = 11.38$). This F-statistic compares with 83.97 for the best fitted function listed in Table 4.5, and the stray light function would be the third best function fit overall to the Log (BCD) vs age data. There is clearly a case for *a priori* regarding the stray light function as describing the data, rather than the arbitrary functions listed in Table 4.5.

The statistically significant fit of the stray light function to the Log (BCD) vs age data clearly indicates that there is very strong evidence to refute the null hypothesis. On the evidence that the stray light function fits the Log (BCD) vs age data, it can be argued there is a very marked correlation between subjective assessment of discomfort glare, measured by Log (BCD), and stray light.

5.3.2.2   Fitting of the Stray Light Function to the Log (BCD) vs C_{th} (no glare) Data

The same process of fitting the inverted stray light function was carried out for the Log (BCD) vs C_{th} (no glare) data. Again the regression showed a statistically very significant fit of the function to the data. This providing verification of the case that light scatter in the optic media has a fundamental effect on subjective rating of discomfort glare, as measured by Log (BCD).

The regression fit is shown in Figure 5.4, and the numerical analysis in Table 5.2. The F-statistic for the regression was 87.22 ($F_{0.1\%, 1, 120} = 11.38$). This compares with an F-statistic value of 88.32 for the best fitted arbitrary function.

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$$\text{D of F Adj } r^2 = 0.4277; \text{ F-statistic} = 87.2$$

$$a = 0.2286; b = 0.0190$$
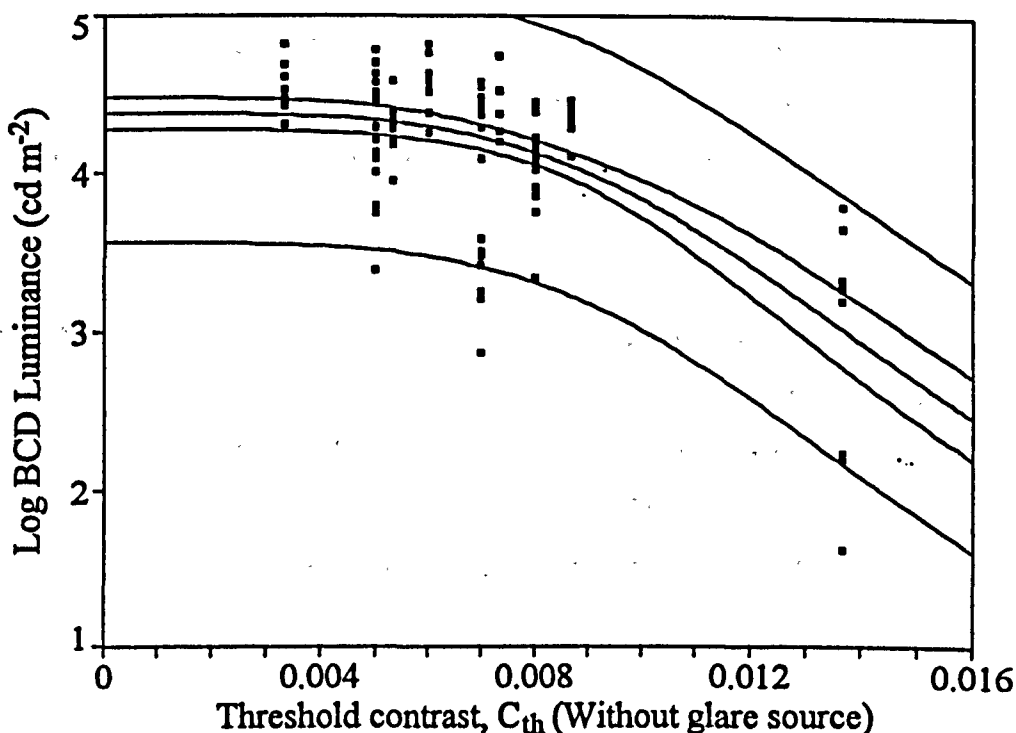
Figure 5.4 The inverted stray light function of Ijspeert et al fitted to the subjectively set Log BCD luminance vs C_{th} data. The intervals about the fitted function have the same meaning as in Figure 5.3. The form of the function fitted to the data was:

$$\text{Log BCD luminance} = (0.2286 + \text{Log}(1 + ((\frac{C_{th}}{0.0190}))))^{-1}$$

DF Adj r2	F-value
0.4277	87.22

Parmameter	Value	Std Error	t-value	95% Confidence Limits
a	0.2286	0.0026	87.05	0.2234 / 0.2338
b	0.0190	0.0008	25.24	0.0175 / 0.0215

Source	Sum of Squares	DF	Mean Square	F
Regression	14.824	1	14.82	87.22
Error	19.035	112	0.169	
Total	33.859	113		

Table 5.2 Regression analysis for the inverted stray light function fitted in Figure 5.4

5.3.2.3 Explaining the Anomaly that Light Scatter Influences Discomfort Glare but Does Not Adversely Effect C_{th} (glare)

There appears to be an anomaly resulting from the data analysis. Light scatter has been found to have an effect on discomfort glare perception, but has not adversely influenced threshold contrast measured with glare present. In fact the C_{th} (glare) data indicate that the glare source changes adaptation state of the visual system, possibly by decreasing pupil diameter, improving image quality and so reducing C_{th}.

The anomaly is explained by considering how light scatter effects the PSF. Light scatter, by definition, see section 5.3.1 above, adds to the energy of the periphery of the PSF. This will reduce the ratio of energy in the central peak of the PSF to that in the periphery, so reducing the signal-to-noise ratio. However, in the case of low magnitude light scatter, the reduction in the signal-to-noise ratio is not sufficient to adversely effect C_{th}.

5.4 Implications of the Result that Discomfort Glare is Correlated with Light Scatter

5.4.1 The Distinction Between Discomfort Glare and Disability Glare

In his 1929 paper Stiles (Stiles, (1929)) concluded that there was only a 15% light loss at the retina that could be attributed to light scatter by the optic media, and that therefore other mechanisms were responsible for causing the elevation in threshold contrast. He subsequently went on to introduce the phenomenon of discomfort glare; refer to Chapter 1, section 2.3.2 ff. He reported:

> 'It may be concluded that the observed rise in the threshold in the presence of glare is due principally to causes other than the light scattered in the eye media, and that the scattering effect can only play a minor role in the phenomenon.'

He then went on to state in the second of his 1929 papers (Stiles, (December, 1929))

> 'Perhaps I may be permitted at this stage to coin a new term and speak of "disability glare" as distinct from "discomfort glare".'

Thus, the distinction was made between the two glare types.

The results of the experimental data and analysis carried out in the study reported here substantially weaken the distinction made by Stiles. Although there is much variance in the data there is clear evidence in the present results to link subjective discomfort glare ratings to light scatter effects using the stray light function of Ipsjeert et al. That there is very substantial variance in the data does not weaken the argument, as the variance is typical of that found in ergonomics experiments, including glare experiments. However, this issue is discussed further in section 5.5 below.

5.4.2 A New Model of Discomfort Glare

The distinction made by Stiles between discomfort and disability glare led directly to the work of Hopkinson and Petherbridge, and of Guth and others, in developing models of discomfort glare. While the development of the disability glare model based on light scatter effects took place independently of all the work on discomfort glare; refer to chapter 2 above.

The development of discomfort glare models was much more complicated than that of disability glare models, because it was not possible to invoke the principles of physical and geometric optics to help explain discomfort glare phenomena. The present results indicate that the division was artificial, and that it is now possible to use the knowledge of disability glare, in particular stray light effects, to model discomfort glare effects. Although it would be beneficial if the results reported here could be independently verified, and so support this proposition.

On the assumption that the present results are valid, it is possible to propose a new, simpler method of discomfort glare calculation.

5.4.2.1 The Log (BCD) Curve as a Threshold Curve for Discomfort

If, as indicated by the present data analysis, there is a causal link between perceived discomfort from an over bright source and light scatter it is possible to propose a simpler model for calculating discomfort glare.

The parameter used in the experiment to measure discomfort glare was the borderline between comfort and discomfort. This is a threshold measure, estimated using an experimental technique designed for measuring visual thresholds ie the adaptive probit estimation method (APE). Thus, the function fitted to the data can be interpreted as a threshold curve, that estimates the threshold of discomfort glare.

The existing models of discomfort glare show that perceived discomfort is dependent on luminance difference ie $L_{source}/L_{background}$. The present analysis does not invalidate this assumption. The present data were collected at a background luminance of 24 cd m^{-2}, with a log value of approximately 1.4. This log luminance value needs to be subtracted from the fitted function value, also a log value, to achieve the luminance ratio between background and source at which discomfort glare is likely to occur. Thus the threshold to discomfort occurs, in general, at the following log luminance values for the minimum and maximum age of subjects used in the study:

i. at age 21 years:

   calculated log BCD luminance value ≈ 4.5;

   subtract log background luminance value ≈1.4;

   luminance ratio threshold to discomfort @ 24 cd m^{-2}
   background = 3.1 log units = 1000: 1

ii. at age 51 years:

   calculated log BCD luminance value ≈ 3.4;

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subtract log background luminance value ≈1.4;

luminance ratio threshold to discomfort @ 24 cd m^{-2}
background = 2 log units = 100:1

So in the design of an installation the designer needs to ensure that no luminance ratio in the space exceeds 3.1 log units for a young population ie near to 20 years of age. For an office population that is closer to 50 years the maximum luminance ratio in the space should not exceed 2 log units.

This proposed new model of discomfort glare is simpler than the existing glare models. This particularly true for the Glare Index system. There is now only one value of glare that needs to be considered, and not different values for different environments, as is the case for the Glare Index system. This single value is the threshold to glare, represented by the function fitted to the data, the inverted function fitted by Ipsjeert et al.

5.4.2.2   The New Model's Parameters

The present data and analysis provide information about how the discomfort glare threshold changes with age, and with position of the glare source. The proposed model of glare does not negate any of the parameters in the existing models of discomfort glare. It does however introduce a significant new parameter, the need to take into account the age of the population that an environment is being designed for.

The existing models of discomfort glare also show that discomfort glare varies with background luminance, and with size of source. The present experiment did not investigate how BCD settings varied with background luminance, save for the single subject data over a narrow range of luminances. Also, the experiment did not investigate how the BCD settings varied with size of the source. The dependence of BCD on these two parameters needs to be re-established in future studies, using similar techniques as used in the present experiment. Lukiesh and Guth (Lukiesh and Guth, (1949)) have already reported this data, but using different techniques eg intermittent presentation of the glare source.

5.4.3 The Disparity Between Models of Discomfort Glare and Disability Glare

It has been noted by Boyce (Boyce) and inferred by Vos (Vos, (1984)), on the basis of observations made by Stiles and Fry, that there is a difference in the characteristics of the two model curves of discomfort and disability glare. Discomfort glare tends to roll-off much more gradually with position than does disability glare. Vos has attributed this to:

    i.   the assumption that the optic media of the eye are uniformly scattering, an assumption that he states is too simplistic;

    ii.   an incorrect assumption of Rayleigh scattering by Stiles (Stiles, (1929)), and Rayleigh scattering restricted to the forward direction by Fry (Fry, (1954)). Vos states that both assumptions are incorrect;

    iii.   the incorrect assumption that the fundus is a diffusing sphere.

The implication of Vos's assertions are that if more realistic, but necessarily more complex, assumptions are used to model light scatter in the optic media of the human eye, then the differences between the two model curves would be significantly reduced. If this is the case it would further support the conclusions reported here that discomfort glare is significantly dependent on light scattering effects in the optic media. This is another area that requires further investigation.

5.4.4 The Dependence of BCD Settings on C_{th} (no glare)

The data clearly indicate an age dependency of BCD setting. This is also linked to the optical performance of the subject, as measured by C_{th}. However, it is also true that C_{th} can vary for subjects for reasons other than that of age effects on the optic media of the eye. for example uncorrected myopia will have a dramatic effect on the CSF function. This opens the possibility that a subject's overall visual performance, as assessed by C_{th}, ideally CSF, will also influence BCD settings.

In the experiment reported here it was not possible to investigate this hypothesis, as C_{th} was confounded with age. To study this possibility it would be necessary to use a subject group that comprised people of a narrow age range, but with a wide variation in measured CSF, or at least C_{th} for a fixed spatial frequency.

5.5 Experimental Variance, Percentage Explained and the Need for a More General Model of Visual Discomfort

The regression curve fits to the data, particularly those fitting Log (BCD) against age and Log (BCD) against C_{th}, were statistically very significant as indicated by the values of the F-statistics. However, the adjusted coefficients of determination, r^2, indicate that there remains a significant amount of experimental variance left unaccounted for by the regression fits. For example, the regression of the inverted Ipsjeert function fitted to the Log (BCD) vs age data had an adjusted r^2 value of 0.41, indicating that about 59% of the variance was unexplained by the model. Clearly there is a need to explore further what underlies this unexplained variance.

The variance exhibited by the present data is not untypical of that reported by other studies of investigating glare. There has now been a large number of studies reported, over many years and using similar methods, investigating visual discomfort as caused by over bright luminances. As the variance in these studies is always very substantial, there is a case for pursuing an alternative line of investigation to complement the existing body of data, with the objective of increasing our knowledge of visual discomfort in general. If such investigations were successful, they would necessarily increase the proportion of explained variance in the existing models of visual discomfort. Such a preliminary, alternative investigation is reported in Chapter 6.

5.6 Secondary Results from the Study

5.6.1 The BCD as a Scale for Discomfort Glare

The use of BCD, initially reported by Lukiesh and Guth (Lukiesh and Guth, (1949)), has been confirmed as a valid experimental measure of discomfort glare. The use of a threshold parameter of discomfort glare has led to the proposal for a simplified, single parameter model of discomfort glare.

5.6.2 The Use of Adaptive Probit Estimation in Subjective Threshold Experiments

The adaptive probit estimation (APE) (Watt and Andrews, (1981)) method was initially developed for use in measuring physiological thresholds eg C_{th}. The use of APE in the present experiment has extended the application of this technique into subjective rating experiments.

To be able to apply the technique, however, it is necessary to use a threshold criterion for the subjective rating. This was possible in the present study. But in each application the use, or development of an appropriate subjective threshold will need to be considered carefully to ensure valid application of the method.

Chapter 6   Scene Structure, the Visual Response and an Alternative Explanation of Visual Discomfort

6.1   The Underlying Structure of the Visual Environment

The visual system has the apparent capacity to analyze an infinite variety of visual scenes. If this is so, how has the visual system evolved a strategy to solve the problem of efficiently encoding this infinite variety of information from visual scenes, information that in the first instance humans' required to allow them to survive in the natural environment? Despite the superficial appearance of an infinite variety of information that the visual system has to analyze in visual scenes, research has indicated that there is underlying redundancy in scene images. It is the way that this information about, luminance, colour, depth, motion is distributed throughout the visual field that gives rise to the infinite variety of scenes that we see. It is the underlying structure that the visual system has evolved to see.

What is this underlying structure? There is not a single structure, there are at least two and both of these are important for understanding perception of the designed luminous environment.

6.1.1   Spatial Scale of Details in a Scene

Visual scenes are generally made up from a wide range of spatial detail. From large objects, for example trees, clouds, mountains, to medium sized objects such as tree branches, parts of clouds, mountain crags, to very fine details which might include the veins on the leaves of the tree, the detailed structure of clouds or the details of the rocks that form the crags. Each of these examples are defined by their 'spatial scale'.

It is possible to define spatial scale in a variety of different ways. One way is to specify size using linear scale, for example the diameter of a tree trunk is 1.5 metres. A more meaningful way, and one that has been generally adopted, is to specify objects in terms of the angle that they subtend at the eye, or their visual angle. In addition vision scientists also use a measure called 'cycles per degree' (cpd). This represents the number of regularly

spaced one dimensional sinusoidal, or square, waveforms that can be fitted into one visual degree. The greater the cpd the finer the detail.

It is now well established that the human visual system has a different sensitivity to different sizes of objects, defined in terms of cpd. This variation of sensitivity is defined in the 'contrast sensitivity function' (csf), as discussed in Chapters 3, 4 and 5.

6.1.2 The Spatial Information Spectra of Visual Scenes

Research has been reported that has investigated the distribution of spatial information across a range of spatial scales in natural scenes, see for example (Srinivasan, Laughlin and Dubs, (1982); Watt and Morgan, (1985); Pentland, (1984); Tolhurst, Tadmor and Tang Chao, (1992)). This research shows that in one dimension there is an inverse log-linear relationship between the amount of information in a visual scene and the scale at which it appears, see Figure 6. 1.

There is relatively little large scale information, for example the luminance information defining the outline of tree trunks, with more information occurring at medium spatial scales, for example the luminance information defining the outlines of tree branches. By far the largest amount of information is present at very fine spatial scales, for example the details that appear on the leaves such as vein details. At any one viewing distance the visual system will be most sensitive to spatial details that occur in the spatial information range 2-8 cpd.

6.2   A Model for Visual Discomfort

Given that there is a well defined csf and that there are preliminary indications that there is a well defined, underlying spatial structure to natural scenes, it is possible to hypothesize a model for what may be called spatially induced visual discomfort.

