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Development and Evaluation of a New Interior Lighting Design Methodology.

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DEVELOPMENT AND EVALUATION OF A NEW INTERIOR LIGHTING DESIGN METHODOLOGY

By

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Supervisor: Dr Kevin Kelly

School of Multidisciplinary Technologies

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ABSTRACT

This thesis examines the basis of professional practice involved in providing controlled distributions of artificial lighting to provide for the broad range of human activities conducted within buildings, and makes proposals for a new methodology. Current practice for specifying lighting requirements based on task performance is examined, and shortcomings are identified. Proposals that have been advanced for alternative forms of specification are reviewed, including those initiated by the candidate in the five publications that form the major part of this thesis. In these publications, the candidate proposes a basis for general lighting practice based on how lighting may influence the appearance of indoor spaces and their contents. Lighting metrics relating to peoples' responses to the appearance of the lit environment are introduced, and application procedures that may incorporate lighting design objectives based on task performance are discussed. It is recorded that the candidate's publications have aroused interest among the lighting profession, as well as having stimulated research investigations, notably at DIT. The findings from these investigations are evaluated, and it is concluded that while they generally support the candidate's proposals, more research is needed to justify their adoption for general lighting practice, particularly as adoption would involve substantial changes from current practice. Specific recommendations for ongoing research are identified, and it is noted that such research is currently in hand at DIT.

DECLARATION PAGE

I certify that this thesis which I now submit for examination for the award of Doctor of Philosophy by Publication is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

The thesis was prepared according to the regulations for graduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for another award in any other third level institution.

The work reported in this thesis conforms to the principles and requirements of the DIT's guidelines for ethics in research.

DIT has permission to keep, lend or copy this thesis in whole or in part, on condition that any such use of the material of this thesis be duly acknowledged.

Signature

Candidate Date: 26 July 2017

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TERMINOLOGY AND ACRONYMS

Direct flux distribution (DFD)

A specification of the direct flux (lm) required to be received directly (ie, excluding inter-reflected flux) from luminaires or windows by each target surface ($F_{ts(d)}$), to optimally satisfy a LDO combination (see flux utilization).

First reflected flux (FRF)

The total quantity of direct flux that is reflected back into a space from the room surfaces. More specifically, it is the summation of the products of direct surface illuminance, surface area, and surface reflectance; $FRF = \sum E_{rs(d)} A_{rs}\, \rho_{rs}$. FRF may be estimated from Cuttle's formula (see *MRSE*), $FRF = MRSE\ .\ A\alpha$

Flux utilization (U_F)

The efficiency with which direct flux is applied for providing mean room surface exitance. Specifically, $U_F = \sum M_{rs}\, A_{rs} / \sum F_{ts(d)}$, where $\Sigma F_{ts(d)}$ is the total direct flux.

Illumination efficiency

An overall design objective where the LDO combination directs design decisions towards a DFD that prioritises flux utilization.

Illumination hierarchy

An overall design objective where the LDO combination directs design decisions towards a DFD that prioritises an ordered distribution of visual emphasis.

Lighting design objective (LDO)

Describes a specific aspect of lighting to be provided. A LDO should always be described verbally, and whenever practical, should also be specified quantitatively. The overall purpose for which lighting is to be provided for a specific application is defined by a LDO combination.

Mean room surface exitance (MRSE)

The average luminous flux density of the diffusely inter-reflected light field within the volume of an enclosed space. Equal to the area-weighted average of exitance levels of room surfaces, $MRSE = \sum M_{rs} A_{rs} / \sum A_{rs}$. May also serve as measure of ambient illumination. MRSE may be predicted by Duff's precise method [Duff et al, 2016] or estimated by Cuttle's formula, $MRSE = FRF / A\alpha$ [Cuttle, 2010, 2015].

Perceived adequacy of illumination (PAI)

The surrounding exitance level assessed by a (high) proportion of people to provide for the appearance of a space being lit adequately for its associated activity.

Room absorption (Aα)

A measure of the capacity of a space to absorb flux. More specifically, it is the summation of room surface areas and their absorptance values, $A\alpha = \sum A_{rs} (1 - \rho_{rs})$

Room surfaces

The surfaces that form the boundaries of the light field within an enclosed space or room. Typically, room surfaces include furnishings and the areas of ceiling, walls and floor not obscured by furnishings. *Abbreviations: rs, an individual surface; rms, all room surfaces.*

Surrounding brightness (SB)

Assessment of how brightly-lit, or dimly-lit, room surfaces appear to be. May be rated on a seven-point dim/bright scale (See *Section 9.3.1, The SB/MRSE relationship.)*

Target/ambient illuminance ratio (TAIR)

The ratio of the illuminance incident on a selected target surface relative to the ambient inter-reflected light level. Using mean room surface exitance as the measure of ambient illumination level, $TAIR = E_{ts}/MRSE = (E_{ts(d)} + MRSE)/MRSE$

Target surfaces

Room surfaces or objects selected to receive direct flux (see DFD). These may be selected to raise MRSE, or to achieve visual emphasis. *Abbreviations: ts, a target surface; tgs, all target surfaces.*

Visual emphasis

The perceived effect of direct illumination being applied selectively to chosen objects or surfaces, usually for the purpose of making them appear more conspicuous, or to provide for enhanced discrimination of detail.

ACKNOWLEDGEMENTS

The ideas that the candidate has developed through his publications have evolved during a long career in lighting, during which his time as Head of Graduate Education in Lighting at the Lighting Research Center, Rensselaer Polytechnic Institute, Troy, New York, USA, between 1990 and 1999, is of particular note. The Director, Professor Mark Rea, had assembled an outstanding faculty, with whom the candidate's interactions comprised a formative experience. As well as Rea, the candidate acknowledges especially two of his colleagues of that time, Professor Emeritus Peter Boyce and Dr Howard Brandston.

The first step towards this thesis occurred in 2011, when the candidate was contacted by Dr Kevin Kelly, Head of the School of Multidisciplinary Technologies at DIT. He and James Duff had read the candidate's paper that is the first submitted publication and forms Chapter Three of this thesis [Cuttle, 2010], and expressed interest in Duff researching the candidate's proposals for his PhD studies. Duff completed his doctoral studies during the next five years [Duff, 2015], with Dr Kelly as supervisor and this candidate as advisor, and Duff's research is described and evaluated in Sections 8 and 9 of the thesis. This research represents the only formal investigations of the candidate's proposals to be published to date, and the candidate expresses his thanks to Dr Duff for his cooperation and for consenting to him making this use of his research findings.

In 2016, Dr Kelly suggested to the candidate that he should make this application for PhD by publication. His advice, and that of Dr Marek Rebow, Head of Research in the College of Engineering and Built Environment at DIT, have been invaluable, and both are acknowledged with sincere thanks. Also acknowledged with thanks is the assistance of the School Administrator, Ms Jane Cullen, in preparing the thesis for submission. Since then, Dr Kelly has recruited another PhD candidate, Antonello Durante, to continue Dr Duff's research with this candidate again enrolled as advisor, and for this, the candidate expresses thanks to Dr Kelly for the opportunity to continue to be involved in the development of these concepts.

1. INTRODUCTION

1.1. Thesis outline

This thesis examines the controlled distribution of electrically-produced illumination to provide for the broad range of human activities conducted within buildings.

The introduction chapter reviews the origins of the technology that currently guides general lighting practice, and draws attention to shortcomings relating to how the quantity and the distribution of illumination provided for indoor lighting practice are measured and specified. Chapter 2 comprises a literature review that concentrates on proposals for change in general lighting practice that have been advanced by various authors, including the candidate.

The candidate’s five submitted publications comprise Chapters 3 to 7. The first two publications are addressed to the scientific and technical communities within the lighting profession, and propose a new basis for evaluation of illumination quantity and distribution to provide for better correspondence with how people respond to the visual effect of lighting. Chapters 5 and 6 are shorter publications addressed to the lighting design community, which explain how the candidate’s proposals not only support the design process, but if adopted for lighting standards as the basis for regulation, would exercise less constraint of design opportunities than currently exists. The last of the publications, Chapter 7, is a book aimed at educators and researchers, in which the candidate sets his proposals into the broad context of lighting design, basing his approach on exercising control over how lighting influences the appearance of indoor spaces and their contents.

The remaining three chapters analyse and evaluate the outcomes of the candidate’s proposals. Chapter 8 reviews responses by the lighting profession and the academic community; Chapter 9 analyses research studies that have investigated the candidate’s proposals; and Chapter 10 comprises the candidate’s conclusions.

1.2. A basis for regulating general lighting practice

The early development of lighting practice was based on the understanding that the prime purpose of illumination is to provide for visibility, and this has led to the current situation whereby lighting standards are justified on basis that they ensure that the visual component of the principal activity associated with each designated category of indoor activity may be performed with near-optimal efficiency.

Relative visual performance (RVP) is the metric that relates speed and accuracy in performing a visual task to the physical parameters that define the level of difficulty in discriminating visual task detail. These parameters include task illuminance, this being the density of incident luminous flux, measured in lux, or lumens per square metre.

Task illuminance is the generally accepted metric for specifying and regulating the provision of indoor lighting. To avoid the complication of needing to identify the locations and orientations of visual tasks, regulating bodies and professional institutions generally specify minimum task illuminance levels to be provided over a horizontal working plane (HWP). The (UK) Society of Light and Lighting's guidance on office lighting is typical: *"Unless specified otherwise, the recommended maintained illuminance is measured on a horizontal plane at desk height"* [SLL, 2009]. Although specified minimum illuminance levels do vary according to the nature of the human activity, the HWP is the generally accepted measurement plane irrespective of the human activity.

The thesis critically examines this basis for guiding and regulating general lighting practice. The notion that the general purpose for providing illumination is to enable people to perform visual tasks, and that generally these can be assumed to be located on a horizontal working plane, would always have had limited validity, but now may be discounted as irrelevant for general lighting practice. Modern work places, whether industrial, commercial or educational, involve much more varied forms of visual interaction with the tasks to be performed. However, the notion that general lighting practice should be based on solutions devised to make working people productive fails to recognise the manifold ways in which lighting interacts with people. This may be seen to be a fundamental failure to address the potentials for lighting to enhance peoples' quality of life

The remainder of this chapter reviews the contributions of authors whose proposals for alternatives to this basis preceded those advanced by the candidate in the submitted publications, and which form the core of the thesis.

1.3 Evolution of means for specifying illumination quantity

In 1916, Ward Harrison and Earle Anderson presented their paper, *Illumination Efficiencies as determined in an Experimental Room* [Harrison and Anderson, 1916] at the ninth annual convention of the Illuminating Engineering Society of North America, in which they reported the results of a series of experiments in which they measured the illumination due to installations of three different types of luminaire, which they described as direct, horizontal (a bare lamp), and indirect luminaires. The measurements were conducted in an experimental test room that enabled them to vary both the room size, and the reflectance values of the ceiling and walls. In every case, the illuminance was measured at a grid of points on the horizontal "illumination plane", located 0.91 m (3.0 ft) above floor level, and although it was not discussed, it was clear that the authors saw the average value of the illumination on this plane to be the crucial measure of the performance of the lighting installation.

Four years later, the same authors delivered their classic paper, *Coefficients of Utilization* [Harrison and Anderson, 1920] at the 13th Annual Convention of the IESNA. This paper introduced the basis of the calculation process that is now known as the Lumen Method, which they defined with the formula:

$$lumens\ per\ lamp = \frac{footcandles \times depreciation\ factor \times area\ in\ square\ feet}{number\ of\ lamps \times coefficient\ of\ utilization}$$

This paper contains the range concepts that is familiar to today’s lighting practitioners who calculate luminaire layouts to provide for efficient, economical compliance with current indoor lighting standards. These include the room ratio (or room index), the ceiling/wall/floor reflectance combination, the depreciation (or maintenance) factor, and last but by no means least, the coefficient of utilization (now referred to as the utilization factor). The authors defined this last term as the ratio of “useful lumens” to the lamp lumens, making it clear that any lumens emitted by the lamp that were not incident, either directly or indirectly, upon the horizontal illumination plane, were considered useless and wasted.

It should be seen as remarkable that almost one century later, the lumen method continues to be the most widely-used procedure for predicting the performance of interior lighting installations. The notion that horizontal working plane illuminance may serve as an indicator of how people assess the adequacy of illumination not only lacks a research basis, but there seems to be no valid basis for supposing that it might be suitable for that purpose.

1.4 Evolution of means for specifying illumination adequacy

While Harrison and Anderson applied acceptable standards of research methodology to their measurement studies and proposals for a predictive procedure, there was a distinct lack of experimental rigour in contemporary studies of human response to lighting. Defoe [2008] has described an unrecorded study by P.J. Waldram of assessment of illumination adequacy that occurred at “some time during the 1920’s”. Indoor access to daylight illumination was at that time recognised to be a valuable asset, and in the UK, this access was protected by law for premises that could claim ‘ancient lights’ for their windows. Court cases concerning *Rights of Light* required judges to assess whether nearby developments unduly compromised daylight illumination, and Waldram, who had often acted as an expert witness, sought to establish by measurement the illumination level that needed to be maintained for daylight to be assessed as adequate. He assembled a ‘jury’ comprising “six or seven” members who, in an unspecified number of side-lit rooms, read a marked section of *The Times* newspaper laid on a table top. The table was moved towards and away from the windows, and while the actual instructions given to the jurors are not recorded, Defoe states that the aim was to ascertain the point at which “they were able to read comfortably”. The finding was that an illumination level of 1.0 foot-candle (10.76 lux) provided for this condition, and since then, many *Rights of Light* cases have been determined by measurements based on this value.

If it seems remarkable that such a casually gained criterion should gain such a level of acceptance in legal proceedings, it should be even more so that it has also gained and maintained widespread acceptance among lighting professionals for assessing the adequacy of indoor daylight. It was cited by A.W. Beuttell in his 1933 Presidential Address to the IES of Great Britain [Beutell, 1934], in which he proposed a scale of recommended illuminance values to compensate for visual task difficulty. The starting point was Waldram’s 1.0 foot-candle level, for which he explained that it was common experience that this level was sufficient illumination for everyday activities, and so it should become the base level for indoor lighting standards. Then, wherever visual tasks are to be performed, it should be possible to classify the tasks according to their visual difficulty. A scale of multiplying factors could be prescribed, ranging from two for the simplest tasks, through to twelve for the most demanding visual tasks. In this way, lighting standards could specify minimum illuminance values ranging from 2.0 ft-C for activities that involve the most simple visual tasks, through to 12.0 ft-C, where high levels of visual discrimination are required. The basis of this proposal was that for any human activity, the level of illumination could be selected to compensate for the level of visual task difficulty encountered in performing the activity.

Among those who were present for Buetell’s presentation was a scientist from the Medical Research Council, H.C. Weston, and he undertook the task of researching Beuttell’s vision. In two experimental programmes involving human subjects, he measured speed and accuracy in performing controlled visual tasks. These comprised printed charts of Landolt ring tasks, being a series of printed circles, each with a gap that the subject is required to cancel. The gap dimension, together with the reflectance values paper and printing ink, enable the experimenter to control of both the angular size and the luminance contrast of the detail to be discriminated. By recording the time taken and the number of errors made in completing a block of ring tasks when presented under four decades of illuminance, ranging from 0.5 to 500 ftC (5.38 – 5380 lux), Weston was able to relate speed and accuracy in performing visual tasks to illuminance. His findings were published as a MRC Report [Weston, 1945], in which Weston established the concept of visual performance, and provided a reliable basis for matching the provision of illumination to human visual needs.

Weston's findings did not confirm Beuttell's vision. He found that easy visual tasks may be performed to high levels under quite modest illuminance levels, after which no significant increase in performance is to be gained by increased illuminance. On the other hand, while the performance of difficult tasks benefits substantially from increasing illuminance levels, it may do so without ever reaching the levels of performance readily achieved with easy tasks. In this way, illuminance could only be used to compensate for task difficulty if easy tasks were illuminated to such low levels that their performance was compromised, which as Weston noted, would be an absurd situation.

Since then, visual performance has been the subject of extensive research around the world, leading to the relative visual performance (RVP) model developed at the National Research Council of Canada by Rea and Ouellette [1991]. The basic concept of this model is that, for a given visual task, 100% RVP is achieved when increased illuminance produces no significant increase in performance. This enables regulatory bodies to specify percentage RVP levels to be provided for a broad range of categories of general lighting practice. By classifying activities according to the task difficulty involved, illuminance levels may be prescribed to ensure in all situations a corresponding level of visual performance relative to the maximum level practicably attainable for that task category. The IES of North America adopted the RVP model, and has prescribed a level of 98% RVP in its schedule of recommended minimum illuminance levels [IESNA, 1981].

To reliably determine the illuminance to be provided to satisfy a specified RVP criterion for a specific application would require that the critical visual detail involved in performing the activity is identified, and that measurement is made of both the angular size at the eye in micro-steradian, and the luminance contrast of the elements that form the detail. This calls for equipment far beyond the facilities possessed by today's lighting practitioners, but more critically, the few reported studies of these procedures having been applied in practical applications were performed when office work was concerned with paper-based visual tasks [for example, Blackwell and Blackwell, 1971; Smith and Rea, 1978], and show little relevance to the performance of the activities performed in modern workplaces. As knowledge of visual performance has developed, so has understanding of how visual tasks may be simplified, such as by replacing paper-based reading tasks with self-luminous screen-based presentations, or eliminating visual tasks, as by the use of bar-code readers. Meanwhile, specified illuminance values have increased far beyond levels that could be justified on the basis of visual performance [Cuttle, 2013], even before the visual tasks were simplified or eliminated.