The man made, or synthetic, environment is not constrained by the same conditions that prevail in the natural environment. The synthetic environment is comprised of many more
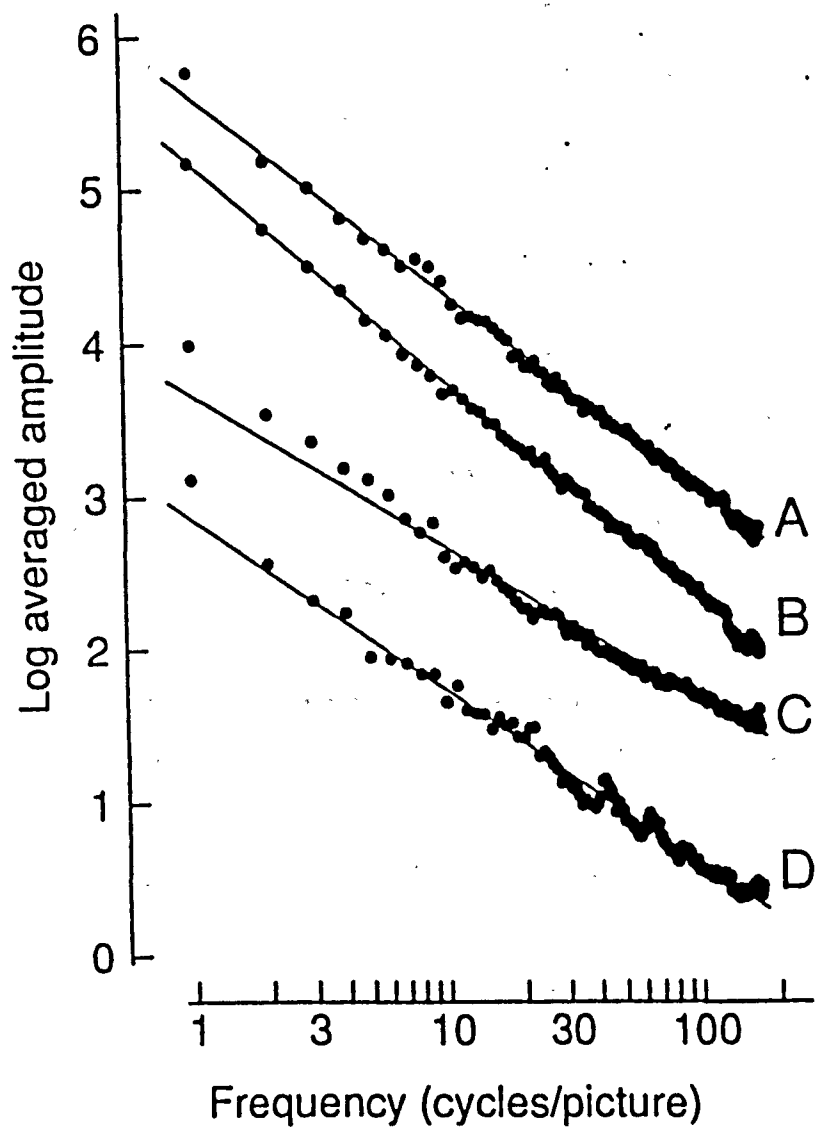
Figure 6.1   Data from Tolhurst, Tadmor and Tang Chao (Tolhurst, Tadmor and Tang Chao, (1992)) showing information content from four scenes, plotted as averaged amplitude spectra. The four scenes used to derive the data were predominantly natural. The graphs show a consistent form, with variations on the gradient between -1.28 and -1.00. The graphs have been displaced vertically for clarity. [Source: Tolhurst, Tadmor and Tang Chao, (1992)]

straight edges and regular geometric patterns than the natural environment. It is potentially quite easy for the spatial information content of the synthetic environment to significantly deviate from the distribution that is found in natural environments.

If the deviations in spatial information content are very significant then there is a likelihood that the part of the visual system that encodes spatial information will become saturated. This sensory response could plausibly lead to the subjective sensation of visual discomfort.

Figure 6.2 shows an extreme of such a spatial pattern. When presented to subjects many of them report a variety of unpleasant visual effects. This is especially true if the pattern occurs in the spatial frequency range 2-8 cpd, ie when it is viewed from 1 metre. The visual effects induced by this particular pattern have been researched and reported (Wilkins, Nimmo-Smith et al (1984)). The results of the investigation showed that the subjects reported that periodic spatial pattern produced a high degree of visual discomfort.

It may be that in the general office environment the appearance of regular geometrical patterns, similar to that shown in Figure 6.2, could lead to reports of visual discomfort. Such incidents of spatially induced visual discomfort have been reported, associated with partially opened venetian blinds viewed with high levels of sky luminance behind (Littlefair, (1988)). There have also been occasional reports in the press that large areas of carpet or wall paper with regular geometric patterns have caused complaints about visual discomfort.

To diagnose whether spatially induced visual discomfort is occurring in an office it will be necessary to have instrumentation that can record the visual information present in the office space and be able to analyze this information to produce a spatial information spectrum for the environment. Comparison of the measured information spectrum against the 'standard', natural information spectrum would indicate whether there is a problem associated with spatially induced visual discomfort.
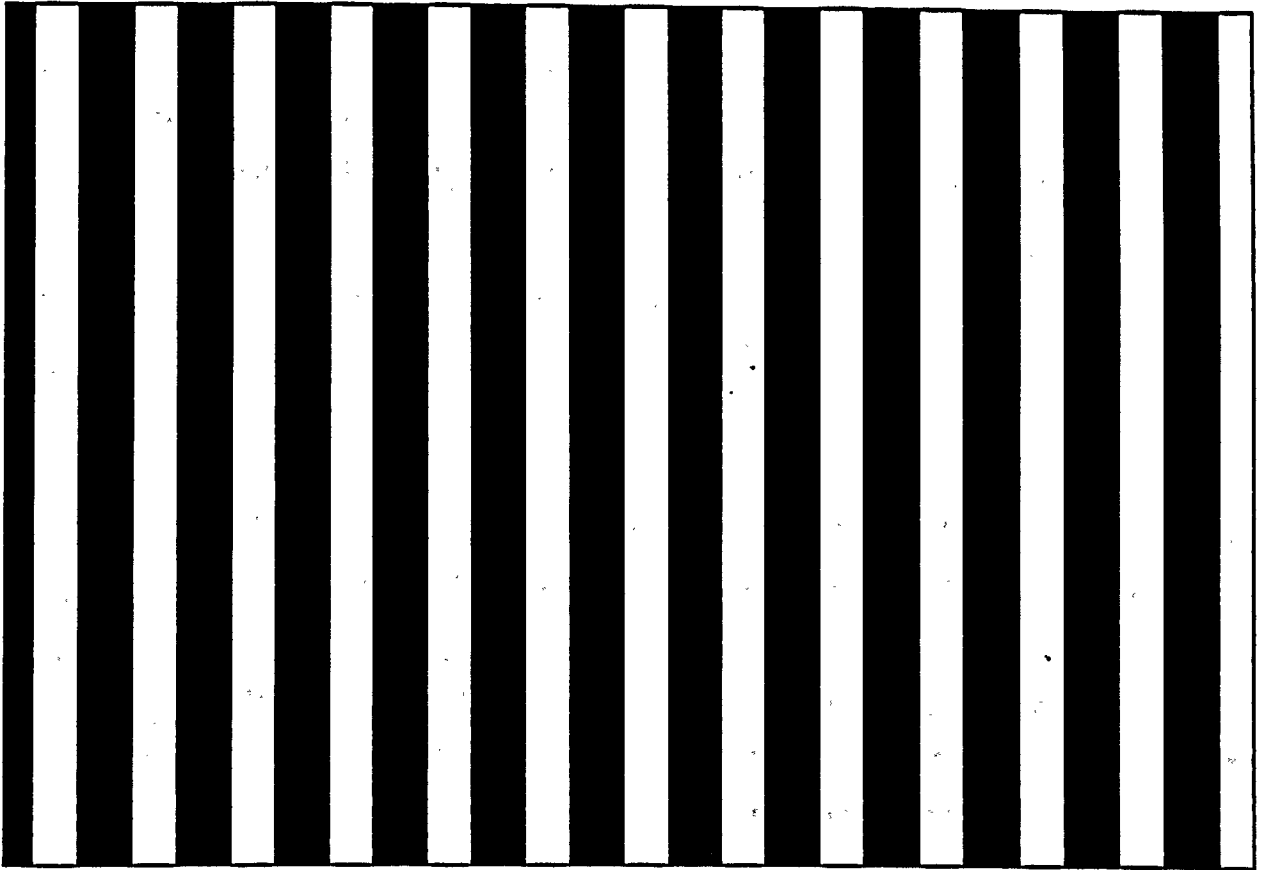
Figure 6.2 The figure shows a square wave grating. The contrast of the grating is defined as:

$$\frac{\text{Lmax-Lmin}}{\text{Lmax+Lmin}}$$

Where Lmax is the luminance of the light bars, and Lmin is the luminance of the dark bars. The spatial frequency of the grating is approximately 1.5 cpd when viewed from 1 metre; in linear dimensions the bar width is approximately 6 mm, the dimension for a complete for a complete cycle of the grating is 12 mm.

6.3   Contrast Distribution in Visual Scenes

Spatial information in the visual field generally exists at more than one contrast, where contrast can be defined in a number of different ways. The more usual definition adopted in lighting design is:

$$\text{Contrast} = \frac{L_t - L_b}{L_b}$$

Where: L_t = Luminance of the detail of interest, usually termed the (visual) task

L_b = Luminance of the background to the detail of interest

There are weaknesses to this definition, especially with regard to defining quite what represents background luminance in a complex scene. However, it has the advantage of being well understood by the lighting community.

In the natural environment contrast in a scene occurs for a variety of reasons, including:

    i.   Reflectance between different surfaces

    ii.   .. Shadow differences

    iii.   Occlusion of one surface by another

The main concern here is with contrast changes arising from differences in surface reflectances. In the natural environment measurements have shown that the range of surface reflectance values is quite constrained, apart from a few surfaces such as snow or coal (Krinov, (1947)). Natural surface reflectance values are generally less than 0.3, where reflectance is formally defined as:

$$\rho = \frac{\text{Reflected flux}}{\text{Incident flux}}$$

A large proportion of the contrasts that occur in a natural scene will be attributable to

differences in surface reflectance. Therefore the range of contrasts that occur will be constrained by the range of surface reflectances that are present in the natural environment. This leads to the intuitive expectation that natural scenes will be comprised principally of low to mid range contrasts with relatively few occurrences of very low or very high contrasts. This has been confirmed by measurements of contrasts and reflectance values in natural scenes (Laughlin, (1983); Burton and Moorhead, (1987); Krinov, (1947)). If a cumulative distribution of contrasts from a natural·scene is plotted it has the form shown in Figure 6.3.

Significantly, measurements of the contrast detection system of invertebrates show a response distribution that closely matches the expected distribution of contrasts, also shown in Figure 6.3. There are good reasons to believe that the same response function will be found in the human contrast response function at any one spatial scale, and repeated across spatial scales.

6.4   A·Model for Discomfort Glare Assessment

The existence of a 'standard', natural contrast distribution and the possible existence of a matched response from the contrast detection mechanism allows the formulation of an hypothesis about the occurrence of visual discomfort attributable to inappropriate luminance contrast. This effect may supplement existing perceived discomfort glare effects.

The range of surface reflectances that can be used in the synthetic environment is much wider than that found in the natural environment. This could result in the much more frequent occurrence of high contrasts in the visual field. Also, and perhaps more significantly, there is a greater incidence of self-luminous surfaces in the synthetic environment, for example light fittings and VDU screens. Examples of self-luminous surfaces in the natural environment are the sun, moon and stars; of these the sun and the moon are probably the most visually significant self-luminous surfaces.

The combined effect of more extreme surface reflectances, and the greater incidence of self-luminous objects in the synthetic environment may be to significantly skew the
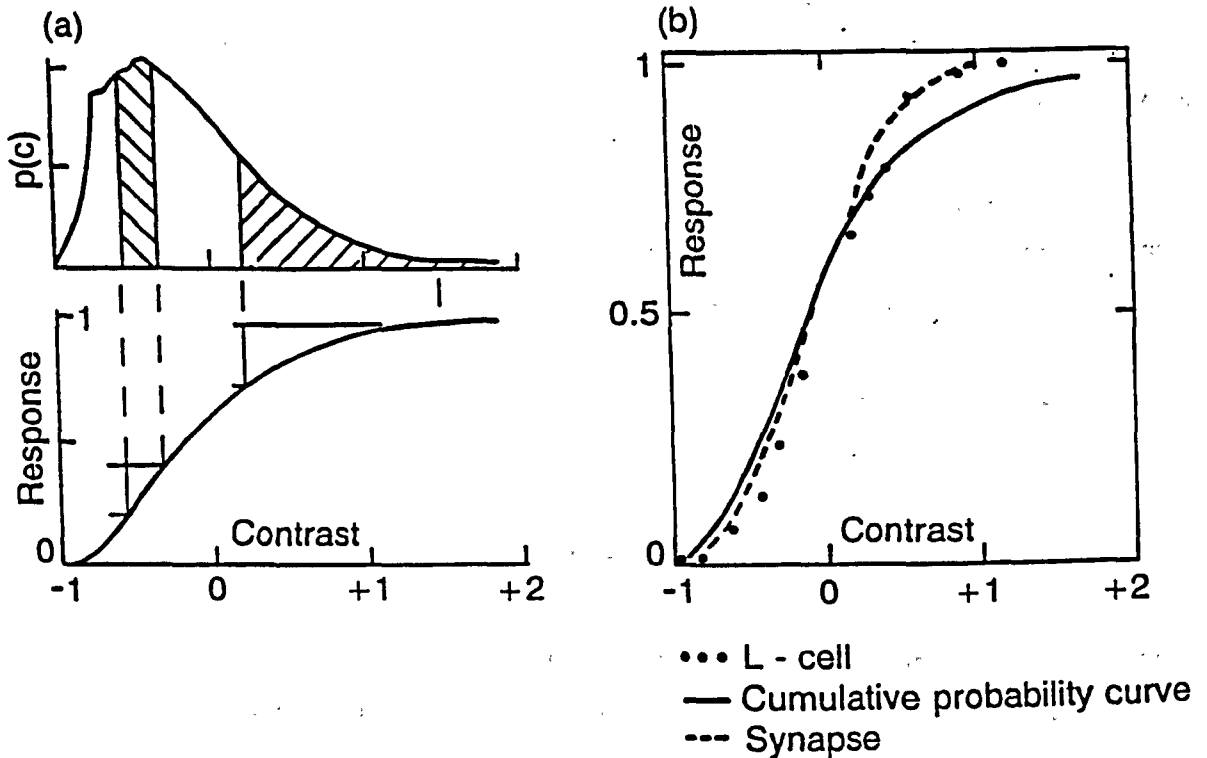
Figure 6.3   Shannon and Weaver (Shannon and Weaver, (1949) stated that the optimal transfer of information through a system will be achieved if all of the response states are used equally often. If contrasts are distributed as in the upper part of (a) then equal probability bands can be achieved by varying the range of contrasts covered by each band. This gives the cumulative probability curve as shown in the lower part of (a).

In practice contrast detection mechanisms are found to have cumulative probability response curves . This implies that the contrast detection mechanisms have evolved with maximum sensitivity to low and mid-range contrasts. [After Laughlin, (1983)]

distribution of contrasts in the environment, relative to the 'standard' distribution. The distribution will be skewed towards the high contrast range. The occurrence of excessive amounts of high contrast information may lead to a sensation of visual discomfort associated with luminance information, and possibly associated with reports of discomfort glare. Particularly if the high contrast is associated with spatial scale information in the range 2-8 cpd.

To test the hypothesis that skewed contrast distributions in the visual field can lead to reports of visual discomfort instrumentation will be required that can simultaneously measure all of the contrast information present in the visual scene across the spatial scale range of interest. This should certainly include the spatial scale range 2-8 cpd. This requirement is the same as that for the measurement of spatial information content in the visual field. The two measurement sets are intimately related.

6.5   The Measurement of Spatial and Contrast Information

6.5.1   Going to the DOGs

In any one visual scene there is usually a very large, but finite amount of information that has to be translated into a form that the visual system can process; this process is called encoding. It is clearly impractical for the visual system to encode very large amounts of information. The visual system has both optical and physiological limits of resolution which practically restricts the amount of information that the visual system can encode at any one time. But this constraint still leaves a very large amount of information to be encoded. What strategy has the visual system adopted to allow the efficient and economical encoding of information in the visual scene, a strategy that must avoid overloading the information handling capacity of the visual system?

A mathematical solution to the problem of handling the large quantities of information found in visual scenes is to use a 'filter' that removes redundant information from the encoded data. There are a range of filters that will accomplish this, but one of the more commonly cited filters is the 'Difference-of-Gaussian', DOG, filter. The operation of this filter is best understood by use of an illustration.

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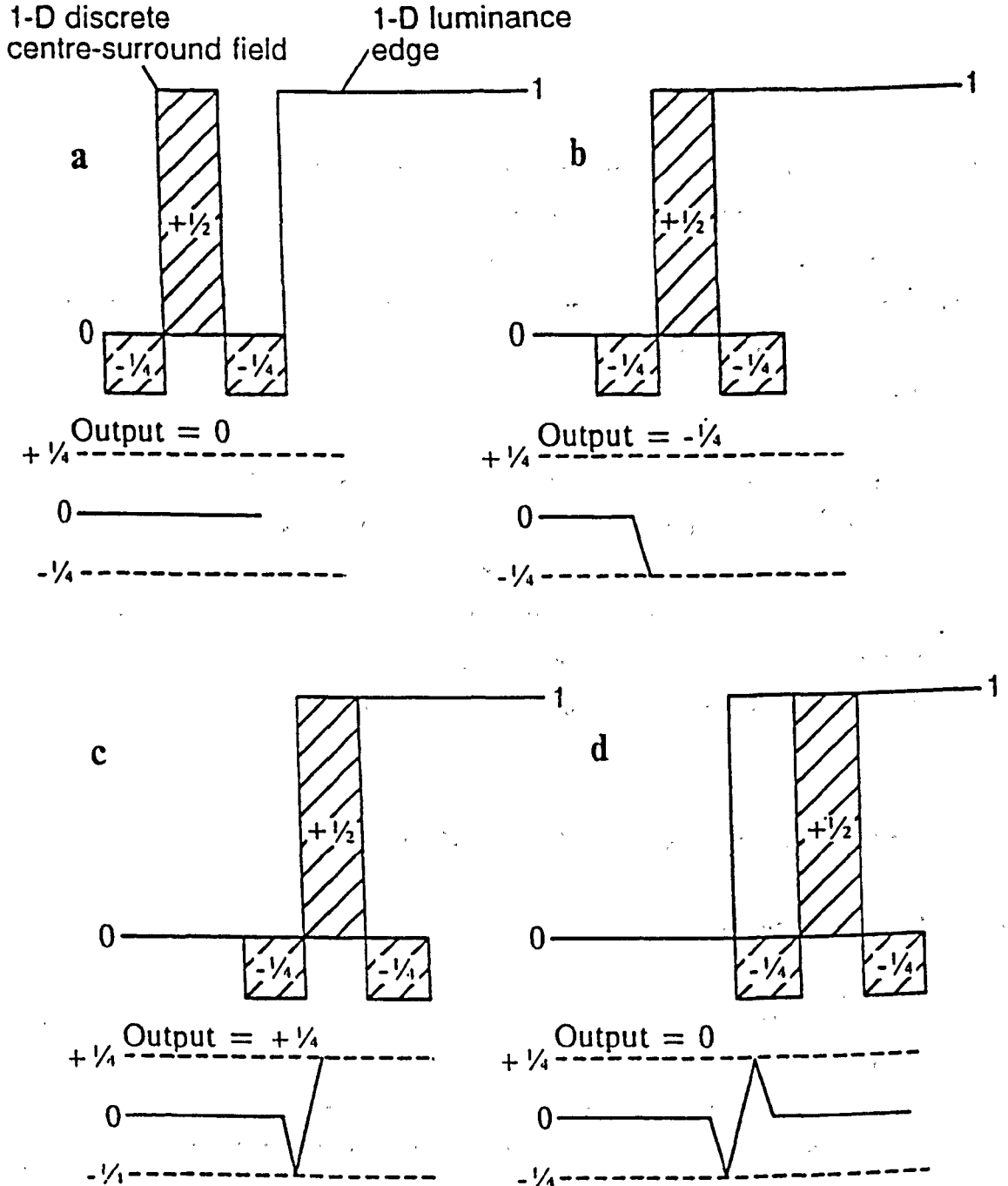
Figure 6.4 Sequence of diagrams showing a discrete 1-D convolution of a centre-surround receptive field with an idealised luminance edge. Below each of the four diagrams is shown the convolution output; a shows the centre-surround field at the start of the convolution, wholly to the left of the luminance edge; b shows the first step of the convolution, with the right hand area of inhibition traversing the unit luminance edge. In c the central area if the excitation also traverses the edge. Finally, in d the whole of the centre-surround field has traversed the luminance edge.

The most significant point to note is that the output is every where zero apart from at the luminance edge. The 2-D receptive fields in the retina display the same characteristics. The luminance detection mechanism of the visual system is primarily concerned with detecting luminance and chromatic changes; this is corroborated by Kuffler's results (Kuffler, (1953))

Figure 6.4 shows a one dimensional approximation to a DOG processing a one dimensional luminance edge. This process is called 'convolution'. Consider that the convolution is started with the DOG filter to the left of the luminance edge, as shown in Figure 6.4a. As the luminance is zero in this region the output from the DOG filter is zero, as might be reasonably expected. In Figure 6.4b the unit luminance edge is convolved with an area of inhibition in the DOG filter. This causes the output from the DOG filter to become negative. In the third stage of the convolution, Figure 6.4c, the central excitatory region is now convolved with the unit luminance edge, in addition to the inhibitory region. As the output of the excitatory region is greater than that from the inhibitory region the convolution now swings positive. In the final stage of the convolution, Figure 6.4d, all of the DOG filter is convolved with the unit luminance edge. The output from the DOG filter now returns to zero, as the output from the excitatory and inhibitory regions is equal.

The essential point to notice in this example is that the output from the DOG filter is zero where there is no change in the value of luminance; this is true for both the region of zero luminance and unit luminance. There is output from the DOG filters <u>only where there is a detectable change in the luminance</u> in the visual field.

6.5.2   Why Edge Detection?

By only detecting changes in luminance, and colour, in the visual field the visual system has reduced very considerably the amount of information that has to be encoded and passed to the brain. In formal terms the visual system has reduced 'redundancy' in the encoded information that is passed to the brain.

There is a further advantage of reducing redundancy in the image of the visual field. The visual mechanisms that process the output from the retinal based DOG filters are able to respond with greater sensitivity to the remaining luminance signal input.
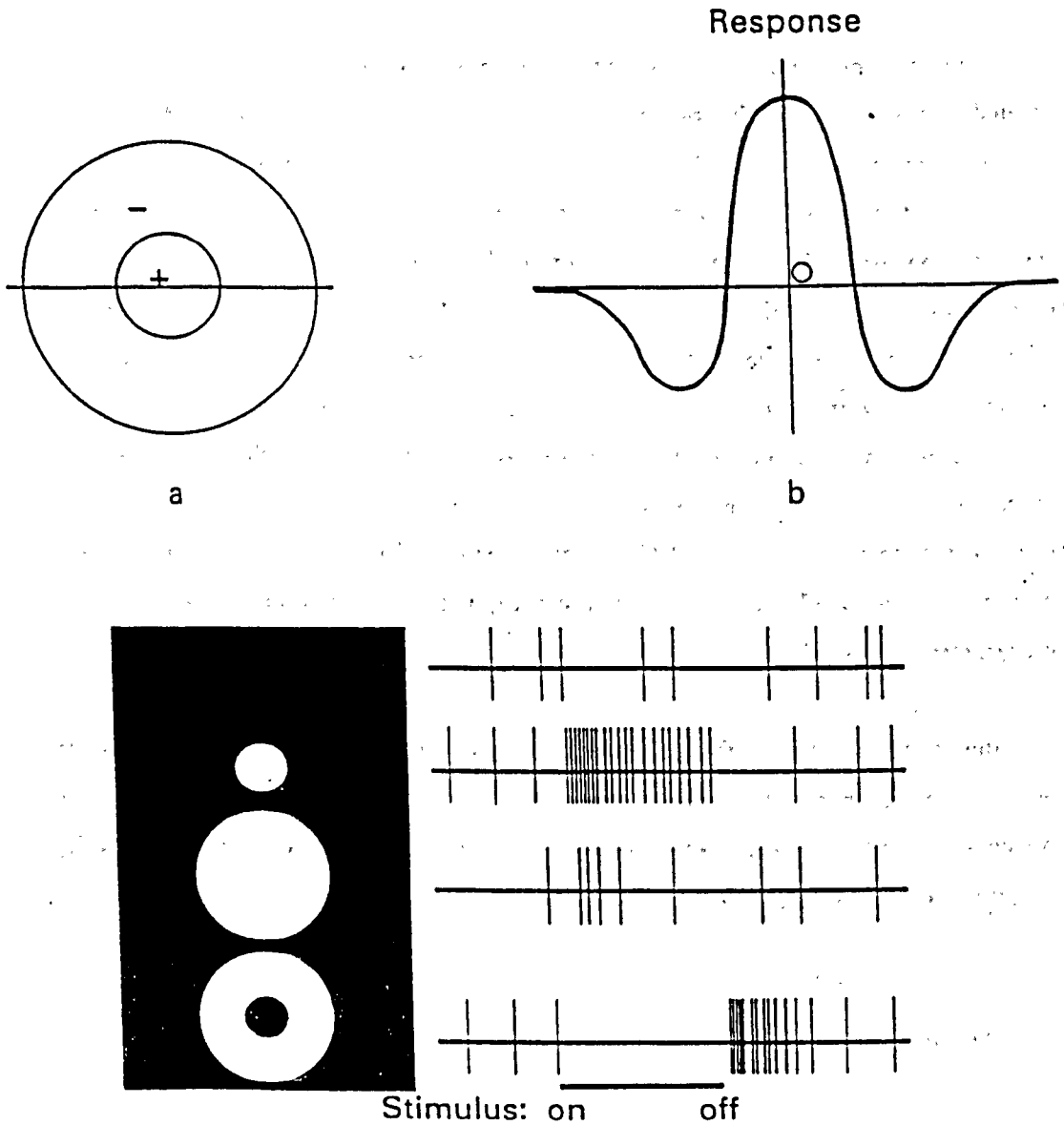
Figure 6.5 Figure showing the form and output characteristics of retinal based receptive fields. The 2-D form of an on-centre receptive field is shown at a. The 1-D response profile of the 2-D receptive field at a is shown at b.

The response of the receptive field to a range of different light stimuli is shown in c. In the null field, top row of c, the output is at its resting state. In the second row the excitatory centre of the cell is stimulated by a small spot of light and the output from the receptive field is markedly increased. If the whole of the receptive field is exposed to a uniform field of light the output returns to its resting state, shown in the third row. Finally, if an annulus of light is shone on the inhibitory surround the output is totally suppressed. There is a short increase in the output once the annulus is turned off.

6.5.3 Physiological Confirmation of the existence of DOG Filters

The characteristic of one dimensional DOG filters described above is also exhibited by two dimensional DOG filters (see Figure 6.5).

In the early 1950s Kuffler carried out investigations to establish the function of the retina (Kuffler, 1953)). He discovered that the one of the functional units of the retina was the receptive field. Each receptive field received its input from a large number of retinal photoreceptors. Also each photoreceptor, in general, input to more than one receptive field. The receptive field units were found by Kuffler to be the physiological implementation of two dimensional DOG filters. Since Kuffler carried out his investigations of the retina there have been many other studies carried out verifying the existence of DOG filters in the retina (Barlow, Hill and Levick, (1964); Micheal, (1973); Maturana, Lettvin, McCulloch and Pitts, (1960)).

Thus the basic element of information for the visual system is the luminance, or chromatic, edge. One method of assessing the visual information content of a scene using a computer image data file, and which correlates with basic visual processes, is to use a DOG type filter set and convolve the filter set with the image data. However, to establish the concept of correlating visual scene information content with the occurrence of discomfort glare, and other adverse subjective responses, it may be appropriate to use an alternative and simpler method.

6.6   The Image Data Recording Technology; CCD Imaging Photometers

To be able to test experimentally, and to develop in the first instance diagnostic, models for visual discomfort and to extend understanding of discomfort glare, it will be necessary to have a practical method for recording, storing and analysing image data. This can be achieved by using 'charge coupled device' (ccd) imaging technology. This technology can be used to simultaneously record image data from a large number of points in the visual field using arrays of light sensitive photo-diodes. The brightness levels recorded by each of the photodiodes can be read out to a computer data file for subsequent processing. By

modifying the internal workings of a suitable ccd camera it is possible to record absolute luminances using the ccd camera; the ccd becomes an imaging photometer if it is used in this way. Such a commercially available imaging photometer was used in the present study. The particular device can simultaneously record 262 144 image luminance values ie it has a pixel array 512x512.

The data recorded by the imaging photometer are stored as a two dimensional array of luminance values. This luminance data is in a form suitable for convolution with DOG filters discussed in section 6.5. The process of convolving the image data with the appropriate DOG filter set would produce the information distribution as required by the models for visual discomfort and discomfort glare.

There are however a number of technical problems that will need to be addressed in order use the ccd imaging photometer for recording the information distribution of visual scenes. These technical problems include:

* Scaling of the DOG filters.

* Deblurring of the image data file.

* Recording a representative field of view.

* Obtaining a representative range of spatial resolution in the recorded image.

Each of these problems is briefly discussed below.

6.6.1 Scaling of the DOG Filters

The information distribution that results from the convolution of the image data file with the DOG filter set should clearly be representative of the information seen by the human visual system. To be able to produce a representative information distribution the DOG

filter set should be scaled to the appropriate size relative to the image data file. A method for deciding the scaling factor for the DOG filters is required.

6.6.2 Blurring in the Image Data File

The human visual system is able to constantly adjust its range of focus so that the information in the visual scene that is if most interest is in best focus. It is unusual to find camera technology with the facility to dynamically adjust its point of focus in real time. The imaging photometer does not have dynamic focusing adjustment. This means that for any particular image that is recorded by the imaging photometer there will be zones in the image in front and behind the best plane of focus that are blurred.

Blurred image data is undesirable because it is not truly representative of the information that is present in the visual field as seen by the visual system. Investigations should be carried out to find a practical solution to deblurring the image data file, without corrupting the information content of the image. Ideally deblurring will reconstruct the missing information in the blurred parts of the image, which is a problem which may be suited to the application of Fourier techniques. Alternatively, and more simply, it may be more pragmatic to accept the blurring that exists in the image data.

6.6.3 The Field of View

The human visual system has an field of view that covers a very large proportion of 2π steradians. Ideally the image data file should cover the same visual field. This is possible with some photographic lenses, however such lenses create gross distortions in the image data; this can easily be seen in photographs taken with a fish-eye lens. To be able to collect data from 2π steradians without distortion it will be necessary to take a patch work of images. A method should be found for marrying the image patches so that there is a continuous image across the visual field, and for eliminating redundant information in the image, which will occur where there are overlaps in the image patches. Alternatively it may be acceptable to regard the image frame to be a large enough area of the field of view to be representative of the whole visual field of view, which will be true for a large number of images.

6.6.4 Range of Resolution; Depth of Field vs Spatial Resolution

Associated with the problem of deblurring is that of selecting an appropriate aperture and focal length combination on the lens used with the imaging photometer. The selection of a compromise aperture and focal length combination is required because of the conflict between the requirement for a wide depth of field with the requirement for a high resolution. This conflict is a fundamental limitation imposed by physical optics, and is common to all optical systems.

Selection of a suitable combination of settings of aperture and focal length will be best made by a process of trial and error experiments. A test chart comprising of a sequence of resolution targets should be used to decide whether the required resolution range has been achieved. To test if the depth of field for the required resolution range is suitable the test chart should be moved towards and away from the lens, noting the points at which the resolution falls below acceptable limits. This will define the depth of field for the particular combination of aperture and focal length settings.

6.6.5 The Solution of the Technical Problems

The technical problems discussed in sections 6.6.1 - 6.6.4 are practical problems that will need to be addressed before using the imaging photometer either for the present application, or for other applications where the imaging photometer will be used to capture an image that is taken as representative of the luminance image seen by the human visual system. Most, if not all, of the problems are thought to have a solution. The most practical solution for the present study was to accept the system with its limitations.

6.7 An Experimental Programme to test the Experimental Hypotheses

The imaging photometer provides the means of recording the image data required for processing to assess the information content of the visual scene. The image data would ideally be convolved with an appropriate filter set, such as the DOG filter set. The convolution would allow the objective measurement of the information content of the

visual scene. The instrumentation and convolution process supply the technology which can be used to carry out an experimental programme.

The models for visual discomfort and discomfort glare discussed in sections 6.2 and 6.4 above present two experimental hypotheses:

i. The visual system expects to see an inverse log-linear relationship between information and spatial scale in the visual scene; there should be relatively little large scale and a large amount of small scale, high resolution, information in the visual scene. Significant deviations from the log-linear relationship will produce an increase in the likelihood of complaints about visual discomfort associated with luminance pattern in the visual environment. This will be particularly true if the excess information occurs at moderate to high contrasts in the spatial frequency range 2-8 cpd.

The relationship between information and spatial scale is called a 'power spectrum', and in this instance is defined for spatial scale.

ii. The visual system expects to see a cumulative contrast distribution in the visual scene; this distribution is a cumulative Gaussian and is most likely matched by the response of the contrast detection mechanism of the human visual system.

If the information content of the contrasts in the visual scene, taken across a range of spatial scales including the range 2-8 cpd, departs significantly from that the visual system would see in natural scenes then there is likely to be an increase in the likelihood of complaints about visual discomfort caused by luminance contrast, and will act in addition to the known mechanisms of discomfort glare.

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What is required to test both of these hypotheses is a method for assessing the contrast information content and spatial power spectra, and more generally information content, for synthetic and natural environments. The measurement of these parameters will allow statistical comparison between the two classes of scene type, natural and synthetic, to establish whether there are objective differences. It should also be possible to correlate these objective scene metrics with subjective data to explicitly test hypotheses i. and ii.

6.7.1 The Measurement of Scene Information Content

The contrast information content and spatial power spectrum of a visual scene are important parameters in defining the information content in the scene. These parameters must ultimately be related to the information capacity of the visual system, and hypotheses i. and ii. are actually testing the nature of the relationship between scene information content and visual system information capacity. Laughlin (Laughlin, (1992)) has proposed an analytical function which provides a definition of information capacity:

$$Information\ capacity = H = 4\int_0^{v_s} v\ \ln\ [1+(\sigma_s^2(v)/\sigma_n^2(v))]\ dv \qquad 1$$

$$Where:\quad \sigma_s^2(v)/\sigma_n^2(v) = \frac{C^2 P^2(v)\ v_s^2\ N\ M_l^2(v)\ M_r^2(v)}{2k^2} \qquad 2$$

Where:

C	=	The mean contrast content of the scene	
$P(v)$	=	Spatial power spectrum of the scene	
k	=	Constant used to normalise the power spectrum	
N	=	Photoreceptor response of the eye	
$M_l(v)$	=	Modulation transfer function of the eye lens imaging system	
$M_r(v)$	=	Modulation transfer function of the imaging part of the photoreceptor mosaic	

This function provides a possible path forward to explicitly testing the hypotheses i. and ii. above. It will first be necessary to establish that the parameters k, N, $M_l(v)$, and $M_r(v)$ can be suitably defined for the present application. Preliminary investigations indicate that this should be possible. Assuming that the values of these parameters can be found the process of testing hypotheses i. and ii. is a straight forward task, relying ultimately on simple

statistical tests.

The parameter C is a measure of the global contrast information content of a scene, and P(v) is the spatial power spectrum. By converting the imaging photometer image data files to single row arrays of luminance values it should be possible to measure both of these parameters by using one dimensional filters. The value of C could be measured by using an appropriately scaled set of one dimensional DOG filters, and P(v) by using one dimensional Fast Fourier Transforms (FFT). Both of these processes are well established mathematical techniques. The measurement of these parameters will allow the calculation of information capacity H using equations 1 and 2 above.