While current lighting standards usually include other criteria dealing with aspects such as control of discomfort glare and colour rendering characteristics of lighting, control of illumination quantity through schedules of minimum illuminance levels for specific activities continue to be widely recognised as fulfilling the prime purpose of the standards. Whether the illuminance values are specified as visual task levels, or levels to be provided over a task plane, the generally accepted practice for ensuring compliance is to measure illuminance at a grid of points located on the horizontal working plane. There is cause for concern regarding the appropriateness of this form of specification for regulating general lighting practice.

2 LITERATURE REVIEW

2.1 Overview

The development of lighting practice during the past century has generated an extensive literature, which has been expertly reviewed by DiLaura [2006], and this should referred to for explanation of the procedures that currently guide general lighting practice.

The literature sources that have been formative in the development of this thesis are referenced in the submitted publications, which form Chapters 3 to 7 of the thesis. Of these, Chapter 7, being the candidate's book, *Lighting Design, A perception-based approach*, is noted in particular as indicating the scope of the literature relevant to this thesis.

As the purpose of the thesis is to develop the option of an alternative to currently accepted practice, this review selects the works of authors who have not merely criticised conventional practice, but who have proposed alternatives, and whose proposals were influential upon the development of the thesis. The innovative nature of the candidate's proposals may be seen in relation to these other proposals which have been advanced during the past 63 years.

2.2 Apparent brightness

In 1954, J.M. Waldram introduced a procedure for "Installation Design for a Specified Gross Apparent Brightness Pattern" [Waldram, 1954], which is now generally referred to as the Designed Appearance Method. This procedure turned the conventional process of lighting design upon its head. Instead of selecting a luminaire, devising an installation layout, and then applying the lumen method to assess the horizontal working plane illuminance that it would deliver, Waldram's procedure reverses the process. The designer starts by specifying a brightness distribution to produce a preconceived appearance for the contents and surrounding surfaces of a space, and then proceeds to determine an installation that would provide it. This is more than simply a change of calculation procedure: it redefines the purpose of lighting.

Waldram's paper preceded introduction of the term 'luminance', and at that time, 'brightness' could refer to either a subjective assessment (it's current meaning) or to a photometric quantity (now defined as luminance). Expressed in current terminology, Waldram had been involved in developing brightness/luminance (B/L) functions that defined the relationship [Hopkinson, Stevens and Waldram, 1941], and his design method involved identifying "by inspection" an adaptation (brightness) level which determined the specific B/L function relevant to the situation. The design objective was specified as a distribution of brightness values for selected surfaces and objects within the space, and he applied the appropriate B/L function to convert these values to luminance levels, for which illumination engineering procedures would then be applied to determine the required luminaire performance characteristics.

In this way, Waldram may be seen to have defined the purpose of lighting in terms of how it affects the appearance of the surrounding surfaces and the contents within a space. He went on to become a prominent lighting designer, and received accolades and awards for his lighting designs, most notably for his lighting of several English cathedrals. While he always insisted that the use of his method had contributed to the successful outcomes, the method was never adopted for general practice.

2.3 Luminance ratios

While RG Hopkinson had recognised the virtue of Waldram's brightness-based design procedure, he proposed a luminance-based approach as an "interim stage" [Hokinson, 1965], which he introduced with a statement of understanding of the purpose of lighting:

> *"Lighting Codes in terms of levels of illumination incident on the visual task have served a valuable purpose for over fifty years. When based on sound principles, they are still valid for*

> *the lighting on the work. The lighting of the building interior, however, should not have to be constrained by the lighting on any specific visual task, and should be planned in relation to the design of the whole building."* [Hopkinson, 1965]

Hopkinson simplified the procedure for achieving this by dropping the adaptation level-dependent brightness/luminance conversion, and stating the lighting design objectives in terms luminance ratios for specific surfaces related to an average luminance value. In this way, he sought a practical way of changing lighting practice from being regulated by light incident on visual tasks, to light incident at the eye.

Like Waldram, Hopkinson saw fundamental change in lighting practice to be imminent, and he saw his simplified procedure to be a step towards facilitating that.

2.4 Luminance distributions

Staff at the Bartlett School of Architecture and Planning, University College London, have sought to extend Hopkinson's proposals with studies relating peoples' assessments of the appearance of their surroundings to scans of the distribution of surface luminance values taken at an observer's viewpoint [Loe *et al*, 2000].

The complexity of the data produced by the luminance scanner developed for this purpose led to difficulties in identifying useful correlations with subjective assessments. The principal findings from these studies was that overall brightness assessments of the lit environment were related to the average luminance of '40 degree band', being a horizontal band extending 20 deg above and below a viewer's eye level, but were not affected by the luminance of the luminaires.

The candidate's thesis includes the proposal that surrounding brightness may be related to the concept of *mean room surface exitance,* which takes account of all surrounding light-reflecting surfaces.

While the ’40 degree band’ concept is inconsistent with the candidate’s proposals, the finding that luminous elements do not affect surrounding brightness assessments is supportive of the mean room surface exitance concept.

2.5 The illumination vector

In 1936, Gershun introduced the concept of the illumination vector [Gershun, 1936], which departs from convention by instead of examining illumination in terms of incidence on a surface, considers the distribution of illumination about a three-dimensional point in space. In 1966, J.A. Lynes and his colleagues employed the concept to indicate how the “flow of light” within a space may be described by flow lines representing the pattern formed by the directional variations of the illumination vector, and how the apparent strength of flow, as it affects the ‘modelling’ of three-dimensional objects (particularly the human features), may be indicated by the vector/scalar ratio [Lynes et al, 1966]. Again, this concept expresses a different understanding of how lighting affects the appearance of lit objects.

The candidate followed this paper by conducting research into the relationship between preferred modelling, and the vector direction and the vector/scalar ratio [Cuttle et al, 1967; Cuttle 1971]. He also proposed the cubic illumination concept as the basis for a practical measurement procedure [Cuttle, 1997]. The modelling preference studies led to recommendations in the 1973, 1977 and 1984 Code for Interior Lighting documents published in the UK by the Society for Light and Lighting.

2.6 Horizontal/vertical illuminance ratios

An alternative approach to specifying lighting to ensure preferred modelling was proposed at about the same time by Hewitt et al [1965]. Their research study recorded subjects’ assessments of the appearance of a 150mm diameter matt white sphere, and alternatively, a model head mounted at the viewing position, when illuminated by different distributions of regular overhead lighting installations. The assessments were found to relate to the ratio of horizontal illuminance (measured in the conventional manner) to the vertical illuminance, which was measured by placing a translucent cylinder vertically over the horizontally mounted photocell.

This work was extended by a study by staff at the Bartlett School of Architecture and Planning, University College London, that started with assessments in a full-scale model office and continued in four general offices, each lit in a different way [Rowlands *et al*, 1983]. It was found that subjects showed preference for vertical/horizontal illuminance ratios within the range 0.3 to 0.6, with indications that ratio values in excess of 0.7 are likely to found unacceptable.

Application of the horizontal/vertical illuminance ratio is restricted to overhead lighting conditions, for which the vector direction is vertically downwards, whereas the vector/scalar ratio may be applied for any specified vector direction. Despite this limitation, the horizontal/vertical illuminance ratio has been adopted for specifying acceptable lighting conditions in the European standard EN 12464-1.

2.7 Multiple criteria design

In 1971, the Illuminating Engineering Society of Great Britain published IES Technical Report No. 15: *A design method for interior electric lighting installations* [IES, 1971]. The MCD method starts with the designer specifying a selection of lighting design criteria appropriate for the situation. It is assumed that the appropriate illuminance and glare index will be selected from the IES Code for interior lighting, and in addition, the method allows the designer to specify criteria for the average wall/HWP illuminance ratio, the ceiling/HWP illuminance ratio, and the vector/scalar ratio. In this way, the method encompasses task illuminance, discomfort glare, and the balance of lighting as it affects the appearance of room surfaces and objects with the space. Charts are provided to enable all of these criteria to be incorporated into a procedure that leads to identification of a limited range of luminaire characteristics that will simultaneously satisfy all of the criteria. These are specified in terms of BZ classification and flux fraction ratio (FFR), which were widely used at the time, and so enabled the designer to select suitable luminaires for a regular lighting installation.

Incidentally, the report carries the following citation:

> *The Society especially wishes to thank C. Cuttle on whose original work the Report is based and who was largely responsible for drafting the Report and preparing the worksheet and Data Charts.*

2.8 Satisfaction surveys

Surveys employing multiple semantic scales have sought to identify the significant aspects of the visual environment that determine overall assessment. A spate of such surveys occurred during the 1970's, and generally they failed to provide any tangible outcome. One exception was a study of 650 office workers in 44 offices identified three criteria – comfort, satisfaction and performance – and from these determined the CSP Index, which takes a value of 0 to 100 that relates to the probability that office workers will be satisfied with their visual environment [Bean and Bell, 1992].

While this approach aroused interest at the time, there is no record of it having been verified in practice. As it is concerned solely with office lighting, the extent of change that has occurred in working practice in modern offices must render this index obsolete.

2.9 Overall brightness assessments

Although luminance is defined as a directionally-specific metric, some researchers have sought to relate overall brightness assessments to average luminance values, which generally are specified as the area-weighted mean luminance of all surfaces viewed from a measurement point located at (or somewhere close to) the centre of the space.

A study by McKennan has been reviewed by the candidate [Cuttle, 2010 (Appendix)] which involved subjects making assessments of overall brightness in a sequentially-viewed series of 16 differently lit spaces, after which they retraced their steps and viewed the spaces in reverse order. McKennan's interest was whether brightness assessments would be influenced by the previously viewed space. He found a significant, but weak, trend indicating that entering from a more dimly-lit space makes the space appear brighter, and vice-versa.

In his review, the candidate has converted the average luminance values to mean room surface (MRSE) values and related them to surrounding brightness (SB). It may be expected that the trend found by McKennan would influence the SB/MRSE function, but more research is needed to determine whether the weak effect that he found would be a significant influence in practical applications. Meanwhile, the fact that McKennan obtained consistent responses for overall assessment of brightness should be noted. This study is the only one that the candidate has been able to find that employs overall assessments of room brightness. Generally, subjects making brightness assessments in research experiments have been presented with restricted fields of view, for which the researcher has been able to record precise distributions of surface luminance values, but obviously, this viewing condition is not representative of how people gain impressions of room brightness. It is a novel concept that overall brightness assessments of spaces, where neither the locations nor the viewing directions of subjects are restrained, may be related to a single lighting metric, but the candidate's experience of teaching assignments for which students record brightness assessments and relate these to illuminance measurements have tended to support the notion that such assessments have validity.

2.10 Exitance-based metrics

Cuttle has proposed metrics based on exitance, and the following five chapters comprise the publications in which he introduced his proposals. These documents are a selection from more than 140 of the candidate's published works, and together, they represent his effort to bring about change in general lighting practice. As such, they are directed towards three distinct sectors of the lighting community.

In the first two papers (Chapters 3 and 4), both published in *Lighting Research & Technology*, Cuttle seeks to establish a sound technical basis for his innovative concepts. In the first of these he introduces the mean room surface exitance (MRSE) concept, being “the average value of the flux density reflected from all surrounding surfaces”, and proposes this metric to replace horizontal working plane illuminance as the basic metric for specifying illumination quantity in general lighting practice. In the following document, he introduces two novel lighting design concepts: perceived adequacy of illumination (PAI) and illumination hierarchy. PAI would be specified in terms of MRSE, enabling illumination quantity to be specified without restricting illumination distribution. The concept of illumination hierarchy may be employed to define distributions, which may be as simple or complex as circumstances require, and so provide a common basis for either routine specification or creative lighting design.

Cuttle has become involved in the Professional Lighting Designer’s bi-annual conventions to gain comment and criticism from the lighting design community. The third submitted publication (Chapter 5) is one of his PLD-Convention papers in which he explains how adoption of MRSE in lighting standards liberates lighting designers from the restriction of having to comply with the uniformity requirements that are an inherent component of current HWP illuminance-based standards.

The fourth submitted publication (Chapter 6) carries his arguments to the heart of the lighting design community. Richard Kelly was an inspirational character in the early development of professional lighting design, and in a 1953 article he described how his design approach balances “three elemental kinds of lighting effect” [Kelly, 1953]. Cuttle explains how these concepts may be realised through application of his exitance-based lighting concepts. While Kelly’s notion was expressed entirely in descriptive terms, Cuttle’s concepts may be defined in terms of measurable and predictable metrics, opening up opportunities to subject these subjective concepts to research examination.

Cuttle has had a long involvement with multiple criteria design (MCD), by which designers employ a variety of criteria to specify their lighting design objectives, and by doing this they are able to define a restricted range of design options that will simultaneously satisfy their objectives [IES, 1977]. The final submitted publication (Chapter 7) is a book in which he sets his own concepts into a broad range of design criteria, some of which are relatively unfamiliar, to create a comprehensive perception-based design approach. Application is facilitated by use of spreadsheets that the candidate has developed, and which are available for free download from the publisher's website.

This chapter has reviewed the literature with respect to attempts to change lighting practice from the century-old concepts that continue to form the basis for current practice, by moving on from visual performance to basing practice on how lighting influences the appearance of our surroundings. While there is no evidence of the lighting metrics reviewed in this chapter having made any impact on general lighting practice, discussion has been stimulated. In summarising the 'Better Metrics for Better Lighting' symposium organised by the editors of *Lighting Research & Technology* in London in 2014, Boyce and Smet commented:

> *"... it is the mean room surface exitance and target/ambient illumination ratio process for light distribution that has the most potential to deliver better lighting. .... A combination of the light distribution metrics of Cuttle and the light spectra metrics of Rea probably offer the best prospect for a quantum leap in lighting quality"* [Boyce and Smet, 2014]

3. FIRST SUBMITTED PUBLICATION

Cuttle C, 2010. Towards the Third Stage of the Lighting Profession. *Lighting Research & Technology*; 42(1):73-93.

The notion of stages of the lighting profession is examined to identify main themes that have directed the objectives of the lighting profession. It is proposed that the objective of the first stage was provision of uniform illumination over a horizontal plane, and that of the second stage has been to provide illuminance suited to human need, based on visual performance. This brings us up to the current era, and it is the author's opinion that the second stage has failed to achieve its objective. While codes and standards pay lip service to visual performance, the reality is that for the vast majority of situations where lighting standards are applied, the aim is to meet user expectations for the spaces they occupy to appear adequately lit. The metrics currently used to specify, measure, and calculate lighting levels are inappropriate for this purpose.

The concept of mean room surface exitance is proposed a basis for lighting standards. Procedures for calculation and measurement lead to some startling conclusions. Familiar notions of lighting effectiveness and efficiency are turned upside down, and an entirely different way of thinking about interior lighting design is revealed. The essential difference is a switch from assessing light incident on planes to assessing light arriving at the eye. Such a change of thinking may be seen as a precursor for the third stage of the lighting profession.

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Towards the third stage of the lighting profession

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1. Three stages of the lighting profession

In an editorial article in the SLL Newsletter, Alan Tulla expressed the view that 'we are at the beginning of the third stage of the lighting profession'.[1] From a first stage of incandescence and through a second stage of discharge and fluorescence, he identified the recent surge of development in solid-state lighting as the advent of the third stage. My own reaction was that this view really describes the current state of the lighting industry, which poses the question, what is the situation of we professional people who work in lighting? Can we see stages in our development, and are we at the beginning of a new and innovative stage? Rather than looking at the many attempts that have occurred over the years to devise better light sources, let us look instead at our role in the development of lighting practice.

1.1 The first stage

Lighting may be said to have emerged as a profession in 1898 when a meeting of gas engineers in Paris laid the basis for an international system of photometry. The incandescent lamp had been invented quite recently, whereas gas lighting had a century of development behind it, and large installations of gas lighting columns had appeared in many urban centres. Those engineers needed photometric data to enable them to specify column heights and spacings to provide prescribed illuminance values evenly over horizontal surfaces. They were familiar with the point-to-point formula $E = I \cos\theta/d^2$, and the roles of the inverse-square and cosine laws

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which it incorporates, so all they needed in order to apply their skills universally was an agreed system for specifying the luminous intensity distribution of the luminaires.

In England the Metropolitan Gas Act of 1860 had defined the term candlepower which involved specifying the burning rate of a pure spermaceti candle, while in France the standard of light was based on a Carcel burner, which was fuelled by colza oil and had about 10 times the luminous intensity of a candle. The notable outcome of this meeting was the establishment of luminous intensity as the primary standard of light, and we may acknowledge (or blame) those gas engineers for the fact that the candela is now defined as one of the seven base units of Système International. However, what has really shaped the development of professional lighting practice has been the underlying objective of those engineers, which was to provide uniform illuminance over a horizontal plane.

As electric lighting came to dominate lighting practice, lighting of indoor spaces gained more attention. The horizontal surface was raised from ground level to become the workplane, and the introduction of the lumen method enabled the effects of interreflected light to be taken into account. The average illuminance of the horizontal workplane and the uniformity ratio became the basis of lighting standards around the world. Meanwhile, some lighting professionals were turning their attention to the question of how much light do people need?