6.7.1.1   The Spatial Amplitude Spectrum as a First Order Approximation of H

The measurement of H would potentially provide the most comprehensive measurement of scene information content. However, evaluation of H's parameters is difficult in practice. More fundamentally for present requirements there are no established results against which to make a comparison. For these reasons it was decided that it would be more appropriate to use the Fourier amplitude spectra from scenes as a first order approximation to information content, as estimated by H.

Implicit information about the contrast distribution in the image is retained using the amplitude spectra, as this is contained within the Fourier amplitude spectra.

6.7.2   The Experimental Data

6.7.2.1   Measurement of Scene Information Content in Practice

The assessment of differences in information content between natural and synthetic environments using the methods described in 6.7.1.1 was carried out as follows.

The imaging photometer was used to collect images from synthetic environments. For each of the images the amplitude spectrum was calculated. The mean and variance of the slope

of the amplitude spectra across were calculated.

A number of authors have reported studies where the gradient of the amplitude spectra for natural scenes, plotted on a log-log scale, has been found to be very close to 1 (Burton and Moorhead, (1987); Tolhurst, Tadmor and Tang Chao, (1992)). The study reported by Burton et al used a Hanning filter to correct for the finite image size. The present study adopted this practice. Thus, for the purpose of comparing gradients from natural and synthetic scenes the value of the natural scene gradient from Burton and Moorhead (Burton and Moorhead, (1987)) was used. Their value obtained by averaging the gradient across image columns and rows, and was reported as 1.05. A value very close to (1/f) scaling.

The assessment of whether natural and synthetic environments have different information contents resolved down to carrying out a statistical comparison between the mean values of the amplitude spectra gradients for natural and synthetic scenes, for example by using a Student t test.

6.8 Comparison of the Image Structure of Natural and Synthetic Scenes by Use of Fourier Amplitude Gradients

6.81 Introduction

The null hypothesis to be tested in this part of the programme of work was:

H_0: there is no difference in the visual structure of synthetic environments and natural environments.

As described in section 6.7.2.1, this hypothesis was to be tested by comparing the Fourier amplitude spectra gradients of synthetic and natural scenes. The Fourier amplitude spectra would be calculated using luminance only. The gradients for synthetic environments would be compared with the value reported by Burton and Moorhead (Burton and Moorhead, (1987)), as this study applied the Hanning window to the images collected during the investigation, so correcting for the finite size of the image. This process removing the bias

in the gradient caused by the high leverage dc and first harmonic components, because of the finite size of the image. The averaged gradient of the vertical and horizontal gradients reported by Burton et al for luminance was 1.05.

6.8.2   Experimental Hardware

6.8.2.1   The CCD Imaging Photometer System

The system used to collect the image data was the CCD imaging photometer system described in section 6.6, and supplied by National Research Council Canada, Institute for Research in Construction. This system comprised:

* CCD camera with a 512x512 pixel array;

* zoom lens (12.5 - 75 mm focal length, F 1.2 - 22 aperture range);

* V(λ) filter mounted on lens;

* proprietary image processing board (PC Vision Plus);

* IBM PC compatible computer;

* controlling software to provide absolutely calibrated luminance images from the camera.

6.8.2.2   Image Specification

The camera image was defined by the luminance map captured by the 512x512 array. Each pixel element supplied an 8-bit grey level representation of an absolutely calibrated luminance. The spatial resolution of an image was constrained by the particular zoom and aperture setting combination. The limitations of the imaging system are discussed in sections **6.6.1 - 6.6.4** above.

6.9 The Office Installation Sample and Method of Data Collection

6.9.1 The Office Installations

The synthetic visual environment set comprised a random selection of different types of office space. These included a variety of open plan and cellular installations, and came either from the commercial sector or were part of an academic institution. The experimental data were collected during late Autumn and Winter of 1993/94.

In practice it was not possible to select the offices used in the study. The offices included in the study were those that were made available by building owners or managers. The sample of offices finally used were not atypical of the range of contemporary office practice found in the UK.

6.9.2 Images of the Office Spaces

In general, for each installation four images were collected. If possible the four images were taken so that the optic axis of the camera system was oriented approximately along the four meridians of the compass ie North, South, East, West. The use of four, orthogonal images ensured that a representative image sample was collected from each office space.

In some instances it was not possible to collect four orthogonal images, in which case the closest approximation to this arrangement for image collection was used.

6.9.3 Lens Settings

Most of the images were collected during hours of darkness. This condition, together with the limitations imposed by the geometry of each space, constrained the lens settings that could be used to collect images of the office spaces. Many of the images were taken using the lower focal length zoom settings eg 12.5 mm, and a wide aperture setting eg F 1.2 or F 2. Table 6.1 gives the zoom focal length and aperture settings for each image.

Installation No	Focal length Setting (mm)	Aperture Setting (F No)
1	12.5	2.8
2	12.5	2.8
3	12.5	2.
4	12.5	2.8
5	20.	2.8
6	20.	2.
7	20.	2.
8	20.	2.
9	20.	2.
10	12.5	1.2
11	12.5	2.
12	20.	1.2
13	20.	2.8
14	20.	2.8
15	20.	2.8
16	20.	2.8
17	12.5	2.
18	12.5	2.
19	12.5	2.
20	12.5	2.
21	12.5	1.2
22	12.5	1.2
23	12.5	1.2
24	12.5	1.2
25	12.5	2.
26	12.5	2.
27	12.5	2.
28	12.5	2.
29	20.	2.
30	12.5	2.
31	12.5	2.
32	12.5	2.
33	12.5	2.
34	12.5	2.
35	12.5	2.
36	12.5	2.

Table 6.1   Table showing zoom focal length and aperture setting for each installation included in the study

6.10   The Method of Analysis

6.10.1   Re-scaling of the Image

Before the images were subjected to Fourier analysis they were processed to ensure that they were equally scaled in the vertical and horizontal directions. The re-scaling was necessary because the CCD camera had a 2/3" image format, imposing unequal spatial scaling along the horizontal and vertical axes of the images.

6.10.2   The Fourier Analysis

After correction for the finite size of the images using a Hanning window, two orthogonal (vertical and horizontal) one dimensional Fourier analyses were carried out on each of the images. This resulted in two sets of amplitude spectra, horizontal and vertical spectra. To remove any residual bias in the gradient of the spectra caused by the finite size of the image, the dc and first harmonic components were removed, and the gradient of spectra calculated from the remaining points.

Consistent with the previous reports relevant to the present study (Burton and Moorhead, (1987); Tolhurst, Tadmor and Tang Chao, (1992)), the Fourier components were calculated using cycles per picture width as the spatial scale. The use of this relative spatial scale allowed comparison of results across studies.

The data were plotted on a log-log grid. The gradient of the Fourier amplitude spectra were obtained by fitting a linear regression lines to the data for each image, where the Fourier amplitude components were plotted against cycles per picture width. Only the positive valued components were used in the analysis.

Log (Cycles/ Picture width)
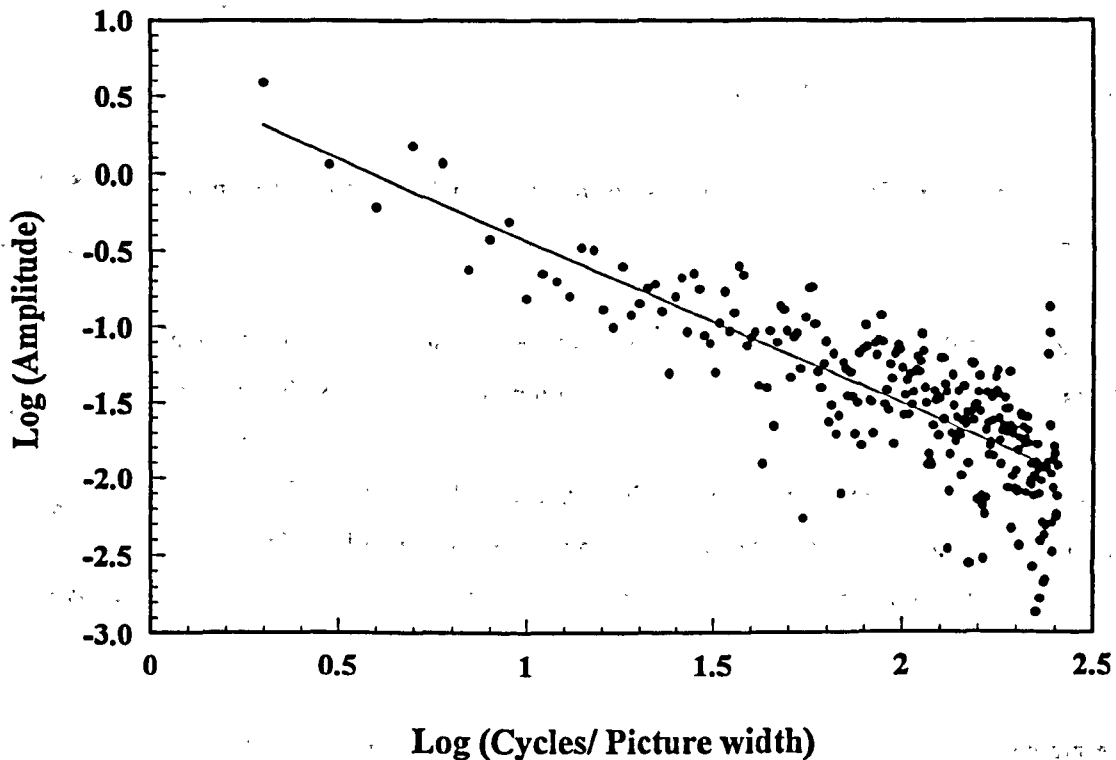
Figure 6.6   An example of the output from the Fourier analysis

Regression Statistics	
R^2	0.6467
Adjusted R^2	0.6453
Standard Error	0.3168
Observations	254

ANOVA

	df	SS	MS	F	Significance F
Regression	1	46.2864	46.2864	461.1985	7.35E-59
Residual	252	25.291	0.1004		
Total	253	71.5774			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.6324	0.101	6.2596	1.65E-09	0.4335	0.8314
X Variable 1	- 1.071	0.0499	- 21.4755	7.35E-59	- 1.1692	- 0.9728

Table 6.2   Regression statistics for the example FFT data and regression fit shown in Figure 6.6

6.11 Results of the Analysis

6.11.1 The Analysis Output

The statistics for the data were derived using the individual values of gradient obtained for each image.

An example of the analysis output is given in Table 6.2 and Figure 6.6. The analysis outputs were all similar to this, and given the volume of output only this example is given.

The value of the gradient is given under the heading 'X Variable 1'. The values of the gradients were collected for all horizontal output tables, and similarly for all vertical output tables. Summary statistics for the horizontal, vertical and overall gradients are given in Table 6.3.

The gradient given by Burton and Moorhead (Burton and Moorhead, (1987)) for luminance was averaged across vertical and horizontal Fourier components. This averaged value of 1.05 was used for comparison with the averaged horizontal and vertical gradients from the present data.

6.11.2 The Vertical and Horizontal Fourier Results

6.11.2.1 The Average Horizontal Gradient

The average of the horizontal gradients has a value of -1.09, and an estimated population standard deviation of 0.17. The 95% confidence range on this average has a minimum value of -1.14, and a maximum value of -1.03. Changing the confidence interval to 99% the range now has a maximum value of -1.01, and a minimum of -1.16. The average value, and the ranges all sit very close to the 1/f gradient of -1.0. Both of the confidence ranges include the value of Burton et al of -1.05.

	Mean	Population std dev	± 95% range	± 99% range
Horizontal gradient	-1.0857	0.1713	-1.1417 / -1.0297	-1.1592 / -1.0122
Vertical gradient	-1.1779	0.1193	-1.2169 / -1.1389	-1.2291 / -1.1267
Overall gradient	-1.1318	0.2087	-1.1800 / -1.0836	-1.1952 / -1.0684

Table 6.3 Table giving mean values and confidence ranges for horizontal, vertical and overall Fourier amplitude spectra gradients for the office sample used in the study.

6.11.2.2   The Average Vertical Gradient

The average of the vertical gradients has a value of -1.18, and an estimated population standard deviation of 0.12. The 95% confidence range on this average has a minimum value of -1.22, and a maximum value of -1.14. Changing the confidence interval to 99% the range now has a maximum value of -1.13, and a minimum of -1.23. The vertical gradients have an average and range that has departed slightly from the 1/f distribution, and there is a statistically significant difference between the horizontal and vertical Fourier component average gradients.

6.11.2.3   The Overall Gradient Statistics

The overall gradient average was -1.13, with a population standard deviation of 0.21. The 95% confidence range had a minimum value of -1.18, and a maximum value of -1.08. The 99% confidence range had a minimum of -1.20, and a maximum of -1.07.

There is a small but statistically significant difference between the overall value of the gradient found for the present data, compared to the value reported by Burton and Moorhead.

6.12   Interpretation of the Results

As there is a statistically significant difference between the average amplitude spectrum gradient measured for the office sample used in this study and the gradient reported by Burton and Moorhead for natural scenes, the null hypothesis is refuted. There are differences in the visual structure of synthetic and natural scenes. However, the magnitude of the difference is small.

6.12.1   The Overall Gradient

The result that the overall averaged amplitude spectra for synthetic scenes is significantly different to that for natural scenes is intuitively plausible. Subjective comparison of, say, a

woodland scene with that of a typical commercial office interior would lead to the expectation that their image structures would be different. The results from the office sample used in the present study show that this intuitive expectation is correct.

It is, however, surprising that the measured difference is not much greater. Laughlin has stated (personal communication) that he considers that unless Fourier amplitude gradients for given image set are substantially less than -1 eg gradient values less than -2, then the values can be regarded as being -1 for all practical purposes. There is clearly a need to carry out further measurements to synthetic environments to improve the reliability of the measurements reported here.

6.12.1.1   Implications for the Understanding of Visual Discomfort in Synthetic Environments

Given that the amplitude spectra gradients for natural and synthetic scenes are different it is possible to propose that the visual structure of synthetic environments eg interior office environments, may contribute to visual discomfort. This effect may be included in the phenomenon of discomfort glare. Apart from luminance and light scatter effects, the spatial arrangement of luminance patterns and interior decoration of an interior space may influence subjective responses. This has to some extent been confirmed by work carried out by Shepherd, Julian and Purcell (Shepherd, Julian and Purcell, (1988)) investigating subjectively reported 'gloom'.

In the synthetic environment the visual system processes information distributions which it had not evolved to 'expect'. This might lead to saturation, or possibly under-loading, of the image processing channels in the visual system. This skewed processing by the visual channels leading ultimately to the subjective sensation of visual discomfort.

Anecdotally this argument is supported by the experience of walking into a large integrating sphere, where the only visual signal is a completely uniform luminance field, covering a visual field of 2π. The sensation on entering the sphere is one of disorientation. The sensation is similar to that reported by military pilots flying fighter type aircraft in

cloudless skies where there are no reference points to provide a orientation cues.

The integrating sphere represents one extreme of information distribution. At the other extreme are the types of spatial pattern used by Wilkins et al (Wilkins, Nimmo-Smith et al, (1984)) in their study of the neurological causes of visual discomfort. They presented sinusoidal gratings of different spatial frequencies to subjects, and asked them to rate the subjective appearance of the gratings. The results of this study showed that the subjects found spatial gratings with spatial frequencies in the range 2-4 cpd to be the most unpleasant. The visual system is most sensitive to spatial frequencies in the range 2-8 cpd. So the result could be interpreted to mean that visual overloading occurs when presented with large areas of periodic pattern, a type of luminance distribution that would produce an extreme value of amplitude gradient.

If, on average, synthetic environments have different gradients, then the visual system might be partially overloaded, leaving it susceptible to overloading, or the under-loading effect such as experienced in the integrating sphere. What has been established here is that there is a small but significant difference in the gradient for synthetic scenes. What now needs to be established is if differences in gradient correlate with subjective responses.

6.12.1.2   Variation in the Gradients

There is a significant amount of variance in the gradients over the range of offices measured in the present study. There is now the possibility of pursuing further the investigation of the correlation between amplitude gradients and subjective responses. What needs to be carried out is a study that assesses the subjective ratings for a range of interior spaces, while simultaneously recording images of the same spaces. The objective of the study being to correlate subjective responses with individually determined amplitude gradients.

Based on the arguments developed in this dissertation, such a study has been initiated and preliminary results reported. These show that there is a statistically significant correlation between subjective ratings and Fourier amplitude spectra gradients. However, more detailed analysis needs to be completed before any firm conclusions can be drawn about these preliminary findings.

Chapter 7 Main Findings and Conclusions, and Recommendations for Further Work

7.1 Introduction

The purpose of this chapter is draw together the main findings and conclusions of the dissertation, and to provide recommendations for further work that might be carried out.

7.2 Conclusions to the Re-investigation of the Causal Links Between Light Scatter and Discomfort Glare

One of the principal findings from the results of this investigation is that there is a very significant effect of age on Log (BCD). This result is independently supported by the correlation between Log (BCD) and C_{th} (no glare), as C_{th} (no glare) was also correlated with age. So, an increase in glare sensitivity, as measured by the decrease in Log(BCD), is correlated with an increase in C_{th} (no glare).

This result led to the conclusion that there is a causal link between subjective assessment of discomfort glare and light scatter. This conclusion substantially weakens the distinction made by Stiles between discomfort and disability glare. Although there is much variance in the data there is clear evidence in the present results to link subjective discomfort glare ratings to light scatter effects using the stray light function of Ipsjeert et al. That there is very substantial variance in the data does not weaken the argument, as the variance is typical of that found in ergonomics experiments, including glare experiments.