1.2 The second stage

During the first stage, several leading members of the lighting profession became involved as experts in Rights of Light lawsuits, which were quite common at the time. This caused the courts focus attention onto the question how to define the amount of light that people need in order to be able to see reasonably well. Peter Defoe[2] has recounted how, in the 1920's, Percy Waldram (the father of J.M. Waldram) gathered the opinions of a 'jury' of experts who visited a series of daylit offices, from which Waldram concluded that one footcandle (10.76 lux) is sufficient to enable people to read comfortably.

In 1934 A.W. Beuttell presented his presidential address to the IES of Great Britain, in which he started from the notion of one footcandle being sufficient for basic needs and proposed:

> that the illumination required for any visual task, as compared with the simplest possible task, depends upon certain conditions adversely affecting its performance; that these conditions can be defined; and that if the relationship can ascertained between each of the conditions and the illumination required to compensate for it, then the illumination suitable for the performance of the task ought to be capable of actual computation.[3]

The notion of illumination compensation for task difficulty stimulated H.C. Weston to conduct his classic series of experiments, the results of which were published in 1945,[4] and which for the first time related visual performance to task illuminance for measured levels of task difficulty as indicated in Figure 1. This may be seen as the start of the second stage, as it gave the lighting profession the new objective of relating illuminance values to user needs. The underlying principle for formulating a 'rational basis' for lighting standards was that a critical visual task is identified in terms of its physical characteristics (angular size and luminance contrast of detail measured at the eye) to determine the illuminance needed to provide for a prescribed level of visual performance.

However, Weston realised that there were problems with this approach. In his own words:

> The only way of making a very poor contrast as visible as a very good one is

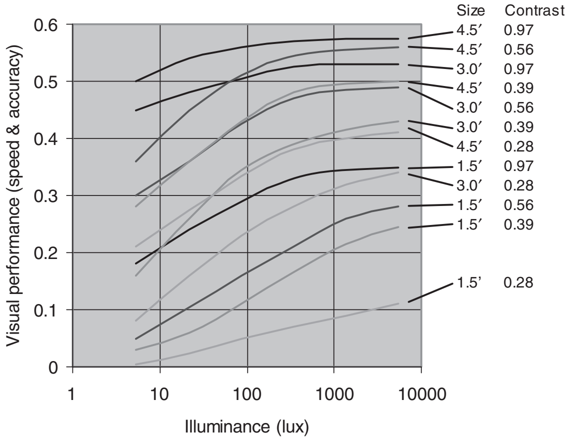


Figure 1 Weston's visual performance (VP) model.[4] VP takes into account speed and accuracy in performing visual tasks, and is plotted against task illuminance in lm/ft^2. Increasing task size, measured in minutes of arc subtended at the eye, and increasing task contrast correspond to reducing task difficulty. It can be seen that VP is high for easy visual tasks even at low illuminance, and is only slightly affected by increasing illuminance to higher levels. For difficult visual tasks, VP is strongly affected by illuminance, and even at the highest level does not reach the levels for easy tasks

> to view the latter in a visually handicapping illumination, that is, an illumination low enough to depress the contrast sensitivity of the eye. Such a procedure would be irrational.[5]

Nonetheless, the 'rational basis' approach was taken up with enthusiasm by Dr Richard Blackwell of the Vision Research Center at the Ohio State University. Starting in the 1950's, he conducted an extensive programme of visual performance measurements, and prescribed a visual performance criterion, which was a high level specified as 99% accuracy of detection, on the basis that lighting should be provided to maximise visual performance in all situations. To complete the system, he developed a visual task evaluator,[6] which was an elaborate optical instrument that enabled an operator to measure visual task difficulty in actual workplaces, and from the data gathered to specify the illuminance required to satisfy the visual performance criterion. A programme of measurements in schools and offices was reported by the IES of North America in the 1966 Lighting Handbook,[7] providing a source of visual performance data gathered on-site. It was found that, for normal-sighted young people reading 12-point black type on white paper, 6 lux is needed to meet the criterion. For 10-point type the required illuminance increases to 10 lux, and for 8-point type it is 12 lux. In an office study, a sample of good quality typewritten material was found to require 11 lux. In fact, it could be said that these measurements confirmed Percy Waldram's findings from the 1920's. It is, therefore, reasonable to ask why the same edition of the Handbook recommended 323 lux (30 Fc) for school classrooms and 1076 lux (100 Fc) for regular office work.

In the same school surveys, samples of spirit-duplicated material were measured, and the quality was found to be variable. The median requirement was 1380 lux, and for the poorer quality copies, it was 7360 lux. In the office, a typed fifth carbon copy required 1430 lux, and a typed original produced with 'an extremely poor ribbon' needed an astronomical 33 800 lux. With such massive variations in illuminance requirements for different visual tasks, it became obvious that the objective of employing illuminance to compensate for task differences was impractical. This is not because there is any deficiency in the concept of visual performance, as we now have a reliable basis for evaluation in the form of the relative visual performance (RVP) model developed by Rea and Ouellette[8,9] and confirmed by Eklund et al.,[10] but rather it is because, as Weston foresaw, our knowledge of visual performance refutes Beuttell's notion that illumination may be applied generally to compensate for task difficulty.

Circumstances have moved on since Blackwell completed his studies in the pre-Xerox era. Where now are the carbon copies and the typewritten material produced with a poor ribbon? Paper-based tasks in offices and schools now comprise high quality laser-printed or photocopied material, while for much of the time, these people are engaging with self-luminous screen-based tasks for which high illuminance levels have the unwanted effect of reducing task luminance contrast. Moving on to industrial tasks, analogue instruments have been replaced by digital read-out displays, and in many cases, quality control that used to require visual inspection has been automated. The fact is that wherever detail is difficult to see, technology can offer better solutions than high illuminance, and the results of this are all around us. Surgeons monitor their operations on-screen by inserting fibre optic probes into their patients, and bar code readers have left supermarket check-out operators with no task more visually demanding than engaging customers in eye contact while delivering trained smiles. In fact, just about the only indoor activities where difficult visual tasks remain are those sports for which the ability to respond to small and rapidly moving objects is an essential component of the activity.

Our situation today is that if we took the trouble to measure the actual visual tasks that people perform in their workplaces, we would find generally that the illuminance being provided is well in excess of the level they need in order to perform those tasks. Does this mean that we would be justified in making wholesale reductions in workplace illuminance to levels around 10 lux? Despite the obvious energy-saving advantages, the answer is a resounding ‘No’. People would be outraged if expected to work in such miserable environments, even if it could be scientifically demonstrated that the lighting levels were sufficient to enable them to read the high quality printed paperwork or to operate the screen-based tasks that form the basis of their work.

Herein lies the key to the demise of the second stage. The illuminance levels that must be provided to meet peoples’ expectations for adequately illuminated surroundings exceed the levels that they need in order to cope with the simple visual tasks that they encounter in modern, well-equipped workplaces. While lighting standards may claim to be performance-based, this is false, as the levels specified cannot be justified on the basis of visual performance. Of course individual cases occur where the nature of the work or the visual abilities of the worker cause difficulties, and usually these would best be dealt with by local task lighting. More generally, when people in workplaces equipped with modern, efficient lighting complain about the lighting, their objections are likely to be directed towards the appearance of their surroundings. They may find the appearance of the workplace to be dull or gloomy, or the effect of the lighting to be harsh, producing dense and unattractive shadows.

We should not allow ourselves to suppose that we are so responsive to peoples’ concerns that such situations would be quickly corrected, for our record in responding to short-coming of lighting quality is poor. Consider for example the LG3 saga. In 1989, the Lighting Division of the CIBSE produced *Lighting Guide 3: Areas for Visual Display Terminals,* which introduced a three-category system for downlighter luminaires. The aim was to avoid unwanted reflections in the screens of the CRT terminals that were prevalent at the time by severely restricting luminaire luminance above specific angles measured from the downward vertical. Specifiers were quick to adopt this system, as it enabled them to ensure appropriate lighting quality simply by stating that ‘All luminaires shall be Category One’ (or perhaps two, but seldom three). The outcome was widespread application of absolutely hideous lighting, contemptuously nicknamed ‘the cave effect’ by justifiably frustrated users. This parlous situation continued until 2005, when *LG3* was superseded by *LG7: Office Lighting* and its

Declaration of Conformity document which requires wall/task (effectively wall/workplane) and ceiling/task illuminance ratios to be within certain limiting values. Where did these limiting values come from? Were they the results of new research? In fact, they were proposed by Peter Jay in 1968[11] on the basis of reason rather than research; they were incorporated into the 1973 Code for Interior Lighting; and moreover, they have appeared in every subsequent edition. It took our profession 16 years to respond to this situation of its own making by drawing attention to the content of its own Code.

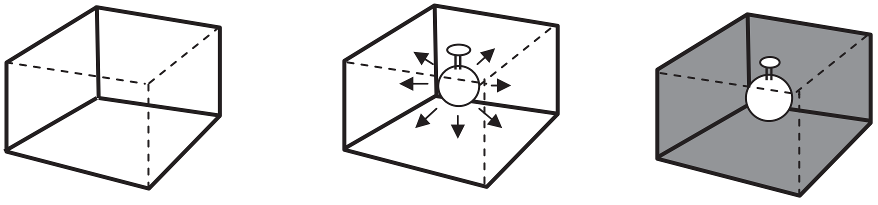
Over the years the performance-based approach has been extended to include other factors that affect task visibility and user comfort, such as contrast rendering and discomfort glare, and this overall understanding of lighting continues to be quoted as the basis of our lighting standards. It is, of course, entirely appropriate that workplace lighting should ensure adequate task visibility and not cause discomfort, but the current situation is that the illuminance levels that the profession advocates bear no sensible relationship to visual performance. This is generally so for workplaces, and invariably it is so for the multitude of other locations for which the illuminance schedules recommend or mandate lighting levels, and yet we measure those levels as if workplane illuminance really matters. Why should it be supposed that we gain any useful information about illumination adequacy in reception areas, meeting rooms, assembly halls, and so forth, by holding a light-meter horizontally 700 mm above the floor? What we need is a lighting metric that provides a reasonably reliable indication of how adequately illuminated a space will appear to be. Is this practical, or even possible? It is time for a thought exercise.

2. A thought exercise

For readers who are not familiar with this type of mental exploration, the first requirement of a thought exercise is that you forget everything you know. Turning to Figure 2(a), imagine a room where the sum total of ceiling, wall, and floor areas is 100 m^2. For Figure 2(b), we add to this room a luminaire that emits 5000 lumens. How well illuminated will this room appear to be? You should not attempt to answer this question because you cannot tell how much light there is in the room from this information. For Figure 2(c), we specify the reflectance ρ of all of the room surfaces to be 0.5, so that half of the incident light is reflected and the other half is absorbed. Now we can assess the amount of light.

All of the 5000 lm emitted by the luminaire will be incident on the room surfaces where half will be reflected back into the room, so from the first reflection we gather another 2500 lm giving a total luminous flux of 7500 lm. From the second reflection we collect another 1250 lm bringing the total flux up to 8750 lm, and so on until the added flux becomes disappearingly small. The total luminous flux F in the room after an infinite number of reflections is given by the expression $F = F_L/(1-\rho)$, where F_L is the initial flux emitted by the luminaire and ρ is the room surface reflectance. In this case, $F = 5000/(1–0.5) = 10\,000$ lm, so that by reflecting half of the incident flux back into the room we have doubled the total amount of light. It follows that the average room surface illuminance is $10\,000/100 = 100$ lux, which gives us the notion that the room should appear to be moderately well lit.

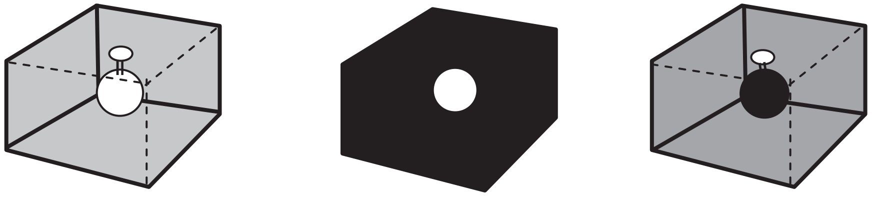
Let us suppose that we want a more brightly lit appearance. We could increase F_L, but having seen how effective reflection can be, let us see what a little more of that may do. For Figure 2(d) we make $\rho = 0.8$, then $F = 5000/0.2 = 25\,000$ lm, and now we have an average room surface illuminance of 250 lux. The room should appear quite brightly lit, and we may note with some satisfaction that the total flux is five times the



(a) Room surface area $A = 100\,\mathrm{m}^2$

(b) Luminaire light output $F_\mathrm{L} = 5000$ lm

(c) Room surface reflectancet $\rho = 0.5$, and illuminance $E = 100$ lx



(d) Increase ρ to 0.8, and E increases to 250 lx

(e) Reduce ρ to 0, and E = 50 lx, and has no visible effect

(f) Mean room surface exitance M_rs = FRF/Aα

Figure 2 A thought exercise

luminaire flux, and this has been achieved with nothing more energy-consuming than a coat of paint. As this is a thought exercise, we might wonder what would be the effect of increasing the value of ρ to 1.0? It is perhaps fortunate that nobody has yet devised a practical way of doing this, because the room inevitably would explode.

What would happen if we go in the other direction? For Figure 2(e) we make $\rho = 0$, so that every incident lumen is absorbed. How well illuminated would the room now appear to be? On entering the room we would be able to see the luminaire, and while it might appear brighter than previously, the room would be totally invisible even though measurement would show the average room surface illuminance to be 50 lux. This makes an important point. The direct flux from the luminaire makes no contribution to the appearance of the room. For an indicator of how well illuminated the room might appear, we should take account of the flux only after it has undergone the first reflection, so in this case, first reflected flux $\mathrm{FRF} = F_\mathrm{L}\rho$. This is the flux that is the source of all the interreflected flux that provides for our impression of the illuminated appearance of this room.

Now we have the opportunity to devise a measure that bears a simple relationship to a likely impression of how well illuminated this room would appear. The appearance of the luminaire is simply a distraction, so for Figure 2(f) we make the luminaire black, although we have to keep in mind that it still emits 5000 lm. The measure that will be useful for our purpose is not illuminance but exitance M, or the lumens per square metre reflected from, or exiting, the room surfaces, and we obtain the average exitance M simply by dividing the first reflected flux FRF by the room absorption $A\alpha$. This latter term is the measure of the light absorbing capacity of the room, which assesses the room in terms of the equivalent area of a perfect absorber.[12] Although it is our usual practice to specify surface reflectances, we could equally use absorptance α where $\alpha = (1 - \rho)$, so a perfect absorber is a hypothetical surface for which $\alpha = 1$ and $\rho = 0$. One square metre of room absorption is provided by 2 m^2 of $\rho = 0.5$, or 5 m^2 of $\rho = 0.8$.

For this imaginary room, we arrive at the finding that the average exitance $M = \mathrm{FRF}/A\alpha$ lm/m^2. It may be noted that for this concept the term exitance in lm/m^2 is preferred to luminance in cd/m^2, as luminance is defined in terms of a luminous element viewed in a specific direction, whereas exitance refers simply to the density of luminous flux from the room surfaces. Exitance is the appropriate term to use where there is no specific viewpoint, as well as having the advantage of not involving the value of π in our calculations.

3. Mean room surface exitance

Within an enclosed space, the mean room surface exitance M_{rs} expresses the average value of indirect illuminance incident on any surface, which may include the cornea of an observer's eye. It is therefore the average value of flux density reflected from all surrounding surfaces, and offers the prospect of a simple measure that may relate to how adequately illuminated a space will appear to be.

Table 1 sets out a proposed scale of M_{rs} related to assessments of illumination adequacy. At a first glance these values seem low, but we have to adapt our experience of light levels to excluding direct flux and considering only light reflected from room surfaces. The scale covers just two decades corresponding to the range of assessments that may be encountered in general indoor lighting practice. The basis of this table has been described elsewhere,[13] and it comes from a variety of sources. In part it is based on other people's research, and an example of how I reinterpret reported research is given in the Appendix. Also, there have been many occasions on which I have involved students in exercises that have required them to make brightness assessments, as I believe that among the first things that students need to learn is to continually develop their own observation-based experience. This table has evolved from these activities, and is proposed tentatively as a basis for applying M_{rs} in lighting design.

Table 1 Tentatively proposed range of subjective assessments of lighting appearance related to mean room surface exitance

Mean room surface exitance (lm/m^2)	Subjective assessment
10	Lowest level for reasonable colour discrimination
30	Dim appearance
100	Lowest level for 'acceptably bright' appearance
300	Bright appearance
1000	Distinctly bright appearance

Real rooms do not have uniform reflectance, so for a more realistic space, let us consider this rectangular room:

> Dimensions: length, 5.2 m; width, 4.6 m; height 3.0 m
> Reflectances: ceiling, 0.75; walls 0.45, floor 0.2

Whatever the activity proposed for this room, our first consideration is that it should appear to be adequately illuminated. For some activities, a subdued or slightly dim appearance might be appropriate, and for this, Table 1 guides us towards a M_{rs} value of 30 lm/m^2. Providing people are not entering from a significantly brighter space, they are unlikely to find the room appearance gloomy, and safe movement will not be a problem providing hazards are reasonably well identified by contrasting surface reflectances. For locations where people will spend prolonged periods, the minimum M_{rs} level of 100 lm/m^2 for 'acceptably bright' appearance may be seen as appropriate, but for this exercise, let us suppose that we wish to provide for a bright appearance, and we aim for an M_{rs} level of 300 lm/m^2.

As we noted at the end of the thought exercise, mean room surface exitance:

$$M_{\mathrm{rs}} = \mathrm{FRF}/A\alpha \; \mathrm{lm/m^2}$$

First reflected flux FRF is the sum of the direct flux reflected from each surface s:

$$\mathrm{FRF} = \Sigma F_{\mathrm{s(d)}} \rho_{\mathrm{s}}$$

And room absorption $A\alpha$ is the sum of surface areas times their absorptance values:

$$A\alpha = \Sigma A_{\mathrm{s}}(1 - \rho_{\mathrm{s}})$$

Room surface absorption values:

Ceiling $5.2 \times 4.6 \times (1 - 0.75) = 5.98$
Walls $2(5.2 + 4.6) \times 3 \times (1 - 0.45) = 32.34$
Floor $5.2 \times 4.6 \times (1 - 0.2) = 19.14$

Room absorption $= 57.5\,\mathrm{m}^2$

$$\mathrm{FRF} = M_{\mathrm{rs}} A_{\alpha} = 300 \times 57.5 = 17\,250\,\mathrm{lm}$$

If we were to use a lighting installation that distributes its flux in various proportions onto the ceiling, walls and floor, we would need to deal separately with the direct flux onto each surface. A procedure for dealing with such situations, which includes internet searching to find luminaires having appropriate light distributions and making use of free download software to complete the calculations, is described elsewhere.[13] For this exercise we will consider the three alternative types of installation indicated in Figure 3, where each installation directs all of its flux onto a single room surface. For each receiving surface s, the total flux from the luminaires $F_{\mathrm{L}} = \mathrm{FRF}/\rho_{\mathrm{s}}$.

For Option 1(Downlighting),

$$F_{\mathrm{L}} = \frac{17\,250}{0.2} = 86\,000\mathrm{lm}$$

For Option 2(Wallwashing),

$$F_{\mathrm{L}} = \frac{17\,250}{0.45} = 38\,000\mathrm{lm}$$

For Option 3(Uplighting),

$$F_{\mathrm{L}} = \frac{17\,250}{0.75} = 23\,000\,\mathrm{lm}$$

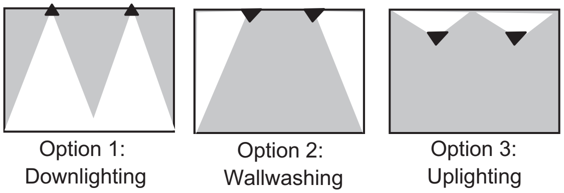


Figure 3 Three alternative ways of lighting the room, where the entire luminaire flux F_{L} is incident either on the floor (downlighting), the walls (walllwashing), or the ceiling (uplighting)

These are the required lumen output values of the luminaires to achieve similarly bright overall impressions in this room, but surely, something must be wrong. We all know that downlighting, provided by high efficacy lamps in mirror-optics luminaires, is the most efficient form of lighting, but it is shown here to need nearly four times as many lumens as uplighting, and this is to achieve the same assessment of illumination adequacy. We also know that uplighting and wallwashing may produce attractive effects, but they are never used where efficiency is a concern. How can this comparison be correct?

The answer is that where the aim is to provide an adequately lit room, it makes sense to direct lumens onto surfaces that will reflect most of them back into the room. The traditional way of measuring illumination gives a totally misleading impression. To hold a light-meter horizontally under a downlighting installation is to measure a stream of photons passing through the space without visible effect on their way to being decimated beneath your feet upon contact with the floor. This may be an efficient way of illuminating the light-meter, but it is a grossly inefficient way of bringing light to the eye from the surrounding environment.

Figure 4 shows the intelligent way to use a light-meter. The operator takes up an overall view of the room and holds the meter up to the eye, shielding it from direct light from the luminaires so that it responds only to reflected light from the room surfaces. The reading in

Figure 4 Using an illuminance meter to gain an indication of mean room surface exitance. Direct light from overhead luminaires is shielded, so the meter responds to reflected light from room surfaces arriving at the eye

lux cannot be regarded as an exact measure of M_{rs} in lm/m^2, as M_{rs} is an average for all directions of view, but this arrangement provides a far better indication of illumination adequacy than measuring the workplane illuminance. It needs to be recognised that this is not simply an alternative way of measuring illumination, but it is a totally different way of thinking about lighting that turns our notions of effectiveness and efficiency upside down. Lamp engineers get excited when they increase the efficiency of one of their products by a few percent, but then, in the name of good practice, we proceed to apply those lamps in ways that under utilise their output by factors of three or four.

Does this mean that we should light every space with uplighting?

Hawkes *et al.*[14] have applied factor analysis to subjects' assessments of 18 widely different lighting distributions in an office, where the only constant aspect of the lighting was that in every case the workplane illuminance was 500 lux. Two independent factors were revealed. One was a brightness dimension, associated with such rating scales as bright/dim, strong/weak, and clear/hazy, and we should expect that this would correlate reasonably well with M_{rs}. The other dimension was named interest, as it was associated with such scales as simple/complex, mysterious/obvious, uninteresting/interesting, and commonplace/special, and for this dimension we should not expect any correspondence at all with M_{rs}.

Returning to the above question, in a room with a conventional arrangement of surface reflectances, uplighting is both an efficient way achieving a M_{rs} target and an effective way of providing for an appearance of brightness. However, this only goes part way towards satisfying peoples' expectations for room appearance, and other aspects of lighting, which may arouse a sense of interest, need to be considered. Apart from the room surfaces, how does the lighting affect the appearance of the objects within the room? To achieve a designed lighting effect, the illuminance distribution has to be tailored for the situation, and this goes beyond the scope of lighting standards.

To specify lighting standards in terms of mean room surface exitance would not guarantee good quality lighting, but nobody should expect standards to do that. The aim of lighting standards should be to specify lighting in terms which relate to user impressions of illumination adequacy, and for that, schedules quoting M_{rs} values would be a significant step forward from current practice.

4. The third stage of the lighting profession

So where are we now? At the beginning of the third stage? Not in this author's opinion. As I see it, the lighting profession is firmly stuck in the rut of a nineteenth century concept. The second stage, with its prospect of rationally based illuminance standards to provide all users with a prescribed high standard of visual performance, has failed. The first stage concept of workplane illuminance dominates not only our standards, but more damagingly, our thinking. We attempt to give the concept credibility by adding to our list of lighting objectives other factors such as visual comfort, but these fail to elevate our thinking to concepts that are anything more than mundane. After all, what is visual comfort other than the elimination of discomfort?

The concept of mean room surface exitance is proposed as a basis for specifying illumination adequacy in lighting standards. This proposal is based on reason rather than research, and it is hoped that someone somewhere will feel motivated to investigate the validity of the concept for this purpose. It is believed that the simple form in which it is being proposed for lighting standards will provide better that current specifications for ensuring adequate, effective, and efficient lighting in general practice, but there is an additional benefit. Research leading to increased knowledge of human assessment of room brightness would have direct relevance to lighting design. McKennan[15] has examined subjective assessments of room brightness as a sequential experience as subjects moved through 16 differently illuminated rooms, and an analysis of his data described in the Appendix reveals not only how likely assessments of brightness may be related to M_{rs}, but also how these assessment may be influenced by previous adaptation. Research findings of this sort may be applied for planning lighting for adjoining spaces that will be experienced in sequence.[13] It may also be noted that the concept ignores direct light from the light sources, and here again, new research could provide useful knowledge on the likely effect of direct flux on assessments of room brightness. Studies by Loe *et al.*, [16,17] which sought a metric for subjective assessment of the effect of lighting on room appearance, concluded that the average luminance of a 40 degrees wide horizontal band gave better agreement with assessments than taking the average luminance of the whole field of view. The reason for this may have been that applying this band to the experimental situation would have had the effect of eliminating direct light from the overhead luminaires. If so, this would tend to confirm that ignoring direct light is better than including it, but perhaps further research would show that including it as a negative factor would give still better agreement.

Although it has been convenient to examine the concept for electric lighting installations, the M_{rs} concept should be equally valid for daylight, and this opens up another long-standing field of misapplied science. The locations where daylighting standards have been applied with some rigour include school classrooms, hospital wards, and multi-storey apartments, and almost invariably the standards are specified in terms of the daylight factor, which is defined in terms of relative daylight illuminance on an indoor horizontal workplane. It should be a matter of wonder that since quite early in the last century the prevailing wisdom has been that people's assessments of how adequately illuminated these spaces would appear to be should be determined by the light level on a notional horizontal workplane. The concept that lighting adequacy is determined by ability to read from a sheet of paper placed on a horizontal workplane was a legal argument devised almost one hundred yeas ago, and it continues to dominate all aspects of lighting practice.

What might be the symptoms of the lighting profession actually progressing into the third stage? As I see it, the crucial factor is a switch from thinking about light incident on planes, to light arriving at the eye. We have looked at this through calculations, but let us

Figure 5 Using a 'measuring eye' (in this case a webcam) to capture an image of the field of view, including direct light from the luminaires

look again at light measurement. The light meter being held in Figure 4 might seem to be a technically advanced item of equipment, having a silicon photodiode sensor and a digital LCD readout, but it measures the nineteenth century metric of cosine-weighted planar illuminance. In Figure 5, this meter is replaced by a 'measuring eye'. The instrument being held is actually a webcam, and to suit our purpose it would need to be calibrated, and probably would need a rather higher dynamic range. Nonetheless, this ubiquitous instrument serves to illustrate the principle. The operator views the room, and the image is captured on a laptop computer. The next task is to separate the direct and indirect flux. This could be done using a mouse to identify the luminaires, and an appropriate software package would make this task fairly simple. After that, the computer would be able to provide a prompt measure of mean room surface exitance, the accuracy of which would depend on the extent to which the chosen view was representative of the overall view. Not only this, but it could also provide direct measurement of discomfort glare. In this way, a third stage lighting professional would be able to quickly assess both illumination adequacy and discomfort glare on site and without being restricted to regular installations. In fact, the effects of reflected glare, and of combinations of daylight and electric lighting, could all be included in the measurement.

Other applications for this approach come to mind. To specify lighting standards in terms of M_{rs} does not mean that task lighting should be ignored. Visibility problems in workplaces inevitably occur, even in adequately illuminated rooms, whether due to intrinsic difficulties in certain visual tasks or visual limitations of individual operators. Instead of regarding the visual task as the determinant of the overall illuminance level, the aim should be to provide appropriate room brightness, and then to identify visual problems and deal with them wherever they occur. The measuring eye could be used to examine a visual task where the aim is to foresee situations where the general illumination might not be satisfactory for some users. Two images would be required: one of the user's field of view to enable disability glare to be taken into account, and the other, for which a lens attachment would be required, to capture a foveal view of the visual task. We should become accustomed to the idea that well equipped and well lit workplaces would not only make task lights available to staff who request them, but would also provide guidance on how to apply them effectively. This is better practice than ramping up the general lighting to provide for the most problematic situation that might occur.

Once the lighting profession has woken up to the potential offered by 21st century measuring equipment, it would be only a small step to add a CCD-based spectrometer that plugs into a USB port to enable on-site measurement of visual parameters such as colour temperature, colour rendering, scotopic/photopic ratio and mesopic illuminance. It also opens the door for lighting professionals to become involved in non-visible effects of light exposure, such as photobiological, erythemal (skin reddening) and photochemical (fading) responses. All the necessary hardware is currently available, and there is no reason why its application in lighting practice should not be provided for in reasonably affordable packages. This development could serve to free lighting professionals from the restricting effects of having the fundamental concepts of photometry defined in terms that assume the achromatic visual response of a photopically adapted human eye to be the only effect of light exposure.

To bring this discussion back to general lighting practice, the emphasis that has been given to lighting standards is because they underpin so much of the process of indoor lighting design. Although some insist that what is currently specified is illuminance on the actual task plane, we all know that 'a 500 lux installation' is one that delivers that illuminance on the horizontal workplane. In general practice, the illuminance specified in the standard is a prerequisite, after which higher order aspects of design may be attended to, or not, according to the aspirations of the designer and the client.

To specify indoor lighting standards in terms of reflected light at the eye would be to rethink the first step of the procedure. No doubt lighting manufacturers would be quick to offer standardised economical solutions to satisfy the new standards, but creative designers would have a new dimension of freedom. The approach that I advocate to my students is to think of the room that they are to illuminate as a secondary luminaire which illuminates the eye. Just as they examine the optical properties of the primary sources, whether luminaires or windows, in order to understand how they will distribute flux within the room, so they may examine the optical properties of the room surfaces to understand how they will interact with the distribution of direct flux and present light to the eye. I believe that this approach has the potential to enable lighting professionals to interact more closely with other design professionals, particularly architects and interior designers.

5. Summary and conclusions

The prime role of standards is to ensure provision of adequate illumination, and conventionally this has been seen as providing for human need to perform common visual tasks. However, studies of light levels required to satisfy this need, such as reading printed material, show that they are far below the levels that are currently provided to satisfy occupants' demands for spaces to appear acceptably bright. It is only when difficult visual tasks are encountered that visual performance becomes a relevant design criterion, and in recent years technology has effectively eliminated such tasks from most indoor workplaces.

The central argument of this paper is that for the great majority of indoor locations, including workplaces, the prime purpose of the lighting is to provide for surroundings that appear acceptably bright, at least to the extent of avoiding the appearance of being dull or gloomy. The convention of specifying illumination standards in terms of illuminance incident on workplanes is inappropriate for this purpose. Instead, a metric is needed that corresponds to reflected light arriving at the eye from surrounding room surfaces.

The concept of mean room surface exitance M_{rs} is proposed as a potentially suitable metric. It is the measure of average illuminance at all points within the space due to reflected light from the room surfaces, with direct light from either luminaires or windows excluded. This is a simple metric, and as discussed, research might suggest that it needs some elaboration for reliable application. Procedures for calculating and measuring M_{rs} are outlined, and a table of M_{rs} values related to likely subjective assessments of room brightness is tentatively proposed.

The essential difference of specifying general lighting standards in terms of M_{rs} is a change of thinking from light incident on workplanes to light arriving at the eye. The effect would be profound, and it would lead to radical reassessment of how lighting installations should distribute flux within spaces to provide effectively and efficiently for illumination adequacy. The M_{rs} concept also provides a basis for modulating room brightness differences as part of a lighting design strategy.[13]

These ideas are discussed in the context of three stages of the lighting profession, where the objective of the first stage was provision of uniform illuminance on a horizontal plane, and of the second stage, visual performance-based lighting standards. The view is expressed that the second stage has failed, and that current practice remains dominated by the first stage objective. It is suggested that the third stage will have as its objective the provision of acceptably bright surroundings, and for this, lighting standards will be based on reflected light arriving at the eye.

Acknowledgements

The author thanks Mr J.A. Lynes for his comments on a draft of this paper.

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Appendix

G.T. McKennan has reported a study (reference 15 above) in which 10 subjects walked separately through a series of 16 indoor spaces while the experimenter recorded their evaluations of the brightness of each space on a seven-point scale. On completion of the outward journey, the subjects retraced their steps on an inward journey so that 15 of the spaces were evaluated approaching from opposite directions. McKennan's purpose was somewhat different from that of the author, who has used his reported data to explore how the assessments of room brightness related to mean room surface exitance M_{rs}.

Table A1 lists the reported average luminance in cd/m^2 of each location, followed by equivalent M_{rs} values in lm/m^2. The next column gives the mean brightness evaluations B of the 10 subjects for both outward and inward journeys on the following scale:

7 – Very bright
6 – Bright
5 – Light
4 – Satisfactory
3 – Dim
2 – Dark
1 – Very dark

It can readily be seen that B values tend to be influenced by the previous exposure of the subjects. The column of present/previous exposure ratio (PPER) gives the ratios of M_{rs} values that the subjects were exposed to, and the brightness best estimate (BBE) for each location is an estimate of B for PPER = 1.0, that is to say, what the brightness value would be for subjects entering from a space having matching M_{rs}. The following expression was applied to make allowance for the previous exposure condition:

$$\mathrm{BBE} = B_{\mathrm{out}} + (B_{\mathrm{out}} - B_{\mathrm{in}}) \times \left(\frac{\log \mathrm{PPER}_{\mathrm{out}}}{(\log \mathrm{PPER}_{\mathrm{in}} - \log \mathrm{PPER}_{\mathrm{out}})} \right)$$

The data points are plotted in Figure A1, and the regression of the trend line is:

$$\mathrm{BBE} = 1.33 \log M_{rs} + 1.75$$

On the seven-point scale, 3 Dim corresponds to $M_{rs} = 9$ lm/m^2; 4 Satisfactory to 49 lm/m^2; and 5 Light to 274 lm/m^2. These values may be compared with Table 1.

The final column in Table A1 gives the difference in actual brightness assessment and the estimate of what the assessment would be disregarding previous exposure. These values are plotted against log present/previous exposure ratio in Figure A2, where a positive value of log PPER indicates that the subjects have entered from a more dimly lit space. The trend line shows the effect of such previous exposure would be to increase the brightness assessment, and vice versa, but the effect is fairly weak. It takes a 10-fold change of M_{rs} to induce a change of 0.5 units on the seven-point brightness scale.