This conclusion has led the proposal for a new, simpler model of discomfort glare. The model uses the function fitted to the Log (BCD) luminance vs age data as a threshold of discomfort glare. Any luminance difference in the designed luminous environment falling below the threshold is, in general, unlikely to give rise to complaints about discomfort glare. While luminance differences above the threshold have an increased probability of causing complaints about discomfort glare.

Another significant conclusion from the study is that age is a significant parameter influencing discomfort glare assessment. Most if not all of the principally used models of discomfort glare do not explicitly include age as a parameter.

7.3   Secondary Results from the Study

7.3.1   Selection of Fitted Function

Although a very obvious point, the discussion of the analysis went into some detail about the arbitrary nature of selecting a function to fit data, particularly human factors data, where there is no *a priori* procedure for selecting any one function. However obvious the point can often be overlooked when modelling data.

If there is no *a priori* procedure or reason for selecting one function or another then the simplest model that fits the data and satisfies the empirical requirements of the models application is probably the best model.

This argument does not negate the validity of the stray light function fitted to the present data. One of the main conclusions to the investigation of causal links between light scatter and discomfort glare was that there was an association, and this justifies the fitting of the stray light function to the data.

7.3.2   The BCD as a Scale for Discomfort Glare

The use of BCD, initially reported by Lukiesh and Guth (Lukiesh and Guth, (1949)), has been confirmed as a valid experimental measure of discomfort glare. The use of a threshold parameter of discomfort glare has led to the proposal for a simplified, single parameter model of discomfort glare.

7.3.3 The Use of Adaptive Probit Estimation in Subjective Threshold Experiments

The adaptive probit estimation (APE) (Watt and Andrews, (1981)) method was initially developed for use in measuring physiological thresholds eg C_{th}. The use of APE in the present experiment has extended the application of this technique into subjective rating experiments.

To be able to apply the technique, however, it is necessary to use a threshold criterion for the subjective rating. This was possible in the present study. But in each application the use, or development of an appropriate subjective threshold will need to be considered carefully to ensure valid application of the method.

7.4   Recommendations for Further Work on Discomfort Glare

Although the results reported here have established a statistically significant association between light scatter and subjective assessment of discomfort glare the study was necessarily carried out on a small sample of subjects. The results established here would benefit from further verification.

Ideally this would be carried out by establishing Log BCD for a range of subjects, and measuring the integrated forward scatter function for the same subjects. Correlation of Log BCD with the integrated forward scatter function would provide a fundamental test of the results reported here.

The new discomfort glare model proposed here has advantages over existing models of discomfort glare because it is much simpler to use, and explicitly includes age as a parameter. The possibility of implementing the model as a design tool for application in lighting design procedures should be followed up. The author is to initiate discussions with the Chairman of CIE Technical Committee 1.39: Discomfort Glare Experienced by Elderly People, about the potential application of the model proposed here.

However, the validity of the model to situations where there are multiple glare sources also needs to be established.

7.5 Alternative Explanations of Visual Discomfort

The inverted stray light function fitted to the Log (BCD) vs age, and to the Log (BCD) vs C_{th} data, had a statistically very significant fit. Despite this only about 42% of the total variance in the data was explained. This is not atypical for data sets recording subjectively rated discomfort glare. Two conclusions can be drawn from this:

i. There have been very many studies carried out investigating subjective settings of discomfort glare. In the main, the data recorded in these studies have large variances, and the models fitted to the data leave a large proportion of variance unexplained. It may be advantageous to pursue investigations designed specifically to fit multiple regression models to subjectively rated discomfort glare data in future studies.

ii. Accepting that there are other factors contributing to discomfort glare, or more generally visual discomfort, the second part of this dissertation carried out the first stage of a study to investigate the potential influence of scene visual structure on visual discomfort.

The investigation scene visual structure concluded that there is a small but statistically significant difference between natural and synthetic environments, as measured by averaged amplitude spectra gradients.

Given that the amplitude spectra gradients for natural and synthetic scenes are different it is possible to propose that the visual structure of synthetic environments eg interior office environments, may contribute to visual discomfort. This effect may be included in the phenomenon of discomfort glare. Apart from luminance and light scatter effects, the spatial arrangement of luminance patterns and interior decoration of an interior space may influence subjective responses. This has to some extent been confirmed by work carried out by Shepherd, Julian and Purcell (Shepherd, Julian and Purcell, (1988)) investigating subjectively reported 'gloom'.

7.6   Recommendations for Further Work on Visual Structure

In the data collected from offices in this study there is a significant amount of variance in the amplitude gradients. There is now the possibility of further pursuing the investigation of the correlation between amplitude gradients and subjective responses. What needs to be carried out is a study that assesses the subjective ratings for a range of interior spaces, while simultaneously recording images of the same spaces. The objective of the study being to correlate subjective responses with individually determined amplitude gradients.

Based directly on the arguments developed in this dissertation, the author initiated a collaborative study to assess the correlation between amplitude gradients and subjective ratings of interior office environments. Preliminary results indicate that there is a statistically significant correlation between subjective ratings and Fourier amplitude spectra gradients. However, more detailed analysis needs to be completed before any firm conclusions can be drawn about these preliminary findings.

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Appendix A

Overview of CIE TC 3.13 Technical Report:

Discomfort Glare in Interior Lighting

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A1.0 Introduction

The Technical Report is comprised four chapters and five appendices. The first chapter is by way of an introduction to the report, and includes some background information on both the committee and the development of the UGR system.

The second chapter discusses the Unified Glare Rating formula, and how this has been derived as a compromise formula from Einhorn's formula.

The main bulk of the report is contained in chapter 3, which discusses the calculation of UGR values by the tabulated method. The committee have adopted the view that this is likely to be the most commonly used method for calculating UGR values, and there is a corresponding amount of detail given to describing this method.

Chapter 4 gives a very brief description of how to use the graphical method to arrive at UGR values. There are substantial caveats attached to the use of the graphical method, which reflect the inaccuracies inherent in using the method.

The appendices to the report provide technical information on the derivation of UGR tables, directed principally at luminaire manufacturers who are likely to be the main source of UGR tables. Also the appendices describe technical information related to luminaires, and this information should be tabulated for UGR calculation purposes. Additionally, the appendices give case studies illustrating the use of the UGR system.

The remainder of this section reviews chapters 2,3 and 4, as it is these chapters which form the core of the report.

A2.0 Chapter 2: The Unified Glare Rating Formula

The CIE Glare Index formula is introduced at the start of the chapter. It is stated that is formula is the best mathematical compromise that could be achieved between the various

national glare models, which was Einhorn's remit, and has been discussed above; see section 2.5.5.2. The formula is repeated here for convenience.

$$CGI = 8Log2\frac{(1 + E_d/500)}{E_d + E_i} \sum \frac{L^2\omega}{p^2}$$

This formula is then simplified to the from:

$$Glare\ Rating = C_1 Log(C_2\ f_{room} \sum f_{luminaire})$$

Where: C_1 = a constant

C_2 = a constant

f_{room} = a factor related to the room and the background luminance

$f_{luminaire}$ = a factor related to the luminaires and their positions

The report states that the factor f_{room} includes terms which account for both direct and indirect illuminance at the eye. The indirect illuminance is taken as a measure of background luminance. It has not been practicable to include in the UGR system a method for estimating direct illuminance at the eye; it is argued that the exclusion of direct illuminance at the eye is of no practical significance in rooms with surface illuminances in the range recommended for interior environments. No justification is given for this statement.

The factor $f_{luminaire}$ has been adopted unmodified from CIE Publication N° 55.

Having stated the assumptions and constraints of the simplified formula, the UGR formula is given:

$$UGR = 8Log\ \frac{0.25}{L_b} \sum \frac{L^2\omega}{p^2}$$

Where: L_b = background luminance

L = luminance of the luminous parts of each of the luminaires

ω = the solid angle subtended by the luminous parts of each luminaire

p = the Guth Position Index for each luminaire

L_b is the indirect luminance at the eye of the observer, excluding glare source luminance, and is obtained from the relationship:

$$L_b = E_i/\pi$$

Where E_i is the indirect illuminance at the eye of the observer. This value can be obtained either by direct calculations, most probably obtained by use of computer, or from use of the indirect utilisation factor with distribution and transfer factors; the draft report refers to the method adopted in CIBSE Technical Memorandum N° 10 (CIBSE Technical Memorandum N ^{o} 10, (1985)).

For any one luminaire the UGR formula is constrained to a range of solid angles, ω, from 0.0003 steradians to 0.1 steradians.

The Position Index is obtained from tabulated data. It is possible to derive values for p directly from use of the Position Index equation as discussed above, although in most cases the tabulated data will be used.

Chapter 2 of the report states that the preferred method for calculating Unified Glare Ratings is by use of the formula. However this will in most instances be impractical where there is not access to computer software that carries out the calculation of UGR values from first principles. Therefore two alternative methods are offered which are:

-   By use of tabulated data for standard luminaire arrangements, very similar to the tabulated method used in CIBSE TM 10.

-   By use of the graphical method to obtain very approximate estimations of the UGR value. This method may be excluded from the final report.

A3.0 Chapter 3: The Unified Glare Rating Tables

It is likely that the most common method used for the calculation of UGR values will be the tabular method. That is unless software which can calculate UGR values from first principles becomes widely available. The tabular method described in the report closely resembles the method used in CIBSE TM N^O 10, with the obvious difference that the UGR tables should be used. Of course as the report is still in draft form there are no tables of UGR values available. .

The publication of UGR tables is entirely dependent on luminaire manufacturers adopting the UGR system. As many luminaire manufacturers are already producing glare data using one of the existing glare systems there may be some resistance to the change to the UGR system. Any proposed change will be subject to negotiation with luminaire manufacturers.

There are a number of different groups of environmental parameters that influence UGR values. These groups are:

- Properties of the luminaires
- Properties of the lighting installation
- Properties of the room
- Conditions of observation

The report deals with each of these in turn.

A3.1 Properties of the luminaires

To derive a UGR value for an installation for a particular line of sight the projected area of the luminous parts, as seen by the observer, must be known for each luminaire included in the calculation.

The luminance distribution data for a luminaire are normally obtained from tables of intensity distribution data provided by the luminaire manufacturers. Appendix C of the report provides technical details of the information that the luminaire manufacturer should provide about luminaires to allow UGR calculations to be carried out.

If the luminance distribution of the luminaire is approximately constant then an estimate of the projected area in a given direction can be obtained from:

$$A_p = I/L$$

Where: A_p = the projected area

I = intensity

L = luminance

The report recommends that the tables of UGR data are provided using a reference value of 1000 lumens, Φ_0, a reference luminous area, A_0, and a reference light output ratio, η_0. If the luminaire is used so that the reference values no longer apply the UGR values can be modified using correction factors, which allow for changes of:

-    The use of the luminaire with more, or less, lamps so changing the 'total bare lamp luminous flux'. In which case the correction factor

$$+ Log \frac{\Phi}{\Phi_0}$$

applies.

-    The use of a similar luminaire differing only in total luminous area, A. This change can be corrected by using the factor:

$$- Log \frac{A}{A_0}$$

- Changes in light output ratio, which are corrected for by applying the factor:

$$+ Log \frac{\eta}{\eta_0}$$

A3.2 Properties of the lighting Installation

The UGR tables will be produced for standard type lighting installations. This assumes:

i. That the room is rectangular in plan; room dimensions are specified in units of the mounting height, H, above the eye height of the observer eg width = 2H, length = 4H. The length and width of the room are denoted by x, y; see Figure A1.

ii. That the luminaires are uniformly spaced.

iii. That the nominal observer occupies one of two standard viewing positions in the room. These are the centres of two adjacent walls.

iv. The lines of sight at each of these viewing positions are parallel and perpendicular to the longitudinal and transverse axes of the luminaires. The lines of sight are denoted 'endwise' for longitudinal viewing and 'crosswise' for transverse viewing. UGR values are tabulated for each of the two viewing positions

v. That UGR values are independent of the mounting height of the luminaires.

dimension endwise

spacing

dimension
crosswise

H

viewed
endwise

spacing

viewed crosswise.
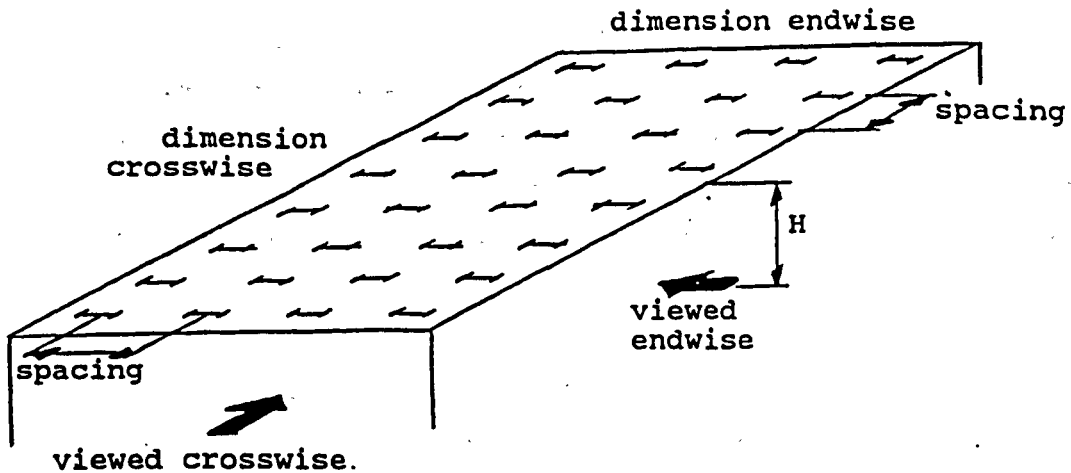
Conventional lighting installation with identical lumi-
naires mounted with uniform spacings in a horizontal
mounting plane.

Also indicated are two conventional observer positions,
at the middle of respective walls and normally at a
height of 1,2 m above the floor.

The luminaires are at a height H above the position of
the observer's eye.

The dimensions of the installation, in terms of the
height H, are normally related to the line of sight, by
x being perpendicular to, and y being parallel to the
line of sight. Thus:

viewed crosswise $\left\{ \begin{array}{l} x = dimension\ endwise \\ y = dimension\ crosswise \end{array} \right.$

viewed endwise $\left\{ \begin{array}{l} x = dimension\ crosswise \\ y = dimension\ endwise \end{array} \right.$

Figure A1

vi. The reference value of 1000 lumens per luminaire produces a working plane illuminance of 4000 lux.

With reference to item **ii**, the spacing is currently set at $0.25H_0$, where $H_0 = 2$ m. Thus the reference spacing $S_0 = 0.5$ m. The report states that this value of S_0 is convenient for the purposes of production of the tables. There is no fundamental constraint that sets this value of S_0, which is impractical because many types of luminaire could not be set at a uniform spacing of 0.5 m. The value of S_0 in the final report may differ from that in the current draft.

The report suggests that ultimately UGR tables will be produced in a few standard forms only, to cover a range of room dimensions and surface reflectances. Correction factors will be applied to the standard table values to modify the values to suit specific luminaires.

A3.3 Properties of the room

The role of the room, with reference to glare calculations, is to provide background luminance. In the, so called, comprehensive UGR tables a range of room surface reflectances are provided. The reflectances are given for ceiling cavity, floor cavity and wall surfaces between ceiling and floor cavities. Typical reflectances are:

* Ceiling cavity - 0.70, 0.50, 0.30

* Wall surfaces - 0.50, 0.30

* Floor cavity - 0.20

The floor cavity is the area of the room beneath the working plane which is assumed to the horizontal plane at a height of 0.85 m above the floor level.

The comprehensive UGR tables are used in the full form method of UGR calculation. The tables are produced to account for variations in background luminance, and these variations applied as a correction to, the UGR calculation.

There is also a short form of calculation, using reduced UGR tables. The reduced UGR tables do not contain any allowance for variations in background luminance, and so the correction has to be calculated. This requires an estimate of the background luminance.

The background luminance is estimated by correcting the reference value of background luminance, which is related to the reference luminaire flux, Φ_0 , (1000 lumens per luminaire) and the reference working plane illuminance (4000 lux). For these reference values the report states that it is convenient to assume a reference background luminance *of 127.32 cd m*$^{-2}$*. This corresponds to* 1 cd m^{-2} per 10π lux.

To determine an estimate of the particular background luminance for an installation a value is first obtained for the relative background luminance, L_R. This is calculated using the utilisation factor (total), UF_{total} and by the utilisation factor (direct), UF_{direct}, thus:

$$L_r = 6UF_{total} - 5UF_{direct}$$

In the comprehensive UGR tables L_R is applied to the tabulated UGR values. In the short form calculation method a further step is required to obtain a value for the background luminance correction. This is given by:

$$b_L = - 8 \, Log \, L_R$$

This is applied to the calculated value of UGR in the same way that the correction factors for Φ, A and η are applied. Figure A2 shows an example of the derivation of L_R.

REFLECTANCES									
ceiling/cavity	0,7	0,7	0,7	0,5	0,5	0,5	0,3	0,3	0
walls	0,5	0,3	0,1	0,5	0,3	0,1	0,3	0,1	0
working plane	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0

ROOM INDEX	UTILIZATION FACTORS IN PERCENT								
k = 0,60	34	29	26	33	29	25	28	25	24
0,80	42	37	34	41	37	34	36	33	32
1,00	48	44	40	47	43	40	42	39	38
1,25	53	49	46	52	48	45	47	44	43
1,50	57	53	50	55	52	49	51	48	46
2,00	62	58	55	*59*	57	54	55	53	*51*
2,50	65	62	59	62	60	58	58	56	54
3,00	67	64	62	64	62	60	60	59	56
4,00	69	67	65	67	65	63	63	61	58
5,00	71	69	67	68	67	65	64	63	60

                                ↑   ↑

utilization	utilization
factors for	factors for
actual re-	reflectances
flectances	of naught
(total illu-	(direct illu-
mination)	mination)

An example of an utilization factor table in a typical
lay-out. The room index is twice the working plane area
divided by the area of those parts of the walls between
the working plane and the mounting plane of the lumi-
naires.

The utilization factor for a certain case is indicated,
both for the total illumination and for the direct
illumination. These two can be used to derive the
relative background luminance by:

$$L_R = 6 \times UF(total) - 5 \times UF(direct)$$
$$= 6 \times 0,59 - 5 \times 0,51 = 0,99$$

Figure A2

A3.4 Conditions of observation

The standard viewing conditions, as discussed above, are normally assumed as this simplifies the production of the UGR tables.

This section of the report offers some justification for the small reference spacing, S_0. If luminaires are small and closely spaced then, the report argues, slight changes in observer position will produce minimal changes in the UGR value. If the spacings of the luminaires are changed then the reduction in UGR is offset by proportional changes in background luminance. By using a small value for S_0 an average UGR value is obtained, even if the installation is not practicable.

Once an average value of UGR is obtained it can then be used in the calculation of the maximum and minimum UGR values. The maximum and minimum values are found by moving the observers position in 0.25 H steps, noting the points at which the maximum differences occur. These differences define the range of variation likely to be found in an installation, and are applied to the calculated values of UGR to find the optimum observer position and the maximum likely UGR value. These variations are tabulated in both the comprehensive and reduced form UGR tables provided by the luminaire manufacturer.

The variations depend principally on the spacing of the luminaire and are tabulated in terms of H thus, 1H, 1.5H and 2H. The variations are tabulated for both endwise and crosswise viewing. There is little or no variation in UGR values with variation in room index values x and y.

A3.5 Use of the UGR Tables

This section of chapter 3 underlines the assumptions and constraints for which the tabular method is valid:

Uncorrected UGR values (at 1000 lm bare lamp luminous flux)										
Reflectances: ceiling/cavity walls working plane	0,70 0,50 0,20	0,70 0,30 0,20	0,50 0,50 0,20	0,50 0,30 0,20	0,30 0,30 0,20	0,70 0,50 0,20	0,70 0,30 0,20	0,50 0,50 0,20	0,50 0,30 0,20	0,30 0,30 0,20
Room dimensions x y	viewed crosswise					viewed endwise				
2H 2H	14,4	15,4	14,6	15,6	16,0	13,5	14,5	13,7	14,7	15,1
3H	14,3	15,3	14,6	15,5	15,8	13,3	14,3	13,6	14,5	14,8
4H	14,2	15,1	14,5	15,3	15,6	13,2	14,1	13,5	14,3	14,6
6H	14,0	14,8	14,4	15,1	15,4	13,0	13,8	13,4	14,1	14,4
8H	14,0	14,8	14,4	15,1	15,4	13,0	13,8	13,4	14,1	14,4
12H	14,0	14,8	14,3	15,0	15,4	13,0	13,8	13,3	14,0	14,4
4H 2H	14,4	15,3	14,7	15,5	15,8	13,6	14,5	13,9	14,7	15,0
3H	14,3	15,1	14,6	15,3	15,7	13,4	14,2	13,7	14,4	14,8
4H	14,1	15,0	14,5	15,2	15,7	13,2	14,1	13,6	14,3	14,8
6H	14,1	14,7	14,6	15,1	15,6	13,2	13,8	13,7	14,2	14,7
8H	14,0	14,6	14,6	15,0	15,5	13,1	13,7	13,7	14,1	14,6
12H	14,0	14,6	14,6	15,0	15,5	13,1	13,7	13,7	14,1	14,6
8H 4H	14,0	14,6	14,6	15,0	15,5	13,1	13,7	13,7	14,1	14,6
6H	14,0	14,5	14,5	14,9	15,3	13,1	13,6	13,6	14,0	14,4
8H	13,9	14,3	14,4	14,7	15,3	13,0	13,4	13,5	13,8	14,4
12H	13,9	14,3	14,4	14,6	15,3	13,0	13,4	13,5	13,7	14,4
12H 4H	14,0	14,6	14,6	15,0	15,5	13,1	13,7	13,7	14,1	14,6
6H	13,9	14,3	14,4	14,7	15,3	13,0	13,4	13,5	13,8	14,4
8H	13,9	14,3	14,4	14,6	15,3	13,0	13,4	13,5	13,7	14,4

Variations with the observer position at spacings:

S = 1 H	+0,9/ -2,1	+0,8/ -1,5
1.5 H	+2,2/ -7,9	+2,6/-12,1
2 H	+4,0/-16,0	+4,0/-22,9

Corrections for other luminaires of the same type:
1 × 18 w : +2,4   1 × 36 w : 0   1 × 58 w : -0,8

Example of a comprehensive UGR table.

viewed		crosswise	endwise
Standard table:		BKO	BKO
Corrections for other luminaires of the same type:	1 × 18 w	-3,1	-4,0
	1 × 36 w	-5,5	-6,4
	1 × 58 w	-6,3	-7,2
Variations with the observer position at spacings:	S = 1 H	+0,9/ -2,1	+0,8/ -1,5
	1,5 H	+2,2/ -7,9	+2,6/-12,1
	2 H	+4,0/-16,0	+4,0/-22,9

Example of a reduced UGR table.

Figure A3

- It is only possible to tabulate UGR values for 'dissymmetric' [sic] luminaires; this is taken to mean UGR data will only be available for luminaires that have longitudinal and transverse symmetry.

- Tables of UGR values assume regular arrays of luminaires.

- The method applies only to rooms that are rectangular, to include square, in plan, and that can be characterised by three surface reflectances for the three major room surfaces ie ceiling cavity, floor cavity and wall surfaces between ceiling and floor cavities.

- The UGR values given apply to the two standard viewing conditions.

Figure A3 show the comprehensive and reduced forms of the UGR tables.

A3.6   The Comprehensive UGR Tables

The calculation of UGR using the comprehensive tables follows the standard form shown in Figure A4. Much of the form is self explanatory.

The mounting height, H, of the luminaires is obtained by subtracting the height above observer eye level (1.2 m seated, 1.7 m standing) from the floor to luminaire height. The width and length of the room are specified in terms of mounting height, H, to give x and y. Which dimension is x and which is y is dependent on the chosen viewing position ie endwise or crosswise. A value for each of the principal room surfaces is estimated.

Using this information a value of the uncorrected UGR is read from the tables for the luminaire type being used. The values for both crosswise and endwise viewing are entered into the second part of the UGR calculation form. The correction values for lamp type is read from the UGR table, and other corrections calculated ie correction for luminous flux.

A. Data for the room and the lighting installation			
mounting height above floor : 3,2 m -eye height : -1,2 m above eyes H : 2,0 m		reflectances ceiling/cavity : 0,5 walls : 0,5 working plane : 0,2	
room dimensions endwise : 8 m = 4 H = crosswise: 16 m = 8 H =		viewed crosswise x y	viewed endwise y x

B. UGR calculation			
uncorrected UGR :		14,6	13,7
corrections for luminaire : 36 W luminous flux Φ : 3250 lm 8×log(Φ/1000 lm)		0,0 4,1	
average UGR :		18,7	17,8
luminaire spacings: variation upwards :		2 m = 1 H 0,9	2 m = 1 H 0,8
maximum UGR :		19,6	18,6

Figure A4

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These corrections are entered into the table as shown. The corrections are added or subtracted, as appropriate, from the uncorrected UGR values to give a value for the average UGR.

The luminaire spacings are calculated as units of H and the upward variation read from the UGR table. This variation is added to the average to obtain an estimate of the likely maximum value of UGR for the installation; refer to Figure A4.

A3.7 The Reduced UGR Table

The calculation of UGR values using the short form tables follows the same procedure the calculation of UGR using the comprehensive tables, except that in place of defining room surface reflectances L_R is calculated and used to derive a value for b_L. An example of a calculation form used with the short form method is shown in Figure A5. The value of b_L is added to the uncorrected UGR values, after correction for lamp flux, to obtain an average value of UGR. The uncorrected values of UGR are obtained from standard tables such as shown in Figure A6. The variation for luminaire spacing is then added as before.

In the calculation of L_R the Room Index is required. The report states that this is calculated in any event in the design process and therefore details are not given.

A4.0 Chapter 4: Unified Glare Rating Curves

A4.1 Derivation of the luminance limit curves

The graphical method included in the report is based directly on the CIE Safeguard system, which is itself a direct derivative of the German Glare Limiting system. The luminance limit curves are plotted on graphs, shown in Figure A7. The axes of the graphs are:

A. Data for the room and the lighting installation			
mounting height above floor : 3,2 m -eye height : -1,2 m above eyes H : 2,0 m	utilization factors UF (total) : 6 x 0,59 UF (direct): - 5 x 0,51 L_R : 0,99		
room dimensions endwise : 8 m = 4 H = crosswise: 16 m = 8 H =	viewed crosswise x y		viewed endwise y x

B. UGR calculation			
standard tables : uncorrected UGR :		BK 0	BK 0
corrections for luminaire : 36 w		−5,5	−6,4
luminous flux Φ : 3250 lm 8×log(Φ/1000 lm)		4,1	
−8logL_R :		0,0	
average UGR :		18,6	17,7
luminaire spacings: variation upwards :		2 m = 1 H	2 m = 1 H
maximum UGR :		19,5	18,5

Example of an UGR calculation using data from the reduced UGR table.

In part A, the room is represented by utilization factors (instead of reflectances) and by means of these, a relative background luminance L_R is calculated.

In part B, the uncorrected glare indices are taken from standard tables, and a further correction for L_R is applied.

Figure A5

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BK00 ---- 20 in all positions -----

BK01

x	2	3	4	6	8	12
y 2	19,0	19,4	19,5	19,5	19,5	19,5
3	19,3	19,7	19,9	19,9	19,9	19,9
4	19,4	19,8	19,9	20,0	20,0	20,0
6	19,4	19,8	19,9	20,0	20,0	20,0
8	19,4	19,8	19,9	20,0	20,0	20,0
12	19,4	19,8	19,9	20,0	20,0	20,0

BK08

x	2	3	4	6	8	12
y 2	12,0	12,8	13,4	13,7	13,7	13,8
3	14,1	15,0	15,7	16,1	16,3	16,3
4	15,0	16,0	16,8	17,3	17,5	17,6
6	15,9	16,9	17,8	18,4	18,7	18,9
8	16,2	17,3	18,2	18,9	19,2	19,5
12	16,5	17,6	18,5	19,3	19,6	20,0

BK02

x	2	3	4	6	8	12
y 2	18,0	18,5	18,7	18,8	18,8	18,8
3	18,7	19,2	19,5	19,6	19,6	19,6
4	18,8	19,4	19,7	19,8	19,9	19,9
6	18,9	19,5	19,8	19,9	20,0	20,0
8	18,9	19,5	19,8	20,0	20,0	20,0
12	18,9	19,5	19,8	20,0	20,0	20,0

BK09

x	2	3	4	6	8	12
y 2	11,0	11,9	12,5	12,8	12,9	12,9
3	13,3	14,3	15,0	15,4	15,6	15,7
4	14,4	15,4	16,2	16,8	17,0	17,1
6	15,3	16,4	17,3	18,0	18,4	18,6
8	15,8	16,9	17,8	18,6	19,0	19,3
12	16,1	17,3	18,3	19,1	19,6	20,0

BK03

x	2	3	4	6	8	12
y 2	17,0	17,6	17,9	18,0	18,0	18,0
3	17,9	18,6	18,9	19,1	19,1	19,2
4	18,2	18,9	19,3	19,5	19,6	19,6
6	18,4	19,1	19,5	19,8	19,8	19,9
8	18,4	19,1	19,6	19,8	19,9	19,9
12	18,5	19,2	19,6	19,9	19,9	20,0

BK10

x	2	3	4	6	8	12
y 2	10,0	10,9	11,5	11,9	12,0	12,0
3	12,5	13,5	14,2	14,8	14,9	15,0
4	13,7	14,7	15,6	16,2	16,5	16,6
6	14,8	15,9	16,9	17,7	18,0	18,3
8	15,3	16,5	17,5	18,4	18,8	19,2
12	15,8	17,0	18,1	19,0	19,5	20,0

BK04

x	2	3	4	6	8	12
y 2	16,0	16,6	17,0	17,1	17,2	17,2
3	17,2	17,9	18,4	18,6	18,7	18,7
4	17,6	18,4	18,9	19,2	19,2	19,3
6	17,9	18,7	19,2	19,6	19,7	19,7
8	18,0	18,8	19,3	19,7	19,8	19,9
12	18,0	18,8	19,4	19,8	19,9	20,0

BK11

x	2	3	4	6	8	12
y 2	9,0	9,9	10,6	11,0	11,1	11,1
3	11,6	12,7	13,5	14,0	14,2	14,3
4	12,9	14,0	14,9	15,6	15,9	16,1
6	14,2	15,4	16,4	17,2	17,6	18,0
8	14,9	16,1	17,1	18,1	18,5	19,0
12	15,5	16,7	17,8	18,9	19,4	20,0

BK05

x	2	3	4	6	8	12
y 2	15,0	15,7	16,1	16,3	16,3	16,3
3	16,5	17,3	17,8	18,0	18,1	18,2
4	17,0	17,8	18,4	18,8	18,9	18,9
6	17,4	18,3	18,9	19,3	19,5	19,6
8	17,5	18,4	19,1	19,5	19,7	19,8
12	17,6	18,5	19,2	19,6	19,8	20,0

BK12

x	2	3	4	6	8	12
y 2	8,0	8,9	9,6	10,1	10,2	10,2
3	10,8	11,8	12,7	13,2	13,5	13,6
4	12,2	13,3	14,2	15,0	15,3	15,5
6	13,7	14,9	15,9	16,8	17,2	17,6
8	14,4	15,7	16,8	17,7	18,3	18,8
12	15,2	16,5	17,6	18,7	19,4	20,0

BK06

x	2	3	4	6	8	12
y 2	14,0	14,7	15,2	15,4	15,5	15,5
3	15,7	16,5	17,1	17,4	17,5	17,6
4	16,4	17,3	17,9	18,3	18,4	18,5
6	16,9	17,8	18,5	19,0	19,2	19,4
8	17,1	18,0	18,8	19,3	19,5	19,7
12	17,2	18,2	18,9	19,5	19,8	20,0

BKBF

x	2	3	4	6	8	12
y 2	11,9	13,0	13,6	14,1	14,3	14,4
3	13,4	14,7	15,4	16,1	16,5	16,7
4	14,0	15,4	16,2	17,1	17,5	17,9
6	14,4	15,9	16,8	17,9	18,4	19,0
8	14,6	16,0	17,0	18,1	18,8	19,5
12	14,7	16,2	17,1	18,4	19,1	20,0

BK07

x	2	3	4	6	8	12
y 2	13,0	13,8	14,3	14,6	14,6	14,6
3	14,9	15,8	16,4	16,8	16,9	17,0
4	15,7	16.7	17,4	17,8	18,0	18,1
6	16,4	17.4	18,2	18,7	19,0	19,1
8	16,6	17,7	18,5	19,1	19,4	19,6
12	16,8	17.9	18,7	19,4	19,7	20,0

BKFF

x	2	3	4	6	8	12
y 2	12,7	13,6	14,1	14,5	14,6	14,7
3	14,3	15,4	15,9	16,5	16,7	16,9
4	15,0	16,1	16,8	17,5	17,8	18,0
6	15,5	16,7	17,4	18,3	18,7	19,1
8	15,7	16,9	17,7	18,6	19,1	19,6
12	15,8	17,1	17,8	18,8	19,4	20,0

Standard tables of uncorrected UGR values.

Figure A6

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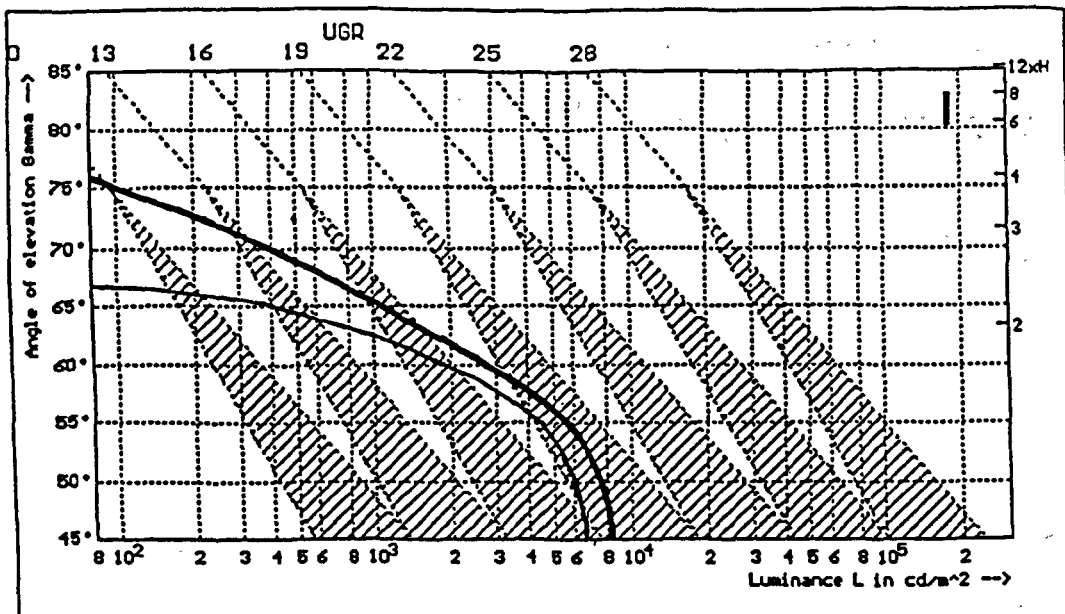
crosswise viewing: thick curve   endwise viewing: thin curve

a.   diagram I for cases of a typical background luminance with
      luminance traces of a luminaire indicated
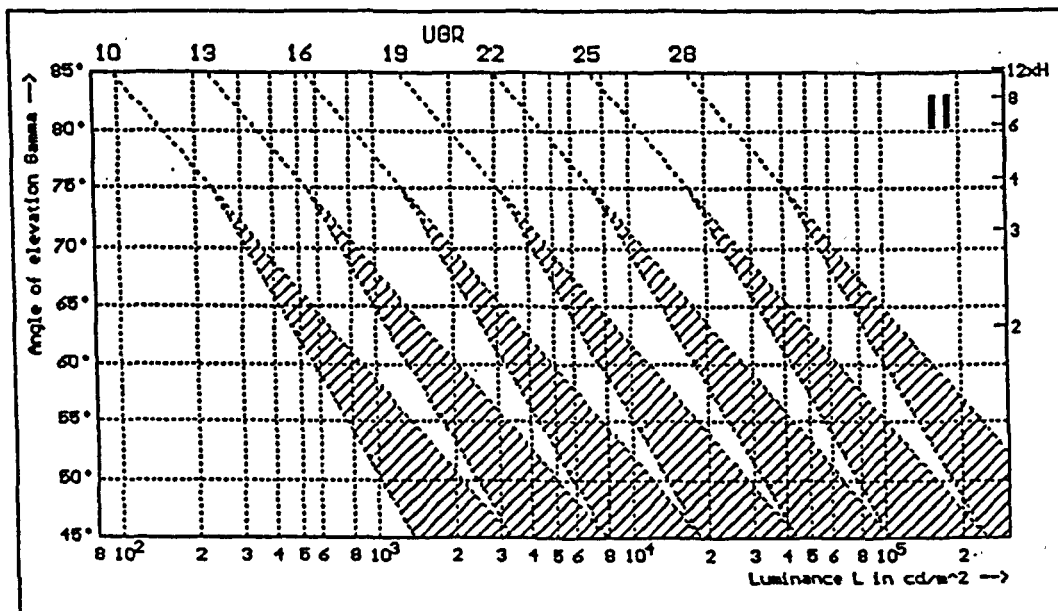
b.   diagram II for cases of a relatively high background lumi-
      nance

      Diagrams showing limiting luminance curves for UGR
      values of 10, 13, 16, 19, 22, 25 and 28. The curves aim
      at average UGR values. The shaded regions adjacent to
      the curves are to be avoided when the maximum UGR is to
      be restricted to the above-mentioned values.