While this analysis gives an indication of how brightness assessments of lit spaces may be related to values of mean room surface exitance, it will require more research of this type to establish reliable data for application in lighting design. A major difficulty in comparing studies from different researchers is the widely different subjective evaluation scales that are used. There is a substantial literature on this topic, and the seven-point scale used in this study serves to illustrate some of the problems. The mid-point of the scale is 'Satisfactory', which is a different type of assessment from judging brightness or darkness. There is a mixture of terms both above and below this mid-point which may have different meanings, and yet these are set on a numerical scale that implies equal intervals between the points. Although I have subjected the data to only simple forms of statistical analysis, these concerns

Table A1 A series of 16 locations (column 1) was viewed in the sequence of an outward journey followed by an inward journey. Columns 2 and 3 show average luminance L (cd/m^2) and mean room surface exitance M_{rs} (lm/m^2), respectively, for each location, and column 4 shows average brightness estimates B on a 7-point scale. The present/previous exitance ratio PPER (column 5) is the ratio of M_{rs} in the present location to that in the previous location, and the best brightness estimate BBE (column 6) is an estimate of what the value of B would have been if PPER = 1.0. The final column gives values for the difference between the actual brightness estimate B, which may be affected by previous adaptation, and the best brightness estimate BBE, which assumes that previous adaptation matches that of the present location. After McKennan, 1981[15]

Location	Luminance L (cd/m^2)	Exitance M_{rs} (lm/m^2)	Brightness B	PPER	BBE	B-BBE
0	90	283	6.0			
1	41	129	4.1	0.46	4.3	−0.2
2	41	129	4.1	1.0	4.1	0
3	15	47	3.3	0.37	3.7	−0.4
4	6	19	2.4	0.4	2.8	−0.4
5	6	19	2.9	1.0	2.9	0
6	72	226	5.0	12.0	4.9	0.1
7	72	226	5.3	1.0	5.4	−0.1
8	72	226	4.7	1.0	4.7	0
9	17	53	4.0	0.24	4.3	−0.3
10	16	50	4.1	0.94	4.1	0
11	5	16	2.8	0.31	3.2	−0.4
12	3	9	3.9	0.6	4.1	−0.2
13	40	126	4.7	13.3	4.4	0.3
14	40	126	5.2	1.0	5.2	0
15	58	182	5.1	1.45	4.9	0.2
16	58	182	6.2	1.0		
15	58	182	4.9	1.0	4.9	0
14	40	127	4.9	0.69	5.2	−0.3
13	40	127	4.4	1.0	4.4	0
12	3	9	2.9	0.07	4.1	−1.2
11	5	16	3.4	1.67	3.2	0.2
10	16	50	4.3	3.2	4.1	0.2
9	17	53	4.3	1.06	4.3	0
8	72	226	5.5	4.24	4.7	0.8
7	72	226	5.6	1.0	5.4	0.2
6	72	226	4.9	1.0	4.9	0
5	6	19	3.1	0.08	2.9	0.2
4	6	19	2.8	1.0	2.8	0
3	15	47	4.1	205	3.7	0.4
2	41	129	4.9	2.73	4.1	0.8
1	41	129	4.3	1.0	4.3	0
0	90	283	5.9	2.2		

raise questions about the validity of the findings. It would be a big step forward if researchers could agree on a scale for subjective assessments of brightness.

The author expresses gratitude to Mr McKennan for the detailed reporting of his experimental data, while he accepts full responsibility for the conclusions that he has drawn from these data. He also thanks Mr J.A. Lynes for drawing his attention to this study.

Discussion

Comment 1:

L Bedocs (Strategic Lighting Applications, Thorn Lighting Ltd, Butchers Race, Green

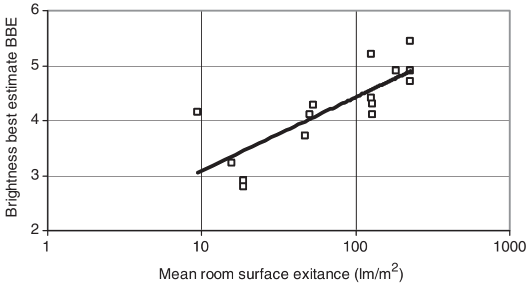

Figure A1 Brightness best estimate for present/previous exposure ratio PPER = 1.0 relative to mean room surface exitance M_{rs}

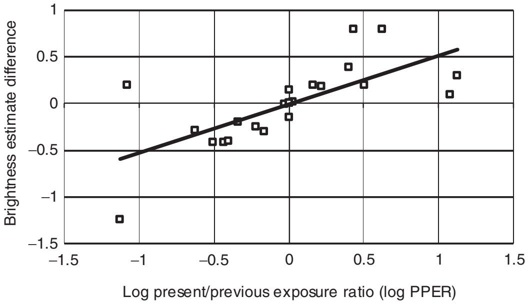

Figure A2 Brightness estimate differences due to the effect of previous exposure relative to logarithmic values of present/previous exposure ratio

Lane Industrial Estate, Spennymoor, County Durham, DL16 6HL, UK)

I much welcome this paper as it provides a useful reminder of the importance of lighting not only for the work plane, but also for the whole interior of the space we occupy. However, I do not agree with the author's claim that our lighting standards, codes and guides only focus on work plane illuminance recommendations and ignore the requirements for adequacy of lighting in interiors. Clearly standards and codes must focus on lighting the task after all that is what we want to see. The task is not always on a horizontal plane and that is why standards and codes no longer specify the illuminance on a horizontal work plane but concentrate on task area illuminance. I wonder why the author had not acknowledged the many other quality lighting criteria recommendations found in the body of standards and codes. We already have recommended criteria for reflectance and illuminance ratios for the major room surfaces that contribute to adequacy of illuminance in the space. It is true that many designers plan lighting schemes to just meet the work plane illuminance and ignore other lighting aspects. I am sure these designers will continue to cut corners and will ignore these new recommendations and will not calculate the proposed 'mean room surface exitance'. Could the author comment on how such designers could be motivated to be more considerate and design schemes to provide good visual environment.

The new criteria the author is proposing is interesting but I feel a great need for quantifying and validating any proposed values particularly if these will be based on illuminance on the eye. I am concerned that we will end up with lot of light on the eye but cannot see the task clearly. In the revision of the EN 12464-1 standard covering lighting of indoor work places we are proposing to introduce minimum illuminance values on the major surfaces and minimum mean cylindrical illuminance in the interior of the space. The aim of these measures I feel is the same as the author's proposal and I would like to know if the author supports this approach. Also, as an enthusiast of uplighting, I am delighted to receive endorsement that this technique not only provides good task illumination, but also gives the best adequacy of illuminance in interiors.

I agree with the author that we are not at the 'third stage of the lighting profession' but not for the same reason. In my 50 years in lighting practice I found that we have moved standards of illumination forward continuously. The stages of developments are more related to steps in technology advances in light sources, lighting techniques and materials. As a result we do have much better lit environments today when I compare to those we had in the 1960s. I, as one who worked with HC Weston on visual performance investigations, feel that lighting the paper based task is still very important. In fact I am reading the paper version of this report on the train travelling home to Darlington. I make this remark to remind the author that although we do use electronic media via screens to do much of our work the paperless workplace predicted some 30 years ago is still a long way from being a reality. In the mean time we must design our lighting solutions to illuminate all task types and provide adequate light in the interior for human comfort.

Comment 2:

KP Mansfield (The Bartlett School of Graduate Studies, University College London, Gower Street, London WC1E 6BT)

I have always felt that Waldram's classic paper on Studies in Interior Lighting[1] provides a useful conceptual framework when considering the lighting of a space: the gross apparent brightness pattern on boundary surfaces which defines architectural volume and the detail apparent brightness pattern which contributes both to the modelling of people and objects set in front of those surfaces and the modelling of the space itself. The author's paper is a welcome contribution to the discussion of boundary surfaces and follows on from his important previous work on modelling when he considered the appearance of solid objects influenced by directional lighting[2] and the development of a system of applied photometry.[3]

The author calls for a research programme to allow the reliable comparison of studies from researchers using widely different subjective evaluation scales. It was my understanding that one of the purposes of a task group set up by the CIE (TC 3-34 Protocols for Describing Lighting)[4] was 'to establish a catalogue of application-independent descriptors of lighting' and 'to develop a measurement protocol for each of the descriptors'. The task group is to report in the spring of 2009. Has the author any knowledge as to whether their conclusions will satisfy his expectations?

The author refers to the use of a webcam to capture views of a room and provide a measure of mean room surface exitance after processing. I think he underestimates the progress that has been made. High Dynamic Range Images (HDRI) can already be created using multiple exposures of a static scene using consumer level digital cameras and in the future manufacturers will build HDR imaging into camera hardware. Jacobs[5] provides an informative review.

From my knowledge of the Loe et al. work quoted by the author, the experimental room was so arranged as to exclude as far as possible a direct view of the luminaires. Thus the metric to which he refers (the average luminance in the 40° horizontal band) rather emphasises the significance of vertical boundary surfaces in the field of view. To my knowledge only a little work has been done on the significance of luminaire luminance. Bernecker and Meier's thesis was that a bright element in an observer's field of view was a determinant to the overall perceived level of brightness in the environment. Their conclusion was that there were two mechanisms – 'one responding to where the light source is, and one responding to the patterns of light themselves'[6] However, Rowlands et al.[7] found no strong correlation between lighting adequacy and luminaire luminance. Their results indicated the importance of the lighting of surfaces of the interior in providing adequate lighting. Contemporary architectural interiors frequently incorporate self-luminous sources and, with the future use of Organic Light Emitting Diodes (OLEDs) resulting in a variety of self-luminous surfaces within interiors, I suspect that we will have to revisit modes of appearance concepts as described by Judd.[8] Thus a stimulus perceived as the coloured surface of an object – the surface mode – is distinguished from light and colour perceived as emerging from a self-luminous body, such as a fluorescent lamp – the illuminant mode. I suggest that mean room surface exitance would be unable to characterise such lit spaces.

The author does not expect mean room surface exitance to have any correspondence with the dimension of interest which as been found in various studies. But what if you capture the luminance data from a view of the room? Such data can be displayed as greyscale images in the spatial domain but image processing science proclaims the 'utility' of working in the frequency domain to perform certain image measurement and processing operations. Fourier transform power spectra of images can reveal characteristic features which can be used for example in the classification of land use from aerial photographs. It seems that Fourier analysis can give useful insights about the structure of images and it has been proposed that the brain performs a 'crude' Fourier analysis of the visual scene.[9] I have described elsewhere how Fourier techniques are a possible way to distinguish between lighting conditions on the psychological construct interest.[10]

However, there are doubts about the use of luminance in this way. The author's suggestion to use mean room surface exitance as a simple, convenient exploratory tool to define the adequacy of illumination in a room is a good one and, in Marsden's words,[11] avoids 'the embarassment of needing to define the adaptation level'. I welcome further dissemination of this tool as a teaching resource for students and as a device to realign lighting design practice.

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Comment 3:

HM Brandston (348 Catskill View Road, PO Box 28, Hollowville, NY 12530, USA)

As a lighting designer with over 50 years of experience I always light the spaces first and then supplement for the tasks. I do not light for the tasks and then supplement for the spaces. Energy code restrictions might not leave enough power to light the spaces appropriately. Most task recommendations significantly exceed what is required to perform the tasks swiftly and accurately as Cuttle points out.

I also believe that all the progress in light source and luminaire technology or current calculation procedures has done little to advance the requirements for or the practice of designing good lighting systems. The attempt to use visual performance criteria resulted in a scattered disarray of over-specification of illuminance levels. It was a foolish premise to believe that task illumination would provide lighting for spaces, a clear case of lighting people being hoodwinked by the tyranny of science. This means that some new 'stage' might hopefully provide an advancement of the art. It certainly is a notion that should be given serious consideration. Before we do that however, we must feel confident about why all previous iterations are truly not working well.

I agree that providing lighting for the horizontal plane or for visual performance have not produced good lighting solutions but it is not clear to me that the aim of any lighting design should be to '… meet user expectations that the spaces that they occupy to be adequately lit.' I think there is much more to it than that. I would hope that the lighting might aid in the occupants liking their spaces. Further, I am not certain that the recommendations or the metrics for specification, calculation and measurement are correct as I am not familiar enough with general practices which, after perusal, I tend to ignore anyway. What puzzles me most is that we had a significant calculation tool in scalar, vector/scalar ratio and mean spherical illuminance that we seem to have been lost. I suggest we go back to the 1973 IES Code For Interior Lighting and reconsider resurrecting those calculations as a tool in the arsenal of designing lighting systems along with some of the other insightful considerations in that tome. When we do that we can more thoroughly reassess where we stand. This 'stage 3' proposal will need to be tested.

I am most insecure that the new proposed calculations will lead to a general acceptance of room lighting. Although numbers may theoretically describe the complexity of the human visual system, they cannot cope with personal perception. When trying to find a solution that is deeply satisfying in human terms, 'numbers methodology' is suspect. Further, we should stop the search for inventing a procedure to lead us to quality lighting. That is a thought-free process. Surely we can do better than that.

Reply to comments:
C Cuttle

A prime purpose of this paper was to stimulate discussion, and what an excellent range of opinions has been presented. However, among the diversity I perceive a common thread that causes me some concern. All three contributors express, in their own ways, the view that there is more to lighting design than I have acknowledged. I am well aware of this, and my own published works cited by myself and Mansfield bear testimony, but this paper is not about lighting design. It deals with the more prosaic topic of lighting codes and standards.

Whether we like it or not, it is the schedules of illuminance values that are generally recognised as encapsulating the authoritative wisdom of the lighting profession, and this is so whether they are issued as recommended minima or mandatory standards. I think it is no exaggeration to say that for every square metre of lighting that has been conceived by an imaginative and creative designer, 100 m^2 of lighting has been planned (I do not say designed) by an engineer whose task has been to devise a layout of air diffusers, loudspeakers, sprinklers, and luminaires. We need to recognise that these are educated people who are aware of the recommendations of the relevant professions for thermal comfort, air quality, background noise level and illumination, and from their perspective, the illuminance schedules that are published either by or with the endorsement of the lighting profession provide the appropriate basis for their work. Even if the illuminance value is not stated to relate to the horizontal work plane, this, together with the uniformity ratio, is assumed both for lack of information about specific task planes and because of their role in determining the lighting power density. This is the reality, and we cannot avoid our responsibility by pointing to the plethora of recommendations that lurk in the text accompanying the schedules. It does matter that the schedules are sensibly related to the expectations of users, because for the great bulk of lighting practice, they are the principal means by which we may influence the provision of lighting. They should be specified in terms that ensure adequacy of illumination; that lead towards efficient lighting practice; and do not get in the way of designers who aim for 'a solution that is deeply satisfying in human terms' (to quote Brandston). My starting point is that the current schedules of workplane illuminance values fail on all three counts.

Bedocs welcomes the paper and then proceeds to staunchly defend the *status quo*. He states that the task is 'what we want to see', but from the arguments that I have advanced in the text it should be clear that I do not see task lighting to be a valid basis for general lighting practice even in workplaces, and definitely not in the broader range of the built environment. Bedocs feels 'a great need for quantifying and validating any proposed values', and goes on to describe his own involvement in the revision of an EN standard that will propose minimum room surface illuminance values and mean cylindrical illuminance within the space. He asks if I support this approach, but I am not aware of any research that quantifies or validates such an approach. I note, though, that his approach relates to illumination incident on viewed surfaces and not to light exiting those surfaces, which makes me unenthusiastic. I do, however, see a ray of hope. Bedocs is 'delighted' to find how well uplighting performs when measured in terms of mean room surface exitance M_{rs}. This is simply because if the aim is to achieve the appearance of a well lit room, it makes sense to direct the light onto surfaces that will reflect high proportions back into the space. Perhaps if he was to see a well lit room to be the primary aim for general lighting, he would find this to be a basis for lighting practice that would accord well with his own observations. There are, however, other areas of disagreement within this discussion that are not likely to be easily resolved. It may be noted that Bedocs' view of the impact of developments in lamp and luminaire technology upon lighting practice, stated in his final paragraph, is diametrically opposed to the view expressed by Brandston in the opening sentence of his second paragraph.

The M_{rs} concept fits comfortably with Brandston's design approach to 'light the spaces first and to then supplement for the tasks.' Of all the ways in which lighting may affect the appearance of a space, the most obvious is making it appear brightly lit, or dimly lit, or something in between. In *Lighting by Design* I explain how the designer may apply M_{rs} to plan the modulation of bright/dim response for a series of differently lit spaces to be viewed sequentially, this being part of a lighting design strategy and, in my opinion, beyond the scope of standards. To employ the same metric to specify a light level that would lead to most people assessing a space to appear adequately lit would be an entirely appropriate role for standards, and its only impact on lighting design would be to restrict designers from providing lighting likely to be assessed as inadequate. Perhaps even Brandston would choose to take account of lighting standards if they were specified in this way, but in the meantime he is justified in ignoring them. They are unrelated to human satisfaction, and, as I have demonstrated in the text, they lead to grossly misleading notions of lighting efficiency.

Brandston mourns the demise of the 1973 IES Code, and I remember that document well as I was working in the UK at the time and my colleagues and I contributed a quite substantial amount of material dealing with the vector/scalar concept to the Code. A few years later, Anthony Slater told me how he and some colleagues at the Building Research Establishment had conducted a survey of major lighting users, and had learned that none of that material was of any interest to them whatsoever. Following their review, the task illuminance schedules were retained and the spatial illumination material was dropped. Although I was disappointed at the time, I now have no argument with that decision. The aim of the Code should be to provide lighting users with the authoritative guidance they need, and this should not be confused with the role of professional lighting societies to nurture the process of design in other ways, particularly through education, research, publication and awards.