      Figure A7

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- angle of elevation, or nadir

- logarithm of the luminance, taken to be the background luminance

There is also an axis scale plotted for H, the height of the luminaire above the observers eye level.

Plotted onto the graph are a series of lines, each of which represents the luminance limit for a particular UGR value over the range 10 - 28, in steps of three UGR glare units. This scale is consistent with the British Glare Index scale. On each glare limit curve, at the intersection with a nadir of 75°, a line is drawn to intersect the next lower glare limit curve at a nadir angle of 45°. The enclosed area bounded by the upper glare limit curve and its branch curve is shaded.

The UGR glare limiting system uses only two sets of curves, these are both shown in Figure A7. One set of curves, Figure A7a, is plotted for the reference background 127.32 cd m^{-2}. The second, Figure A7b, for a background luminance 2.37 times the reference background luminance, 301.75 cd m^{-2}.

Each set of curves is derived from an equation; the two equations are:

1. Reference luminance curves

$$LogL = \frac{(29 + UGR - 0.308\gamma)}{8}$$

2. 2.37 x reference luminance

$$LogL = \frac{(32 + UGR - 0.308\gamma)}{8}$$

Where: L = the limiting luminance; cd m^{-2}

γ = the angle of elevation, or nadir angle

The BZ luminaire classification scheme has been used in the derivation of the luminance limit curves.

A4.2   Use of the UGR curves

In use the lighting practitioner must select one of the two sets of curves, choosing that set which best matches the installation he is considering. Both sets of curves assume the following reflectances:

- ceiling cavity = 0.7
- wall surface = 0.5
- floor cavity = 0.2

The set shown in Figure A7a, denoted by I in the draft report, is for luminaires that give only small, if any, direct illumination to the walls or ceiling. Such luminaires are likely to have small nadir angles for cut-off of the light distribution.

The second set in Figure A7b, denoted by II in the draft report, is for luminaires with wide distributions and some upwardly directed light, providing reflected components of light from the walls or ceiling, or both.

There is considerable potential for error in the use of these curves. These include:

- Errors introduced by mismatch between the assumed luminaire type and the luminaire type that the designer wishes to use

- Errors caused by differences between the assumed background luminances for the curve sets and the background luminance of the installation

- Uncertainty about the precision of the limiting curves; for example it is possible for a luminaire trace that crosses a limiting curve to have a lower UGR value than a luminaire which has a trace contained entirely below the limiting curve.

The report attaches significant caveats to the use of the curves. It is strongly recommended that they are only used for the design of luminaires, and not in the design of lighting installations.

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Appendix B

Brief Discussion of Rayleigh Scattering

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In the discussion of the effects of light scatter on visual task visibility Rayleigh scattering has been assumed. There follows a brief discussion of Rayleigh scattering. A more detailed discussion of Rayleigh scattering in given in, for example, Jenkins and White (Jenkins and White, (1981)).

If light impinges on a small plane that has a minimum dimension that is comparable with the wavelength of the light then reflection and diffraction will occur. This is shown in Figure B1(a). The mechanics of the reflection and spreading of the light are similar to those for light passing through a single slit. Consistent with the diffraction at a single slit, the smaller the plane, the greater the spreading of the light at the edges of the plane.

When the maximum dimension of the reflector becomes much smaller than the wavelength of the light then the diffraction effect dominates, and the reflected waves become almost perfect spherical wavefronts, Figure B1(b). The law of reflection breaks down, and the scattering of the light becomes a special case of diffraction. The wavefronts scattered form the small particles are spherical, irrespective of the shape of the particle. The first quantitative studies of this phenomenon were carried out in 1871 by Rayleigh, and consequently this type of scattering is known as Rayleigh scattering.

Rayleigh scattering is dependent on wavelength of light, and the intensity of scattered light follows the relationship:

$$I_s = k \, \frac{1}{\lambda^4}$$

This relationship is plotted in Figure B2.

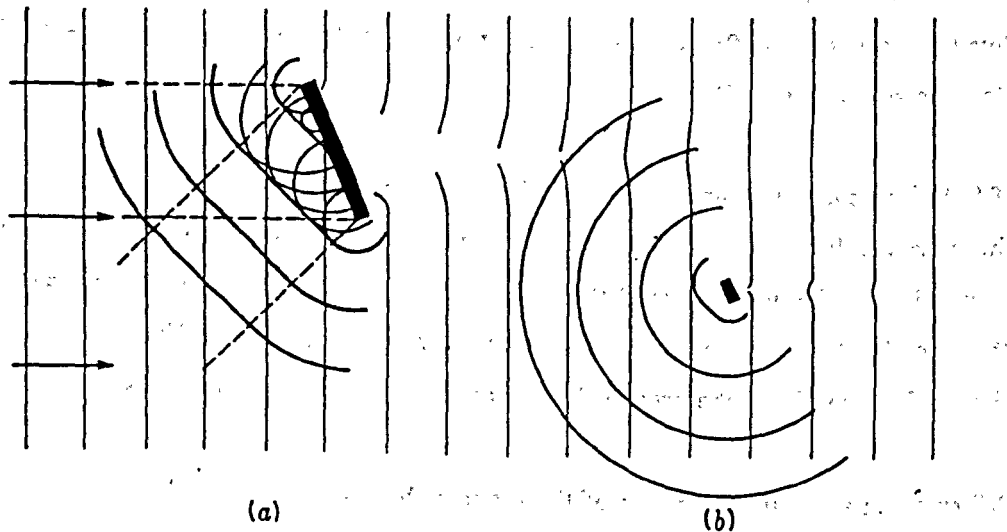**Figure B1**   The reflection and diffraction of light by small objects with dimensions comparable to (a), and much smaller than (b), the wavelength of light. [Source: Jenkins and White, (1981)]
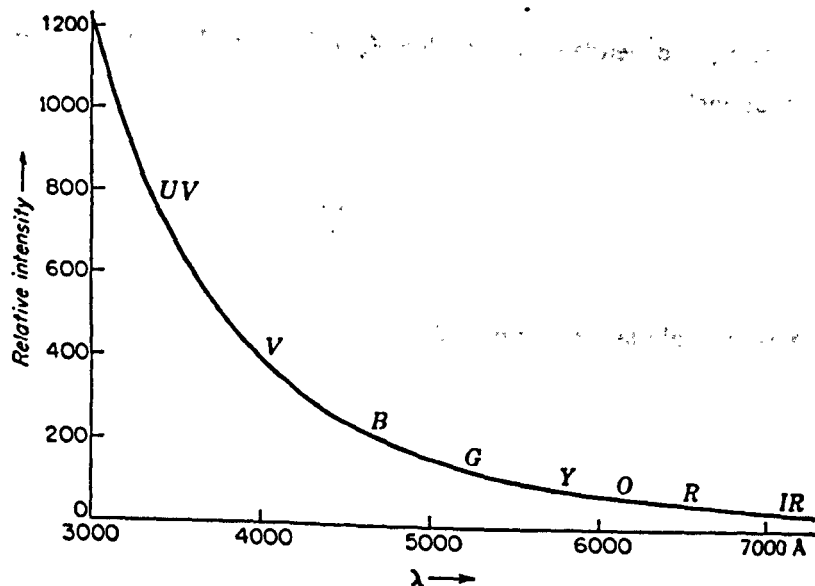
Figure B2   The relationship between intensity of scattered light, I_s, and wavelength of light, λ.

Appendix C

Calibration Data for Glare Source Lumiance and Image Synthesizer Contrast Module

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Table C.1 Calibration of Glare Source at 24 cd m^{-2}

Control Value	Luminance (cd m^{-2})	Mean Luminance	Standard Deviation
4500	16.70		
4500	16.80		
4500	16.30		
4500	16.30		
4500	16.40	16.50	.23
5000	17.60		
5000	17.80		
5000	17.00		
5000	17.10		
5000	17.30	17.36	.34
6000	2580.00		
6000	2560.00		
6000	2530.00		
6000	2490.00		
6000	2500.00	2532.00	38.34
7000	15700.00		
7000	15400.00		
7000	15700.00		
7000	15500.00		
7000	15300.00		178.89
8000	32700.00		
8000	32000.00		
8000	32600.00		
8000	32300.00		
8000	31700.00	32260.00	415.93
9000	47500.00		
9000	46300.00		
9000	47400.00		
9000	46900.00		
9000	45600.00	46740.00	795.61
9500	51700.00		
9500	50500.00		
9500	51500.00		
9500	50800.00		
9500	49600.00	50820.00	840.83
10000	51900.00		
10000	50800.00		
10000	51800.00		
10000	51100.00		
10000	50100.00	51140.00	743.64

Table C.2   Calibration of Glare Source at 10 cd m^{-2}

Control Value	Luminance (cd m^{-2})	Mean Luminance	Standard Deviation
4500	6.60		
4500	6.80		
4500	6.90		
4500	7.00		
4500	7.00	6.86	.17
5000	7.20		
5000	7.20		
5000	7.30		
5000	7.40		
5000	7.40	7.30	.10
6000	2270.00		
6000	2210.00		
6000	2140.00		
6000	2140.00		
6000	2100.00	2172.00	67.60
7000	15100.00		
7000	15000.00		
7000	15100.00		
7000	15000.00		
7000	14800.00		122.47
8000	32000.00		
8000	31600.00		
8000	31800.00		
8000	31900.00		
8000	31200.00	31700.00	316.23
9000	48000.00		
9000	46400.00		
9000	46700.00		
9000	46800.00		
9000	46200.00	46820.00	701.43
9500	52000.00		
9500	51100.00		
9500	51100.00		
9500	51400.00		
9500	50800.00	51280.00	454.97
10000	53300.00		
10000	51600.00		
10000	51500.00		
10000	51500.00		
10000	51400.00	51860.00	808.08

Table C.3 Calibration of CRT image synthesizer contrast module 1;
Background: 24 cd m^{-2}

Condition: No glare source, Neutral Density of filter = 0.3

Control Value	Lmax (cd m^{-2})	Lmin (cd m^{-2})	Michelson Contrast	Mean Contrast	Standard Deviation
1000	24.90	22.40	0.0529		
1000	25.00	22.40	0.0549		
1000	25.70	23.10	0.0533		
1000	25.80	23.10	0.0552		
1000	24.70	22.20	0.0533		
1000	24.70	22.10	0.0556	0.0542	0.0011
750	23.80	22.00	0.0393		
750	23.80	21.70	0.0462		
750	24.20	22.60	0.0342		
750	24.40	22.70	0.0361		
750	23.70	21.80	0.0418		
750	23.50	21.70	0.0398	0.0396	0.0047
500	23.70	22.00	0.0372		
500	23.60	22.00	0.0351		
500	24.20	23.00	0.0254		
500	24.20	23.10	0.0233		
500	23.30	22.20	0.0242		
500	22.90	22.30	0.0133	0.0264	0.0066
250	23.20	22.20	0.0220		
250	23.60	22.50	0.0239		
250	24.10	23.50	0.0126		
250	24.10	23.50	0.0126		
250	23.20	22.70	0.0109		
250	23.00	22.80	0.0044	0.0144	0.0061
100	23.10	22.50	0.0132		
100	23.20	22.20	0.0220		
100	23.90	23.60	0.0063		
100	24.00	23.80	0.0042		
100	23.10	23.10	0.0000		
100	22.80	22.70	0.0022	0.0080	0.0086
50	23.00	22.20	0.0177		
50	23.20	22.30	0.0198		
50	23.80	23.70	0.0021		
50	23.90	23.70	0.0042		
50	22.70	22.80	-0.0022		
50	22.70	22.80	-0.0022	0.0066	0.0098

Table C.4 Calibration of CRT image synthesizer contrast module 1;
Background: 10 cd m^{-2}

Condition: No glare source, Neutral Density of filter = 0.5

| Control Value	Lmax (cd m^{-2})	Lmin (cd m^{-2})	Michelson Contrast	Mean Contrast	Standard Deviation
1000	11.30	10.00	0.0610		
1000	11.10	9.90	0.0571		
1000	11.20	10.10	0.0516		
1000	11.30	10.10	0.0561		
1000	11.00	10.20	0.0377		
1000	11.00	10.20	0.0377	0.0502	0.0090
750	11.20	9.90	0.0616		
750	11.10	9.90	0.0571		
750	11.30	10.30	0.0463		
750	11.30	10.40	0.0415		
750	10.90	10.30	0.0283		
750	10.80	10.30	0.0237	0.0431	0.0132
500	11.00	10.10	0.0427		
500	11.00	10.10	0.0427		
500	11.10	10.60	0.0230		
500	11.20	10.60	0.0275		
500	10.70	10.60	0.0047		
500	10.70	10.50	0.0094	0.0250	0.0158
250	10.70	10.30	0.0190		
250	10.80	10.20	0.0286		
250	11.00	10.80	0.0092		
250	11.00	10.70	0.0138		
250	10.50	10.70	-0.0094		
250	10.50	10.70	-0.0094	0.0086	0.0141
100	10.70	10.30	0.0190		
100	10.80	10.20	0.0286		
100	10.90	10.90	0.0000		
100	10.80	10.90	-0.0046		
100	10.50	10.80	-0.0141		
100	10.50	10.80	-0.0141	0.0025	0.0175

Appendix D

Technical Specifications and Summaries for High Resolution CRT and Image Synthesizer

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Appendix D1

High Resolution CRT
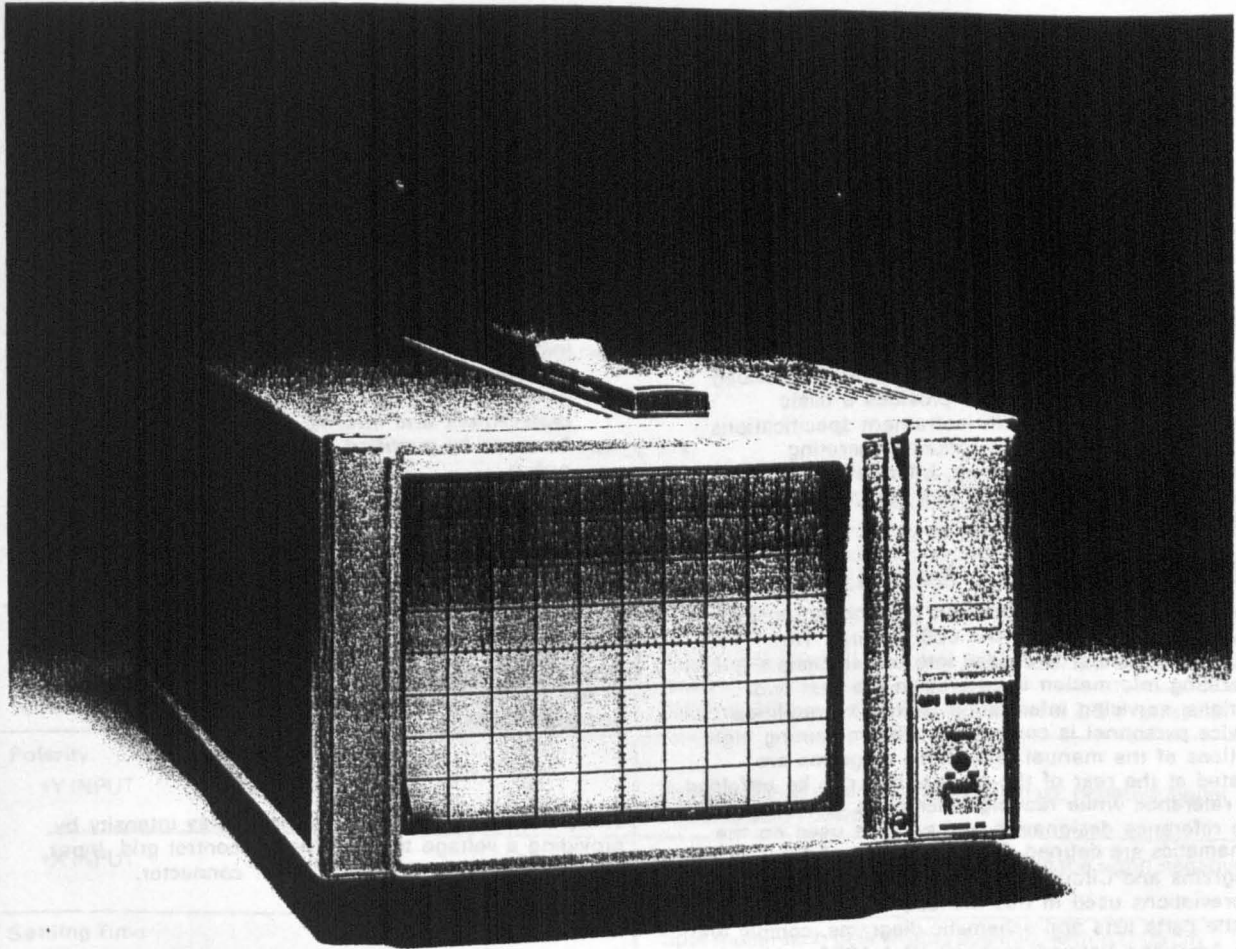
608 FEATURES

The 608 Monitor is a general purpose, high-brightness, high-resolution, X-Y display monitor providing a clear, bright, display of analog data on a large screen area. This instrument is designed for display applications as in ultrasonic detection systems, electron microscope systems, volume and vibration analysis, auger probes, and medical biophysical systems. The 608 Monitor may also be used to provide displays of alphanumeric and graphic information from computers and other data transmission systems. Resolution of the large screen crt (cathode-ray tube) in this instrument is excellent. (Monitor is shown with Option 23.)