Mansfield brings to the discussion the viewpoint of an educator and researcher, and I am grateful to him for directing my attention to some relevant research that had escaped my attention. In reply to his question about the forthcoming report from CIE TC 3-34, although I have contributed to this committee''s work in the past, I have recently been unable to maintain involvement and I am unsure of the current situation.

Mansfield proposes that instead of making the distinction between direct and reflected flux, the relevant distinction is to identify elements that are perceived in the surface mode of appearance, and I would welcome an opportunity to pursue this thoughtful proposal with him. We would, however, need to keep in mind that to be useful, codes or standards have to be capable of simple specification, measurement and calculation. While he points out that HDRI technology has progressed far beyond the webcam example that I have given, this technology is for research applications and is unsuitable for everyday use by practitioners.

To set our own house in order, we need research directed to the fundamental issue of what are the principal photometric parameters that may be used to predict the likely assessment of brightness or dimness of lighting in an enclosed space? It is sobering that at our present stage of evolution we do not have clearly defined answers to this question. The basis of our lighting standards should be to define a minimum level of lighting for a given space that will ensure that a substantial majority of the occupants would assess the illumination to be adequate, meaning that they would not find the appearance of the space dull or gloomy. Light levels based on visual task analysis cannot be relied upon to do this. Whether or not mean room surface exitance is found to be sufficiently reliable, I feel convinced that for a metric to be valid for this purpose, it will have to be based on light at the eye. It will need to be reasonably simple to measure and calculate; to provide a basis for evaluating efficient use of energy and sustainability of lighting practice; and it should serve as a starting point for lighting design.

4. SECOND SUBMITTED PUBLICATION

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45(1): 22-39.

The currently accepted notion that the basic purpose of general lighting practice is to enable performance of visual tasks is examined and found to be lacking in substance. It is proposed that the purpose of lighting should be redefined in terms of the visual experience of illuminated surroundings, and two criteria are proposed for this purpose, both of which represent significant departures from conventional practice. The first assesses the adequacy of illumination for an activity in terms of the density of reflected light from surrounding room surfaces, and the second is concerned with how the luminaire luminous flux is directed onto selected target surfaces. Taken together, these criteria offer a quite new approach for designing lighting installations for general practice.

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A new direction for general lighting practice

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The currently accepted notion that the basic purpose of general lighting practice is to enable performance of visual tasks is examined and found to be lacking in substance. It is proposed that the purpose of lighting should be redefined in terms of the visual experience of illuminated surroundings, and two criteria are proposed for this purpose, both of which represent significant departures from conventional practice. The first assesses the adequacy of illumination for an activity in terms of the density of reflected light from surrounding room surfaces and the second is concerned with how the luminaire luminous flux is directed onto selected target surfaces. Taken together, these criteria offer a quite new approach for designing lighting installations for general practice.

1. A divided profession

The first illuminating engineering societies, formed in the early years of the last century, had no doubt that the purpose of illumination was to provide for visibility, later defined in terms of visual performance. Early schedules of recommended illuminance levels were set for efficient performance of typical visual tasks, but around the middle of the century, soon after the introduction of the fluorescent tube, those levels started to climb towards their current values, despite widespread application of technology over the same period to make visual tasks easier. Nonetheless, visibility continues to be quoted as the fundamental purpose of lighting. This is succinctly expressed in the Illuminating Engineering Society of North America's 'Guide to designing quality lighting for people and buildings' (2008), which opens with 'Task visibility is essential to lighting design; lighting exists to enable vision.'

This viewpoint deserves some examination. Figure 1 shows that, for a normal sighted 25-year-old subject, the typical reading task of black 12-point type on white paper requires just 20 lux to provide for the relative visual performance criterion of $RVP = 0.98$, this value being generally accepted as the highest practical RVP level for lighting applications. It can be seen that the font size would have to be reduced to 6-pt for the required illuminance to exceed 100 lux, or alternatively, reduced to 10-pt but printed onto dark-coloured paper, which has the double effect of reducing the background luminance and the task contrast. However, this value of 100 lux falls far short of the levels conventionally provided for applications where reading tasks are prevalent, which typically fall within the range 300 to 500 lux, and it is clear that such levels can be justified on the basis of visual performance only by presuming that either the users are partially visually defective or that they are persistently required to read very small print with very low contrast on low reflectance backgrounds. We are now surrounded by examples of recommended illuminance levels being far in excess of levels required to satisfy visual performance needs, while users are complaining of 'cave effect' and bland, gloomy workplaces.

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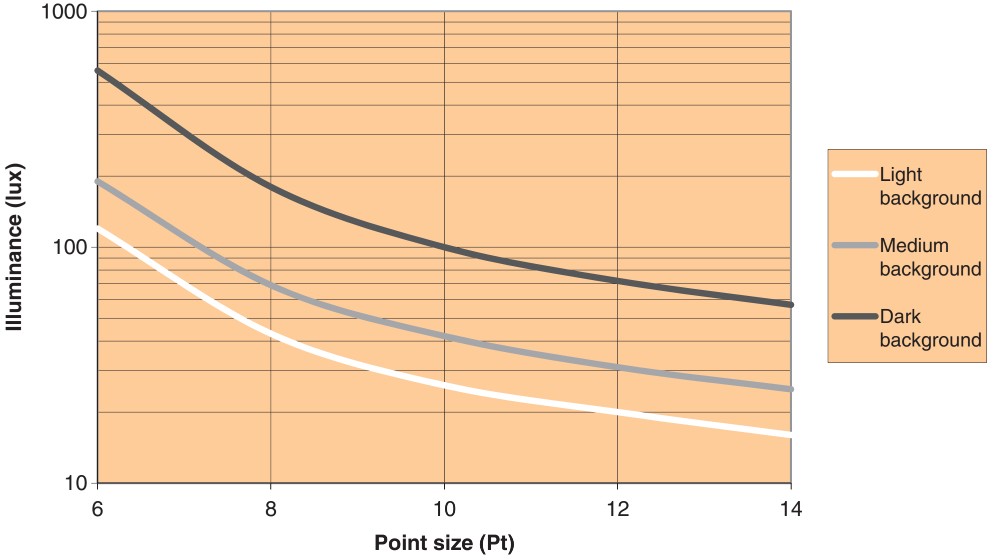

Figure 1. The task illuminance required to provide for relative visual performance RVP = 0.98 for a range of reading tasks. The reader is a normal-sighted 25-year-old with a viewing distance of 350 mm. The reading matter is black print, ranging from 6 - to 14-point size, on three types of paper: light (reflectance $\rho = 0.9$); medium ($\rho = 0.6$); and dark ($\rho = 0.3$).

Also around the middle of the last century, a new breed of lighting designer emerged. In the USA these were often stage lighting designers who had established close working relationships with some of the leading architects of the day and had brought the magic of the theatre into architecture. A rather different approach emerged in the UK that was largely attributable to one man: JM Waldram, originator of the Designed Appearance method.[1] While design philosophies may have differed, these lighting designers saw the purpose of lighting quite differently from the visibility approach: for them, it was a matter of how lighting may be applied to affect the appearance of surroundings, particularly of indoor spaces.

This difference of seeing the purpose of lighting being to provide for *visibility* or *appearance* continues to divide lighting professionals into two distinct camps that read different journals, attend different conferences, and join different professional groups. Worse, the division is widening. Lighting regulations made with the best of intentions – resources management, environment protection, and sustainability – follow the pattern set by the 'visibility' camp in that the provision of illumination is assessed in terms of illuminance values measured on 'visual task planes', which is almost invariably interpreted as referring to the horizontal work plane. A couple of examples will suffice to confirm the extent to which this concept pervades current thinking. The Society of Light and Lighting (SLL) Lighting Handbook (2009) states in relation to office lighting, 'Unless specified otherwise, the recommended maintained illuminance is measured on a horizontal working plane at desk height.' Again, the Handbook, and also the latest European workplace standard, EN 12464-1: 2011, prescribe a 'modelling index' defined as the ratio of mean cylindrical illuminance to the horizontal illuminance. It is obvious that the people who promulgate this index are unable to visualize a 'flow of light' other than vertically downwards, as produced by a uniform, overhead array of luminaires directing light onto the horizontal working plane. A lateral 'flow', as typically produced for highlighting an object of interest, or alternatively, as provided by side windows, gains no acceptance on this modelling index.

This preoccupation with the horizontal working plane means that the schedules intended to specify illumination adequacy have the effect of defining its distribution. As only lumens that are incident on the horizontal working plane count, demands for efficient lighting require that luminaires concentrate light onto that plane. Furthermore, although some standards state that their scope is restricted to workplaces, the lighting solutions that they advocate have become widely recognized as representing efficient lighting practice, so that they are applied much more broadly.

This situation is anathema to the 'appearance' camp, for whom the essence of lighting design is devising light distributions to suit individual locations and activities. They contrast brightness and dimness to influence the overall appearance of space and to produce local emphasis and modelling, which may come from any direction. Minimum work plane illuminance and uniformity requirements simply get in the way of what they are aiming to achieve, and in fact, they do not serve at all well the objectives of either camp. There is a real need for a totally new approach to prescribing the basis of lighting practice.

2. Two lighting design criteria for general practice

It is proposed that the basic purpose of lighting is redefined in terms of two lighting design criteria, both of which relate to the visual experience of lit surroundings, and both of which may be specified in photometric quantities that can be measured and calculated. While this paper deals with indoor spaces illuminated entirely by electric lighting, a future paper dealing with daylighting practice is envisaged.

The first of these criteria is perceived adequacy of illumination (PAI), which refers to the level of illumination that is likely to be judged just sufficient to make a space appear acceptably bright for the activity it houses. It is recognized that spaces where activity levels are high need to appear more brightly lit than those associated with more sedentary activities. The PAI level may be specified in terms of mean room surface exitance (MRSE), which is the measure of the overall density of reflected light within a space, measured in lm/m^2.

The second criterion is illumination hierarchy (IH), which involves devising distributions of illumination to express the visual significance of the activities or the contents of spaces. This may be achieved by controlling the distribution of illumination to express the function of a space or to give emphasis to selected objects. It is specified in terms of the target/ambient illuminance ratio (TAIR), which is the ratio of local illuminance incident on a target surface or object, to the pervading ambient illumination level indicated by the MRSE.

3. Mean room surface exitance

It has been shown[2,3] that:

$$MSRE = \frac{FRF}{A\alpha} \tag{1}$$

where FRF is first reflected flux, being the sum of products for each surface *s* of direct illuminance, area, and reflectance:

$$FRF = \sum E_{S(d)} \cdot A_S \cdot \rho_S \tag{2}$$

And $A\alpha$ is the room absorption, being the sum of products for each surface *s* of area and absorptance:

$$A\alpha = \sum A_S \cdot \alpha_S = \sum A_S \cdot (1 - \rho_S) \tag{3}$$

While it is quite straightforward to calculate MRSE from the above equations, measurement requires some thought. As MRSE is the average of flux densities exiting, or emerging from, all surfaces within the space, no single measurement can completely define its value. An approximate value can be obtained by taking up a position that brings most of the space into view, holding an illuminance meter vertically at eye level, and shielding it from direct light while taking a reading. Making comparative measurements in adjoining spaces with differences of light distribution and perceived levels of brightness can be an instructive exercise, but this procedure would not do for verification.

High dynamic range imaging (HDRi) has been proposed[4,5] for this purpose, and Figure 2 shows an HDR image produced from a series of differently exposed images from a tripod-mounted, calibrated digital camera fitted with a full-field lens. From the series of images, a computer program has generated a single image covering the full range of brightness, enabling every pixel to be recorded on a luminance-based scale. The light sources have been identified on-screen, and they are shown blanked out as they are

Figure 2. Full-field high dynamic range image (HDRi) for which each pixel is calibrated on a luminance-based scale. Light sources, both windows and luminaires, are shown blanked out as they will be disregarded for calculating mean room surface exitance (MRSE).

eliminated for calculating MRSE. It should not escape notice that as this procedure is based on distinguishing between direct and reflected light, it could be developed for also measuring discomfort glare in situ.

The objective for minimum lighting standards should be to ensure that the PAI criterion is satisfied irrespective of the illumination distribution, and it is on this basis that MRSE is proposed as the appropriate metric. More broadly, MRSE may be used as an indicator of how brightly or dimly lit a space appears to be, and Table 1 provides a guide to this aspect of appearance. An MRSE value of 100 $\mathrm{lm/m^2}$ is shown as relating to an 'acceptably bright' appearance, but as has been explained,[2,3] these values have been derived from a range of reported research. More research will be needed to develop a range of values that corresponds to peoples' expectations for the appearance of different categories of indoor spaces, so that a specified MRSE value for a given category of indoor space should define the level below which people are likely to judge the space to appear dull, gloomy, and inadequately lit. As such, designers should treat it as a minimum level which they may exceed to achieve a greater sense of overall brightness, but should be cautious about going below.

4. Target/ambient illumination ratio

While the PAI criterion is concerned with adequate reflected flux (MRSE) within a space, the IH criterion is concerned with how the direct flux from the luminaires may be distributed to create a balanced pattern of illumination brightness that supports selected lighting design objectives, which may range from directing attention to the functional activities of the space to creating aesthetic or artistic effects. The designer selects target surfaces and designates values of TAIR, according to the level of perceived difference of illumination brightness to be achieved between room surfaces and between objects and the surroundings against which they are seen.

MRSE provides a useful measure of the ambient illumination level within a space, and except where there are obvious reasons to the contrary, it is reasonable to assume that the incident illumination on every surface will be the sum of direct illuminance and MRSE, so the total illuminance on a target surface:-

$$E_{tgt} = E_{tgt(d)} + MRSE \qquad (4)$$

and the TAIR:-

$$TAIR = \frac{E_{tgt}}{MRSE} \qquad (5)$$

This concept provides a basis for planning how direct light from the luminaires is to be distributed within the space. It follows that for any chosen target, the direct illuminance:

$$E_{tgt(d)} = MRSE(TAIR - 1) \qquad (6)$$

Table 2 shows degrees of perceived difference, and this concept may be applied for making TAIR design decisions that concern the appearance of adjacent spaces, or of objects that are to receive selective illumination. The lighting designer designates TAIR values for selected surfaces or objects to signal

Table 1. Approximate guide to overall perceived brightness or dimness of illumination related to mean room surface exitance (MRSE)

Mean room surface exitance M_{rs} ($\mathrm{lm/m^2}$)	Appearance of ambient illumination
10	Lowest level for reasonable colour discrimination
30	Dim appearance
100	Lowest level for 'acceptably bright' appearance
300	Bright appearance
1000	Distinctly bright appearance

Table 2. Approximate guide to perceived difference of illumination brightness related to mean room surface exitance (MRSE) difference or target/ambient illumination ratio (TAIR)

Perceived difference	Illuminance ratio
Noticeable	1.5:1
Distinct	3:1
Strong	10:1
Emphatic	40:1

noticeable, distinct, or strong perceived differences of brightness. The direct illuminance to be applied to each surface or object may be calculated from equation (6), and from these data, the distribution of direct luminous flux from the luminaires can be determined. The perceived difference concept (see Table 2) is based on an idea proposed by Lynes and Bedocs[6] that is quite different from that of the perceived brightness (Table 1), and I can say that I feel rather more confident about the reliability of the values shown. They are based on an experiment that involves subjects making assessments of perceived difference,[3] which I have conducted with student groups on numerous occasions and in widely different locations.

A designer may choose a large proportion of the room surfaces to comprise the target area, for example, when lighting a mural covering a whole wall, or an architectural icon, or a library reading area, or perhaps, the horizontal work plane of an industrial assembly shop (but it will happen by design, not by default!). Alternatively, the target area may be a small proportion, such as a solitary sculpture, or a featured retail display, or the preacher in his pulpit. Whichever, the designer who has decided upon the MRSE level can then decide upon the TAIR for each target area, and devise the lighting installation for a planned distribution of flux.

TAIR is not proposed as a suitable metric for lighting standards. Default conditions, such as illumination of the horizontal work plane, can be expected to persist and such conditions could be codified in terms of TAIR. However, the real role of TAIR is that of a tool which enables pursuit of selected lighting design objectives, which may range from very simple through to distinctly complex.

5. Design procedure based on MRSE and TAIR

The flowchart shown in Figure 3 and the spreadsheet shown in Table 3 should be referred to while following this procedure.

1) Consider a level of MRSE that would provide for an appearance of overall brightness or dimness appropriate for the location. Codes or standards specified in task plane illuminance are unlikely to be useful. Should there be a published MRSE value relevant to the location, it probably relates to the perceived adequacy criterion and so should be treated as a minimum value. Consider whether a higher level to give a brighter appearance would be appropriate, referring to Table 1 for guidance. The appearance of this space may be affected by adjacent areas. Consider whether it is to appear brighter or dimmer than those areas, and if so, by how much, this time referring to Table 2 for guidance. Where no minimum levels are specified, designing for an appearance of dimness becomes an option providing safety concerns are kept in mind.

2) Decide upon the design value of MRSE, this being the overall density of reflected flux to be provided within the volume of the space.

3) Estimate the area and reflectance value for each significant surface s within the room, making sure to include any surfaces or objects that you might decide to highlight

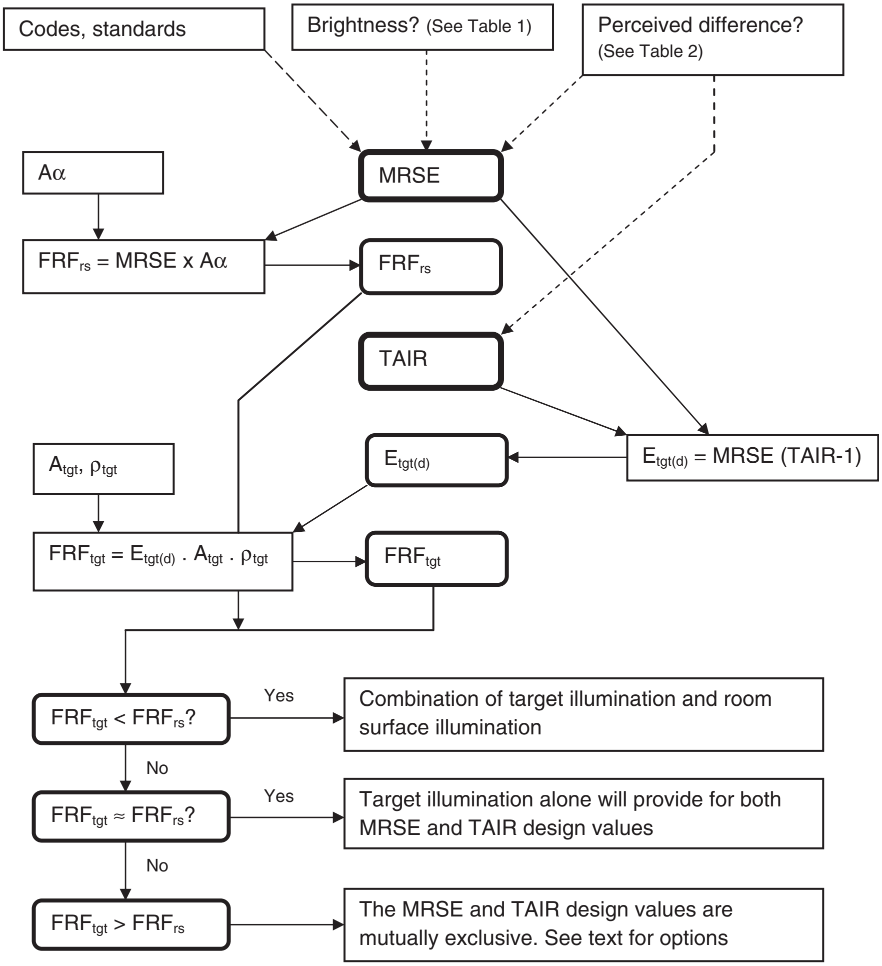

Figure 3. Flowchart for determining lighting options to provide for design targets specified in terms of mean room surface exitance (MRSE) and target/ambient illuminance ratio (TAIR) values.

with selective lighting. Calculate the room absorption for all room surfaces $A\alpha_{rs}$ using equation (3), and then, rearranging equation (1), calculate the first reflected flux reflected from room surfaces, $FRF_{rs} = MRSE \cdot A\alpha_{rs}$. These are the 'first bounce lumens' that initiate the interreflection process. Make a note of this value.

4) Consider the IH that the light distribution is to create in this space. Think about which objects or surface areas you want to highlight with selective lighting, and by how much. You will provide direct light onto these target surfaces, while surrounding areas will be lit mainly, or perhaps entirely, by reflected light.

5) Decide upon the design value of TAIR for each target area, taking account of how the appearance of the selected objects or surfaces will be affected by localized direct illumination. Table 2 may be referred to for guidance. Calculate the direct

Table 3 Spreadsheet for applying mean room surface exitance (MRSE) difference and target/ambient illumination ratio (TAIR) concepts in lighting design, showing the banking premises example described in the text. The user inputs the MRSE value, followed by the surface information in Columns 1–3, and the spreadsheet completes Column 4. The user then inputs *TSIR* values in column 5, and all of the remaining data are computed automatically from equations given in the text.

Project: Banking premises			MRSE (lm/m^2) 200			
Room surface	Surface area A_s (m^2)	Surface reflectance ρ_s	Surface absorption $A\alpha_s$ (m^2)	TAIR	Direct target surface illuminance $E_{ts(d)}$ (lx)	Target surface first reflected flux FRF_{ts} (lm)
Ceiling	113.3	0.75	28.3	1	0	0
Wall 1	19.8	0.65	6.9	1	0	0
Mural, wall 1	29.7	0.35	19.3	3	400	4158
Wall 2	40.3	0.65	14.1	1	0	0
Wall 3	24.8	0.65	8.7	1	0	0
Blinds, wall 3	24.8	0.8	4.9	1	0	0
Wall 4	28.2	0.65	9.9	1	0	0
Blinds, wall 4	12.1	0.8	2.4	1	0	0
Floor, public	5.1	0.25	38.2	1.5	100	1275
Floor, private	45.3	0.15	38.5	3	400	2718
Counter top	17.0	0.55	7.6	5	800	7480
Counter front	21.4	0.3	15.0	3	400	2568
Display panels	3.0	0.5	1.5	10	1800	2700
	Room surface absorption, $A\alpha_{rs}$ (m^2)		195.5	Target surface first reflected flux, FRF_{ts} (lm)		20 899
	Room surface first reflected flux, FRF_{rs} (lm)		39 096	FRF difference, $FRF_{rs} - FRF_{ts}$		18 197

illuminance $E_{ts(d)}$ to be applied to each individual target surface *ts* using equation (4).

6) Calculate first reflected flux from each target surface area A_{ts} and sum them, so that the total first reflected flux due to all target surfaces $FRF_{tgt} = \sum E_{ts(d)} \cdot A_{ts} \cdot \rho_{ts}$.

Then:

- If $FRF_{tgt} < FRF_{rs}$, then in addition to the light directed onto the target areas, the surrounding room surfaces will need some direct illumination to make up for the difference $FRF_{rs} - FRF_{tgt}$. This is needed to ensure that the MRSE design value will be achieved. The direct illumination onto the room surfaces does not need to be applied uniformly, and often the most effective way will be to spread light over large, high-reflectance surrounding surfaces such as ceiling and walls. Concentrating this light onto small areas may cause them to compete visually with the target areas. There is plenty of scope for ingenuity in devising ways of raising the overall illumination brightness without detracting from the selected targets.

- If $FRF_{tgt} \approx FRF_{rs}$, the target illumination alone will provide for the design values for both MRSE and TAIR. This is because reflected light from the target surfaces will both provide the design level of ambient illumination and achieve the intended balance of target/ambient levels. A serendipitous outcome.

- If $FRF_{tgt} > FRF_{rs}$, the design values of MRSE and TAIR cannot be achieved simultaneously in this situation. The reason is that if the direct target illuminance is applied, the reflected flux will raise MRSE above the design level and reduce TAIR below the design levels. Usually the most effective remedial action will be to reduce the total target area, such as by concentrating the objects to receive direct light into more restricted areas. Otherwise, it will be necessary to reduce either, or both, ρ_{tgt} and ρ_{rs}, but unfortunately, lighting designers seldom have much influence over reflectance values. A compromise may be inevitable, but at least the outcome will not come as an unpleasant surprise.

6. Example: a banking premises

For this example, Table 3 shows the output of a spreadsheet that is easy to set up and greatly facilitates the calculations. The designer has decided upon an MRSE level of 200 lm/m^2, and has input this value, and also the first three columns listing room surfaces and their properties. Column 4 gives the computed room absorption values, and at the bottom shows that 39 096 lumens of first reflected flux from the room surfaces is required to provide the MRSE level. Next the designer enters a TAIR value for every surface. This is the vital stage of the process, and Column 5 forms the statement of design intent for IH. The two remaining columns are completed automatically from these data, and show that 20 899 lm of the required FRF will be provided from the target surfaces, which means that the difference of 18 197 lm will need to be made up by reflected light from other room surfaces.

At this point, we can turn to familiar illumination engineering techniques for determining the luminaire layout. Various options for providing the deficit FRF may come to mind, but a simple and efficient solution would be uplighting. The direct average ceiling illuminance:

$$E_{clg(d)} = \frac{FRF_{clg}}{A_{clg} \cdot \rho_{clg}} = \frac{18197}{113.3 \times 0.75} = 214\,\mathrm{lux} \qquad (7)$$

This direct illuminance added to the MRSE would give total ceiling illuminance E_{clg} of

414 lux, giving a TAIR value of just over two. Table 2 indicates that this would correspond to a perceived difference between noticeable and distinct, but this effect could be reduced to something less than noticeable by also applying some light onto the walls and so reducing $E_{clg(d)}$ and the TAIR value for the celling. Those two walls with the light-coloured blinds could get some wallwashing, which would work providing that the staff could be relied upon to pull down the blinds during darkness. It would be necessary to check about that, and after all, this is the way that lighting design happens, and it is part of the reason why no two designers would come up with identical schemes.

Moving on to the to the target surfaces, Column 6 lists the direct illuminance levels required. Familiar design software can be used, the trick being to set all reflectance values to zero so that the computed illuminance values given are direct illuminance. This works well for the larger surfaces, but for spotlighting individual three-dimensional objects I prefer to use the cubic illumination[7] concept which sums the illuminance contributions from multiple sources on the faces of a small cube. Table 4 shows a spreadsheet output in which each luminaire is located relative to the cube by dimensions on x, y, and z axes. The full version of this spreadsheet includes vector and scalar data, which are beyond the scope of this paper.

7. Discussion

The foregoing design procedure leads to a solution based upon satisfying predetermined design objectives for:

- Overall perceived brightness or dimness of illumination.
- Perceived difference of brightness of illumination between the design space and adjacent spaces.
- An IH, which involves creating a light distribution to give graded levels of perceived difference of illumination between selected room surfaces, or objects and their surroundings.

This leaves open the question, how well will this lighting enable people to perform visual tasks? What has happened to the notion of providing illumination to compensate for visual task difficulty? I am conscious that Mark Rea has recently commented[8] that my approach completely ignores task visibility, so let me set the record straight.

Table 4 Spreadsheet for direct illuminance calculations for multiple light sources based on the cubic illumination concept.[7] The cube is located at the intersection of x, y and z axes, and for each source the user inputs the luminous intensity in column 2, and locates the source relative to the cube by distances X or –X, Y, or –Y, and Z or –Z on the corresponding axes. The illuminance values on each face of the cube are computed by the spreadsheet, where $E_{(x)} = X(I/D^3)$.

Source	I (cd)	Distance on x, y, z axes (m)						D (m)	I/D^3	Cubic illuminance values (on cube surfaces)					
		X	$-X$	Y	$-Y$	Z	$-Z$			$E_{(x)}$	$E_{(-x)}$	$E_{(y)}$	$E_{(-y)}$	$E_{(z)}$	$E_{(-z)}$
S1	1000	2.2		3.7		1.6		4.59	10.32	22.7	0	38.2	0	16. 5	0
S2	1200	0	4.1	1.9		2.8		5.32	7.99	0	32.7	15.2	0	22.4	0
S3	800	3.2			2.7		0.8	4.26	10.32	33.1	0	0	27.9	0	8.3
S4	220	0	2.6	2.9			2.2	4.47	2.46	0	6.4	07.1	0	0	5.4
S5		1						1	0	0	0	0	0	0	0
S6		1						1	0	0	0	0	0	0	0
						Total cubic illuminance values (lx)				55.8	39.1	60.5	27.9	38.9	13.7

It is evident from Figure 1 that the illumination levels that are routinely provided in workplaces are sufficient to enable normal-sighted people to perform moderately demanding visual tasks with high levels of visual performance. I should add that any competent designer who applies the foregoing procedure in a workplace would take into account the distribution of work activities in allocating TAIR values. Furthermore, during the past half century we have seen many examples of technology eliminating difficult visual tasks or replacing them with new forms of display, but still, some activities remain that depend on fine visual discrimination. Examples occur in surgery and quality control inspection (both situations where it is usually impractical to alter the task), and where such visually-demanding activities occur, my argument is that the first concern of the lighting designer should be to provide a well-lit space in which workers are adapted to at least moderately high brightness levels with total absence of glare, of both discomfort and disability varieties. After that, attention should be given to devising spatial and spectral distributions of illumination to maximize the luminance contrast of the critical detail of each visually-demanding task. This requires illumination engineering skill, and often the solution will comprise some form of local lighting with a degree of operative control. While high illuminance may be part of the solution, the old notion that illuminance is applied to compensate for task difficulty is inappropriate. Visually-demanding tasks call for specific solutions that are separate from the means for providing well-lit environments. Such situations apart, however, we should acknowledge that we live in era when most of the things that we need to be able to see have been designed to be seen.

It needs to be recognized that while equation (1) is endearingly simple, it is imprecise. This is because it assumes that reflected flux is distributed evenly over all room surfaces, whereas each surface 'sees' only other surfaces. For the flux reflected from a large room surface, such as a ceiling, some error is inevitable and whether it is significant will depend on circumstance. It should not be expected that the PAI criterion, being an indicator of subjective response, will ever be specified with such precision that MRSE differences of a few percent will matter, but when a supplier is held to meeting a standard rather different judgments apply. We can expect that the prospect of MRSE-based standards would lead to rapid development of design software that would accurately model complex interreflection processes.

Switching from current procedures involves far more than a change of numbers. It will lead to a changed understanding of how light may be distributed within an interior space for visual effectiveness and energy efficiency. Consider, for example, a situation where you want to achieve a high value of TAIR: What should you do to maximize its value? For a start, choose your target object, and light it with minimum spill so that it is the only surface to receive direct light. Then the maximum value of task/ambient illuminance ratio:-

$$\begin{aligned} TAIR_{\max} &= \frac{E_{tgt(d)} + MRSE}{MRSE} \\ &= \frac{A_{rs}(1-\rho_{rs}) + A_{tgt}\cdot\rho_{tgt}}{A_{tgt}\cdot\rho_{tgt}} \\ &= 1 + \frac{A\alpha_{rs}}{A\rho_{tgt}} \end{aligned} \tag{8}$$

The first surprise is that the direct target illuminance $E_{tgt(d)}$ is not a factor, meaning that as you adjust the light level up and down, the target/ambient balance remains unchanged. The ratio value is simply proportional to the room absorption [equation (3)] and inversely proportional to the target reflection, this being the product of target area and reflectance. So the answer is to choose a small, low-reflectance object and display it in a large, low-reflectance space. If you replace the object with one of high reflectance, you will raise MRSE, but not $E_{tgt(d)}$, so that TAIR will reduce. Jay[9] has reported a similar study examining maximum attainable luminance contrast.

Another aspect that will present a fairly steep learning curve will be the increased emphasis upon room surface reflection properties. In particular:

- If the aim is to achieve room brightness with high energy efficiency, high room surface reflectance values are as important as lamp efficacy and luminaire efficiency, and of particular importance are the reflectance values of the surfaces which provide the first reflected flux. It will often be found that uplighting and wallwashing are more energy efficient than downlighting.
- If the aim is to achieve high TAIRs, then low room surface reflectance values are necessary, particularly if the target area comprises a substantial proportion of the total room surface area. The problem here is that the first reflected flux from the target may raise MRSE to a level that prevents even moderately high levels of TAIR from being achieved.

Some emphasis has been placed on the proposal that lighting standards should be specified in MRSE, as this is seen to be the catalyst for change. That there is a need for standards that specify illumination minima is abundantly evident, but what is less obvious is the extent to which the form in which this is currently specified sets a pattern of thinking that pervades general lighting practice. The ubiquitous workplane governs not just calculations and measurement procedure, but luminaire design, installation practice, as well as monitoring and the operation of lighting controls. All of this follows from standards that dictate one particular distribution of illumination. Conversely, MRSE specifies adequacy without restricting distribution, and TAIR empowers designers to provide balanced illumination distributions to suit individual spaces, their contents, and the human activities that they house. It is time for change.

8. Summary

A case has been made for the prime criterion for future indoor lighting standards to be PAI specified in terms of MRSE. This differs from current practice on three main counts.

- Illumination adequacy is specified in terms of density of reflected light, not incident light.
- The specified level is an ambient quantity, not related to a particular plane, position, or direction of view.
- The distribution of illumination within the space is not defined, and uniformity is not stated to be an objective.

The aims of this proposal are that:-

- Lighting designers may start from the shared understanding that the fundamental purpose of indoor lighting is to satisfy the PAI criterion.
- That all compliant indoor spaces covered by lighting standards based on PAI have a high probability of being assessed as adequately illuminated.
- Once the PAI criterion is satisfied, designers have freedom to prioritize their design objectives. This may be achieved by determining an IH specified in terms of TAIR values.
- The foregoing will be a step towards closing the division within the lighting profession

that is discussed in the opening section of this paper.

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Comment 1:

I Macrae (President of the Society of Light and Lighting and Head of Global Lighting Applications Management, Thorn Lighting)

It is always with intrigue that I open a paper that develops the idea of lighting a space around metrics other than the widely accepted and much maligned illuminance of the working plane. Yet again Kit, as with many others, questions the way that we should light a working plane, and do it to perform a wide range of visual tasks across a multitude of media, times of day and human beings.

The proposals in Kit's paper deserve deep thought and respect, but I would vouch remain fundamentally flawed in the same way as workplane illuminance is.