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GENERAL INFORMATION

INTRODUCTION

OPERATORS MANUAL

The Operators Manual contains information necessary to effectively operate the 608 Monitor and is divided into three sections: Section 1 provides a basic description of the 608 with instrument specifications and accessories. Section 2 contains operating information for the instrument. Information on the options available for the 608 Monitor is located in section 3 of the manual.

INSTRUCTION MANUAL

The Instruction Manual provides both operating and servicing information for the 608 Monitor. The Instruction Manual is divided into ten sections. Operating information is covered in the first two sections; servicing information for use by qualified service personnel is contained in the remaining eight sections of the manual. Schematic diagrams are located at the rear of the manual and can be unfolded for reference while reading other parts of the manual. The reference designators and symbols used on the schematics are defined on the first page of the Diagrams and Circuit Board Illustrations section. All abbreviations used in this manual, with the exception of the parts lists and schematic diagrams, comply with the American National Institute Y1.1-1972 publication. The parts lists are computer printouts and use computer-supplied abbreviations. Information on the options available for the 608 Monitor is located in section 9 of the Instruction Manual.

INSTRUMENT DESCRIPTION

The 608 Monitor is a compact, solid-state instrument with excellent resolution, providing accurate displays of information from the X, Y, and Z signal inputs.

Vertical and horizontal signals to be displayed on the crt are supplied to the Deflection Amplifiers through the appropriate X and Y INPUT connectors. The Deflection Amplifiers process the input signals and provide push-pull outputs to drive the deflection plates of the crt. Both Deflection Amplifiers contain position and gain controls.

The Z-Axis Amplifier controls the display intensity by providing a voltage to drive the crt control grid. Input signals are applied to the Z INPUT connector.

The Dynamic Focus circuit provides focus correction for the display when the crt beam is deflected from the crt center. Thus, by varying the voltage to the crt focus element, the Dynamic Focus circuit compensates for geometric defocusing.

The High-Voltage and Low-Voltage Power Supplies provide all the voltages necessary for operation of this instrument.

SPECIFICATION

The electrical specifications listed in Table 1-1 apply when the following conditions are met: (1) The instrument must have been adjusted at an ambient temperature between -15° and +25° C (+59° and +77° F), (2) the instrument must be operating in an ambient temperature between 0° and +50° C (+32° and +122° F) and (3) the instrument must have been operating for at least 20 minutes.

NOTE

Electrical specifications for the available options are located in the Instrument Options section of this manual.

TABLE 1-1

Electrical Characteristics

Characteristic	Performance Requirement
VERTICAL AND HORIZONTAL AMPLIFIERS	
Deflection Factor	
Vertical (Y)	Adjustable from 0.5 V, or less, to at least 2.5 V full scale.
Horizontal (X)	Adjustable from 0.5 V, or less, to at least 2.5 V full scale.
Polarity	
+Y INPUT	Positive signal applied deflects beam up; negative signal deflects beam down.
+X INPUT	Positive signal applied deflects beam to the right; negative signal deflects beam to the left.
Settling Time	Spot must reach new writing position, within 0.05 cm (0.02 in), within 300 ns of deflection from any on-screen position.
Bandwidth (With 80% Full-Screen Reference Signal)	Dc to at least 5 MHz at -3 dB point.
Rise Time	70 ns or less.
Phase Difference (DC to 1.5 MHz)	1° or less between X and Y amplifiers. X and Y amplifier gain (V/div) must be set for the same deflection factor.
Position Stability	0.5 mm or less of drift per hour (after 20 minute warm-up).
Gain Stability	1% or less of drift (after 20 minute warm-up).
Displayed Noise (Tangentially Measured)	0.05 mm, or less, with all inputs terminated into 1 kΩ or less.
Input RC (Both Inputs)	1 MΩ, within 1%, paralleled by 60 pF or less.
Maximum Nondestructive Input Voltage (Fault Condition Only)	+100 V or -100 V (dc + peak ac).
Position Range (With Nc Input Signals Applied)	Front panel controls allow spot to be set anywhere within the viewing area.
Dynamic Range	At least 1.5 screen diameters from center screen.

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TABLE 1-2

Environmental Characteristics

Characteristic	Information

NOTE

This instrument will meet the electrical characteristics given in the Performance Requirement column of Table 1-1 over the following environmental limits.

Temperature	
Operating	0° to +50° C (+32° to +122° F).
Nonoperating	-40° to +70° C (-40° to +158° F).
Altitude	
Operating	To 4.6 km (15,000 ft.).
Nonoperating	To 12.6 km (50,000 ft.).
Humidity	To 95% at 40° C.
Transportation	Qualified under National Safe Transit Committee Test Procedure 1A, Category II.

TABLE 1-3

Physical Characteristics

Characteristic	Information
Net Weight	About 8.2 kg (18 pounds).
Overall Dimensions	See Figure 1-1.

STANDARD ACCESSORIES

1 ea ....Operators Manual

1 ea ....Instruction Manual

1 ea .... Lined Crt Implosion Shield
(8 X 10 division graticule)

For more detailed information, refer to tabbed Accessories page in the 608 Instruction Manual.

OVERALL DIMENSIONS
(MEASURED AT MAXIMUM POINTS)
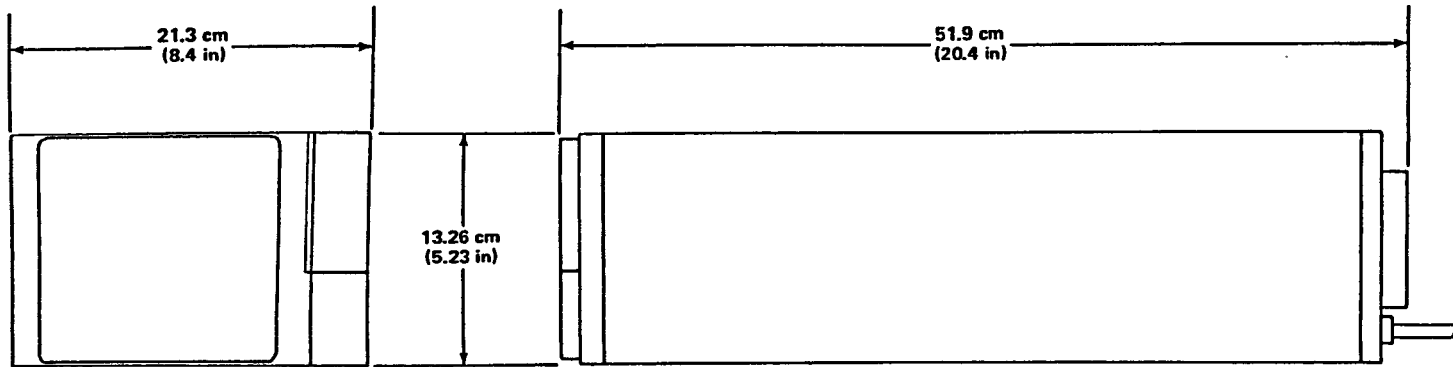
Figure 1-1. 608 Overall dimensional drawing.

21.3 cm
(8.4 in)

51.9 cm
(20.4 in)

13.26 cm
(5.23 in)

NOTE: DIMENSIONS ARE GIVEN WITH TOP FIGURE
IN CENTIMETERS AND BOTTOM FIGURE
IN INCHES.

REFER TO DIAGRAMS AND CIRCUIT BOARD
ILLUSTRATIONS FOR A DETAILED DIMEN-
SIONAL DRAWING.

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Appendix D2

Image Synthesizer

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Part I. General Functional Description

The overall functional organization of the system is described
in reference to the four basic sections of the main circuit board,
as demarcated in Figure 1 at the end of Part I, page 3.

Section I contains the complete circuitry for the # 1 digital spatio-
temporal pattern generator. One full sinewave cycle is stored in the
8K EPROM memory # 1, whose 7-bit input address is determined by counters
23 and 24 and whose 8-bit output word goes via latches # 41 and 42
to D-to-A Converter # 7. Sinewave phase is determined by counters #
27 and 28, which latch in either a specified phase word from the front
panel or produce a constantly incrementing or decrementing phase word
(clocked by VCO # 101), which is read by counters # 23 and 24 during
each frame deadtime, to create a steadily drifting grating. Full adder
27 permits discrete phase shifts. VCO # 37 and buffering one-shot
38 control the rate of memory address counter increment and thus
control the spatial frequency. Enabler gates # 33 and 34 select
between sinewave and squarewave waveforms. Transistor # 93 resynchronizes
the VCO clock during each frame deadtime.

Section II contains the complete circuitry for the # 2 digital spatio-
temporal pattern generator. One full sinewave cycle is stored in the
8K EPROM memory # 2, whose 7-bit input address is determined by counters
25 and 26 and whose 8-bit output word goes via latches # 43 and 44
to D-to-A Converter # 8. Sinewave phase is determined by counters #
29 and 30, which latch in either a specified phase word from the front
panel or produce a constantly incrementing or decrementing phase word
(clocked by VCO # 102), which is read by counters # 25 and 26 during
each frame deadtime, to create a steadily drifting grating. Full adder
29 permits discrete phase shifts. VCO # 39 and buffering one-shot
40 control the rate of memory address counter increment and thus
control the spatial frequency. Enabler gates # 35 and 36 select
between sinewave and squarewave waveforms. Transistor # 94 resynchronizes
the VCO clock during each frame deadtime.

Section III contains the 10-bit digital image rotator and LED display
controller, and circuitry for the two-dimensional window generator.
Counters # 67, 68, and 69, cascaded, are incremented or decremented by
each frame pulse via the front panel manual orientation control switch,
and the top 10 bits of their collective 12-bit word constitute the input
to memories # 3, 4, 5, and 6.   Memories 5 and 6 are code converters

(continued)

Innisfree

(Part I. General Functional Description, continued)

which change their 10-bit addresses into binary-coded-decimal
4-bit words to drive BCD-to-seven-segment-converters/drivers
70, 71, and 72, which in turn drive the three front panel
LED displays via current-limiting resistor networks # 74, 75, and
76. The 10-bit word from counters # 67, 68, and 69 also goes
to memories # 3 and 4, whose output 8-bit words correspond to the
sine and the cosine of their inputs, respectively. These sine and
cosine values form the multiplicative factors for the Euler matrix

$$\begin{bmatrix} X' \\ Y' \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix}$$

which are multiplied by their associated X and Y vectors through
the four-quadrant multiplying D-to-A converters # 9, 10, 11, and 12,
supported by dual summing op-amps # 13, 14, 15, and 16. The four
output values (Xcos, Xsin, Ycos, and Ysin) are appropriately combined
in dual op-amp # 59, whose outputs are the final X and Y-axis signals
to the C.R.T. Analog multipliers # 17 and 18 mediate the high-speed
multiplication of the Y-axis ramp times sine and cosine, with Voltage
Reference # 22 feeding D-to-A Converters # 13 and 14. High-speed
comparators # 60 and 61 determine the two edges of the Width parameter
for rectilinear apertures, while comparators # 62 and 63 do the same
for the Length parameter. Comparator # 64 compares the specified
DC-voltage corresponding to the radius of the circular window with
the sum $(X-X_o)^2 + (Y-Y_o)^2$, as determined by analog multipliers # 19
and 20 and summing op-amp # 55.

Section IV contains aperture control circuitry, raster generation
circuitry, and final Z-axis output circuitry. Quadruple op-amps # 45
and 46 support Generator # 1 and 2 D-to-A Converters # 7 and 8, respec-
tively. Analog switch # 57 selects between their two Z-axis signals
(for the inside and outside of the window), and also between their
partition and their sum. Its output is mixed with blanking pulses
through transistors # 91 and 92 in the final Z-axis wideband summing
op-amp # 21. One-shot # 56 determines the duration of the Y-axis
blanking pulse. Timers # 50 and 51 generate the X and Y-axis rasters,
supported by BIFET quadruple op-amps # 52 and 53 and resistor networks
82 and 83. Quadruple op-amps # 47, 48, and 49 buffer and compute
the rectilinear aperture boundaries, supported by resistor networks
80, 81, 78, and 79. Op-amp #54 buffers the circular aperture radius
control, while multipliers # 19 and 20, supported by dual op-amp # 55
and resistor network # 77, compute the Pythagorean $(X-X_o)^2 + (Y-Y_o)^2$.

TABLE 1-1 (CONT.)
Electrical Characteristics

Characteristic	Performance Requirement
Crosstalk Between X and Y Amplifiers At 500 kHz	0.25 mm, or less, of deflection on the grounded channel (X or Y) with a 1 V signal applied on the other channel (Y or X).
At 5 MHz	0.38 mm, or less, of deflection on the grounded channel (X or Y) with a 1 V signal applied on the other channel (Y or X).

Z-AXIS AMPLIFIER

Characteristic	Performance Requirement
Useful Input Voltage Range (+Z INPUT)	Adjustable. With Z Gain at maximum, no more than +1 V will provide full intensity. With Z Gain at minimum, at least +5 V is required to produce full intensity. (-1 V input signal cuts off visible intensity.)
Useful Frequency Range	Dc to at least 10 MHz at -3 dB point.
Rise Time	35 ns or less.
Noise	No visible intensity modulation with Z INPUT terminated into 1 kΩ or less.
Input RC	1 MΩ, within 1%, paralleled by 60 pF or less.
Maximum Nondestructive Input Voltage (Fault Condition Only)	+100 V or -100 V (dc + peak ac) with crt beam positioned off the viewing area.
Crosstalk Between Z-Axis Amplifier and X or Y Amplifier 0 to 500 kHz	0.25 mm or less, with X and Y INPUTS grounded and a 1 V signal applied to the Z-Axis Amplifier. (Z-Axis Gain set for maximum.)
500 kHz to 5 MHz	0.38 mm or less, with X and Y INPUTS grounded and a 1 V signal applied to the Z-Axis Amplifier. (Z-Axis Gain set at minimum.)

CATHODE-RAY TUBE DISPLAY

Characteristic	Performance Requirement
Usable Screen Area	9.8 X 12.2 centimeters.
Quality Area	9 X 11 centimeters.
Geometry (Within Graticule Area)	Bowing or tilt is 0.1 division or less.
Orthogonality (Within Graticule Area)	90° within 0.7°.
Accelerating Potential	22.5 kV.
Phosphor	P31 standard.
Deflection	Electrostatic.
Brightness	Light output is at least 240 cd/m² (70 fL) with a 0.33 mm, or less, centered spot size. Measured with the crt screen area flooded by a raster, 60 Hz refresh rate, 308 horizontal lines.

<div align="center">TABLE 1-1 (CONT.)</div>

<div align="center">Electrical Characteristics</div>

Characteristic	Performance Requirement
Uniformity	Light output does not vary more than 20% in the crt quality area, at moderate intensity 34 cd/m² (10 fL). Measured with the quality area flooded by a raster, 60 Hz refresh rate, 320 horizontal lines.
Light Output (Option 24 only)	Linear function of Z-Axis input voltage between 2% and 100% of maximum brightness, ±20% of maximum brightness.
Spot Size #1	0.031 cm (0.012 in) or less, anywhere inside the quality area, with the intensity set to produce 170 cd/m² (50 fL) brightness, with a full screen raster refreshed at a 60 Hz rate. Measured with the shrinking raster method.
#2	0.026 cm (0.010 in) or less, at 0.5 μA beam current. Measured with the shrinking raster method.
Resolution	Spot size does not vary more than 10% in the quality area at a constant intensity.

POWER SOURCE

Line Voltage (ac, rms)	
Low Range, P951	
Low (100 V ac)	90 to 110 V ac.
Medium (110 V ac)	99 to 121 Vac.
High (120 V ac)	108 to 132 V ac.
High Range, P952	
Low (200 V ac)	180 to 220 V ac.
Medium (220 V ac)	198 to 242 V ac.
High (240 V ac)	216 to 250 V ac.
Line Frequency	48 to 440 Hz.
Maximum Power Consumption (120 V ac, 60 Hz)	61 watts, 0.7 ampere.