Firstly, it is worth pointing out that a good lighting designer does not play to illuminance, or to a working plane, and more often than not will be thinking and perhaps even calculating the play of luminance across a range of surfaces. At the other end of the scale there is a group of 'lighters' who barely understand the concept of illuminance and work to minimum numbers as tick boxes of so called design. Herein lies the first problem with Mean Room Surface Exitance (MRSE) and other luminance-based design methods. They demand an understanding of lighting, the flow of light, contrast and reflectance beyond that which most practitioners of lighting design possess. Legislation and guidance has indeed made this type of designer more prevalent, some 80% of design is done to numbers by those with a basic understanding of light. But there have been some changes that this paper has overlooked, perhaps. A move away from workplane illuminance to task-based illuminance started many years ago. Agreed the move is slow, but now the task is not horizontal or based on a fictitious workplane, and there is no stipulation that illuminance is the only appropriate measure, it just happens to be the easiest for the building industry to work and to litigate with. Also, we see moves to recognise cylindrical illuminance, background and surround illuminance in addition to other numbers. Not ideal as Kit rightly points out, but a positive move nonetheless.

The building industry dominates building design and does so in order to deliver low cost and fast buildings for the most part, and that influences so much in the design process. Though a laudable approach, the use of design methods for lighting that demand rooms to be well defined with detailed surface finishes and furniture layouts, and indeed based around a known task and relatively fixed viewing position are dead before they start in most building design. Design for appearance works well when you can control task, location, view, and colour, but in most modern multitasking and constantly changing environments, the problems with a fixed lighting design is that it will need to change too. Until we have luminaires that offer complete flexibility in luminance and distribution, most clients are not going to change the lighting when the office is moved around.

This is my second problem with measures such as perceived adequacy of illumination and mean room surface exitance. Knowing the viewing position and task is often difficult, except in deliberately staged scenes. How does the MRSE method deal effectively with reading for instance? Assuming you know roughly where the paper will be held then it is possible to balance the brightness of the relevant surfaces to make the room feel adequate and the text on the page to still stand out, but for who and is that really paper? I ask who, because the eye of the beholder is important, specifically its age and condition, and I raise paper because I read Kit's proposal on an iPad, of course a self-lit task over which Kit's method has no control. Add to this that the chair I sit on is on wheels and allows me to rotate, move or recline and I would ask can a lighting designer really cater for all these changes and devise a hierarchy of illumination that works for myself, my task, my view, and the view of the other ten people in the office? Finally, I sit at a desk, uniformly lit, to a lighting level that does not suit me, but which suits my colleague sat next to me, suggesting a need for task, ambient and accent lighting, and the task lighting would change completely the MRSE received at the eyes of a number of people in the space.

Actually, I like MRSE as a concept, much in the way I like luminance-based design overall, it is just the fit to modern building design that makes it difficult to practice. Turning up on site to explain poor illuminance levels often results in discussions around the change of the wall colour to deep blue, or the furniture from pine to mahogany, actually its not the lighting measure that's always at fault. Agreed illuminance and luminance both suffer problems. Perhaps we should correct the design process first, then the lighting design methods?

This goes for target/ambient ratios too, unless you have a space that is really well-defined, in which case MRSE and TAIR make perfect sense.

There are many elements of Kit's proposal that loosely fit with where we are going. Task lighting balanced with ambient, ratio of ambient to task, or task to surround and background, reflectance versus absoptance, cubic illuminance versus cylindrical illuminance all sound familiar. In fact a good designer working with illuminance and reflectance, or luminance, exitance, and absoptance will be thinking about how the surfaces in a room will balance, how the light will flow, how much light is needed and how well the task is lit whatever that task may be.

My final problem with MRSE is the measurement. In real life we have to measure a room in a short space of time, often just before handover. The use of an illuminance meter may not be clever, but it is simple and quick. The use of a cubic illuminance meter could be relatively fast, but demands much more thought. The use of HDR imaging makes things far too complicated. We will have to define the viewpoint(s) and direction(s) for multiple measures, then blank out roughly the luminaires, and then calculate the MRSE. This set-up and post-processing will be simply too complicated to be accepted by our customers who already think illuminance measurement takes too long.

The problem is not one of method, it is one of process; the process of designing lighting involves many other practitioners, with many other priorities and few with a focus on the lit effect. The problem is not with 500 lx or task uniformity, we can change these numbers and most people would not complain (as long as they get lower). The problem with Kit's proposal is that it would demand a change in process and a lighting design profession who did all lighting design and integrated this with the architect and interior designer, so whilst the proposal is deserving of merit, we have a long way to go until it can be realised practically.

Comment 2:

MB Wilde (MBW Lighting)

My first 15 years of design were probably as a technocrat lighting engineer using prescriptive recommendations from the various Guides and Codes and applying them through predictive techniques to generally dump sufficient lumens onto horizontal planes to meet the prescribed visibility or performance illumination values.

Around 1975, I had a 'road to Damascus' event that showed me that this route of prescriptive and predictive design was fraught with problems, particularly in the office workplace, not the least of which is that of not knowing what the appearance of the space would be like until it was actually completed . . . and so often met with disappointment. It would achieve the various prescribed criteria, but fail miserably with its appearance.

I realised that knowledge and experience had to be led by visionary intent . . . that laws can only predict, they cannot create. I had to know and agree what space should look like and how it would operate from an end user point of view. From that time until now I have endeavoured to carry out lighting design based around an ethos of ambient, task/display . . . to separate and deal with each of these factors before combining them as composites to achieve an agreed spatial appearance with appropriate vision objectives.

In a career spanning 50+ years, I have seen no evidence that the visibility or performance route has led to either increased satisfaction or productivity in the workplace. In fact, often this approach has led to quite the reverse . . . dull, lifeless, non-motivational and disappointing spaces accompanied by continual complaints and moans from end users.

Moreover, this route when applied to offices, designing a horizontal illuminance of 300–500 lux from wall-wall, when the actual total task plane is probably less than 15% of net lettable floor area, and that this task plane is possibly never more than 50% in use because of occupancy patterns, has led to a gigantic misuse of energy (both embedded and consumed) over a considerable period of time! And, unfortunately, still does.

I both welcome and concur with the author's views that it is time to change from a basis of 'visibility' to one of 'appearance'. I would go further and say that in my view it is probably at least 30 years too late!

The idea of redefining the lighting of space in respect of two design criteria, perceived adequacy of illumination (PAI) and illumination hierarchy (IH) clearly captures the idea of lighting for ambient and task/display, an idea that has long been discussed by designers. It must surely be welcomed by any discerning designer. There have been previous attempts to devise predictive methods for 'appearance,'[1,2] none of which have ever found general usage.

Whether this reluctance was brought about by the complexity of operation and computation, laziness on the part of the designer, or reluctance to accept responsibility for design, we will never know. This last comment is driven from a paper I delivered at a British Council for Offices conference in 2004. I proposed a shift in design to an ambient/task/display philosophy and was met with opposition from a number of very senior Directors in Building Services Design companies that declared they would only ever do what was in the SLL Code for Lighting or the British/Euronorm Standards (horizontal illuminance)... because that is what was required of them by their Professional Indemnity Insurance, the Great God PII (the tail wagging the dog!!)

So with this history of 'reluctance', I do have concerns with the author's proposal. How many lighting designers or lighting engineers would actually use an appearance method, which by its very nature will require more complex calculations? Cuttle addresses this in his proposal, that we need new software programs to carry out this part of the predictive process. So a part of the development of his proposal must be discussions with lighting software developers such as Dialux, Relux, AGi32 etc. At least having the necessary software would reduce the risk of excuse from many lighting designers that it was too onerous and fee consuming!

Would the method proposed actually deliver a designers 'vision' or would it deliver an institutionalised vision formed by some technical committee or other. I say this in the anticipation that to be accepted nationally, the Lighting Institutions, Associations and Societies of each country would need to incorporate the methodology into Guides, Handbooks, and/or Codes.

At the moment I suspect very few designers would use the method proposed, except for perhaps a few exemplar projects. What does a designer do for the 'speculative' space. That space where its interior design, space planning and surfaces are unknown. Developers appear to be unbending in their desire to implement pre-tenancy agreement lighting fit out, letting tenants supplement with post tenancy agreement enhancements. Would they agree to a base level appearance scheme, one that could change dramatically as spaces are let? How would post tenancy agreement lighting enhancements inserted into pre-tenancy agreement lighting fit out modify or change responsibilities as to a design audit?

The author indicates Tables 1 and 2 to be approximate, and suggests that more research is necessary to develop a range of values that corresponds to peoples' expectations for the appearance of different categories of indoor space. I would agree that this is necessary, five MRSE values and four Illuminance Ratio values hardly instil confidence as a route to satisfactory appearance. A problem perhaps exists that if these criteria are over specified, many designers will continue the way they have for many years.... prescriptive criteria selection, calculation prediction (computer) and completely overlook their essential 'visionary' role in creating a visually satisfying and functional space!

The author is correct in his view that lighting design is split into two distinct camps 'appearance' and 'visibility'. I do agree with this view and it does raise a potential problem, in that, many in the 'appearance camp' are conceptualists and novate the technical workings to manufacturers. 'Credentialling' could perhaps resolve this problem. This is a discussion currently being held in USA and also UK, that all Lighting Designers hold and are qualified to discharge a level of professional responsibility, and that all designs are subject to audit.

I would urge the author to continue with the development of this appearance concept, but it does need to be 'sold' to the various lighting societies, associations and institutions if it is ever to get off the ground, perhaps its biggest obstacle for success. In this respect, it would seem appropriate during the next year or so to present this proposal to National and International Lighting Conferences and to lobby support for its inclusion into National Lighting Guides, Codes, Handbooks. The SLL is planning and calling for papers for its International Lighting Conference in Dublin April 2013, perhaps a venue for the author to get the ball rolling on effecting this much needed change in lighting design.

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Reply to comments:

C Cuttle

The positives in these two responses are notable. Macrae declares that he likes MRSE as a concept, and Wilde agrees that we need to switch from 'visibility' to 'appearance' as a basis for standards. Both discussers recognize that the current situation needs to change (Wilde considers it 30 years overdue!), but both see rafts of reasons why such change would be problematical, impractical, and simply unable to happen. Wilde cites examples of earlier attempts to rationalize lighting practice, all of which were dismal failures, and both seem to expect that this proposal has no chance of avoiding a similar fate. So let me see if I can suggest a brighter option.

Macrae sees 'the first problem' with MRSE to be that it demands 'an understanding of lighting . . . beyond that which most practitioners of lighting possess.' Well, what sort of a profession do we all see ourselves to be part of? If we are to accept that the only changes that can be considered as practical are ones that fall within the scope of those who, to use Wilde's phrase, 'dump sufficient lumens onto horizontal work planes to meet the prescribed visibility or performance illumination values,' then we have a bleak future indeed. Wilde describes a 'history of reluctance,' and questions how many lighting designers or engineers would use a method which, 'by its very nature will require more complex calculations?' Does the Lumen Method really push the mathematical skills of our designers and engineers to their limits? Think of our CIBSE colleagues who design air conditioning and sound systems in buildings – they deal with far more challenging calculations. To all this I would add that I teach Advanced Lighting Design at the Queensland University of Technology in Brisbane, Australia, and the students respond with enthusiasm to the concepts that I have covered in this paper (and more besides) but then some of them tell me that they doubt whether they will ever get opportunities to apply the concepts in their work. If we assume that people are not capable of anything more than mundane work, we are ensuring that that is all that will occur.

Wilde gives a chilling account of the 'very senior Directors in Building Services Design companies' whose lighting decisions are governed by professional indemnity concerns. The contents of the SLL Code and the EN Standards are seen by these people not just as frameworks within which lighting design options may be explored but as specifications to be rigidly applied. Even though the recent SLL Code refers to task planes without assuming them to be horizontal, it will take far more than that to change current attitudes. As Macrae says of the horizontal work plane (HWP), 'it just happens to be the easiest [concept] for the building industry to work and litigate with.' Easy it may be, but it bears no sensible relationship to illumination adequacy. My experience leads me to agree wholeheartedly with Wilde's observation that he has 'seen no evidence that the visibility or performance route has led to either increased satisfaction or productivity in the workplace.' Surely, we cannot continue indefinitely to accept this situation.

A few years ago, Howard Brandston and I taught the two Lighting Design Studios in the graduate lighting program at the Lighting Research Center, Rensselaer Polytechnic Institute, in New York. One of Howard's maxims was, 'First light the space; then attend to the details.' The details could be work-related tasks; or they could be retail displays; or artworks; or architectural details; or simply anything that deserves attention. This breaks away from treating every space to be lit as a workplace, or worse still as an office, and it is for this reason that I refer to details for attention as 'targets', not 'tasks'. Wilde asks, "Would the method proposed actually deliver a designer's 'vision', or would it deliver an institutionalised vision..." and the answer is that it could do either. Let us imagine a space for which the prevailing standard specifies (or mandates) a minimum MRSE value of 150 lm/m^2. An individual could choose, or an institution could require, that the HWP be uniformly lit to, say, 300 lux. The designer/engineer would designate the HWP to be the target area and would set the target/ambient illuminance ratio (TAIR) to a value of 2. Entering these values into one of the updated lighting software packages that would (in this imagined situation) have become available would produce a quite unexceptional grid-plan luminaire layout fully compliant with the standard. So what is the point of making the change? The difference is that this lighting distribution has been chosen. A designer/engineer who is not so constrained could choose targets and TAIR values leading to different lighting distributions giving quite different appearances to the space and its contents, any of which could comply with the standard. An MRSE standard does not demand creative design, but it does not get in the way of it.

The world of lighting is in a spate of change. The impact of the new technologies for light sources and controls is massive. Society is changing in how it uses buildings (not just workplaces) and what it expects from its surroundings. The idea that we can persist with our 19th century notion of lighting visual tasks for productivity is untenable, but changing the standards will require concerted effort. This is a crucial step, not only for the reasons discussed but because it will set new curricula for lighting education programmes. We need young people who have been taught that devising lighting installations is an activity that requires thought. We need new research into how people assess illumination adequacy. We need to take a new approach to how we guide general lighting practice.

5. THIRD SUBMITTED PUBLICATION

Cuttle C, 2011. Perceived Adequacy of Illumination: A new basis for lighting Practice. *Proceedings of the 3rd PLDC Professional Lighting Design Convention, Madrid; 81-83.*

Lighting designers exercise their creativity against a backdrop of codes, standards, and recommended practice documents, each specifying a range of lighting parameters for compliance, foremost among which is a schedule of minimum illuminance values related to various indoor activities. While it is accepted that standards are necessary for general lighting practice, it has been quite common in the past for designers to disregard these standards as being irrelevant to their work. That attitude has become untenable due to the growth of regulations governing energy efficiency and sustainability. The practice of specifying indoor illumination in terms of workplane illuminance has been firmly established by the illumination engineering-based lighting societies and the CIE, and the energy regulators have unquestioningly followed this practice.

This paper makes the following points:

- Workplane illuminance specifications are based on the objective of providing for human visual needs, and that objective is obsolete.
- The *Perceived Adequacy of Illumination (PAI)*, which is an assessment of whether or not the users of a space are likely to judge the illumination adequate, provides an appropriate criterion for lighting standards.
- A lighting metric that would act as a reliable indicator of PAI would measure light reflected from room surfaces received at the eye.
- Lighting standards based on PAI would bring about fundamental rethinking of how light may be distributed in indoor spaces, providing designers scope in which to pursue visual design objectives and opening new opportunities for achieving energy efficiency.

Christopher Cuttle/NZ

PERCEIVED ADEQUACY OF ILLUMINATION:
A new basis for lighting practice

Introduction

Lighting designers exercise their creativity against a backdrop of codes, standards, and recommended practice documents, each specifying a range of lighting parameters for compliance, foremost among which is a schedule of minimum illuminance values related to various indoor activities. While it is accepted that standards are necessary for general lighting practice, it has been quite common in the past for designers to disregard these standards as being irrelevant to their work. That attitude has become untenable due to the growth of regulations governing energy efficiency and sustainability. The practice of specifying indoor illumination in terms of workplane illuminance has been firmly established by the illumination engineering-based lighting societies and the CIE, and the energy regulators have unquestioningly followed this practice.

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- Lighting standards based on PAI would bring about fundamental rethinking of how light may be distributed in indoor spaces, providing designers scope in which to pursue visual design objectives and opening new opportunities for achieving energy efficiency .

The basis of illuminance schedules

Although specifying bodies have added various ‘lighting quality’ criteria to their pronouncements, the central factor remains the workplane illuminance, and it is claimed that this quantity is determined primarily by the category of the visual task. The *IESNA Lighting Handbook* states that “Changes in visual performance as a function of task contrast and size, background reflectance, and observer age can be calculated precisely”[1], and the author has applied the referenced procedure[2] to examine how the illuminance required for a high standard of visual performance relates various reading tasks.

Figure 1 shows that, for the typical reading task of 12-pt type on white paper, it requires just 20 lux to provide for the relative visual performance criterion of RVP=0.98, this value being generally accepted as the highest practical RVP level for lighting applications. It can be seen that the font size would have to be reduced to 6-pt for the required illuminance to exceed 100 lux, or alternatively, reduced to 10-pt but printed onto dark-coloured paper, which has the double effect of reducing the background luminance and the task contrast. However, this value of 100 lux falls far short of the levels conventionally provided for applications where reading tasks are prevalent, which typically fall within the range 300 to 500 lux, and it is clear that such levels can be justified on the basis of visual performance only by presuming that either the users are partially visually defective, or that they are persistently required to read very small print with very low contrast on low reflectance backgrounds.

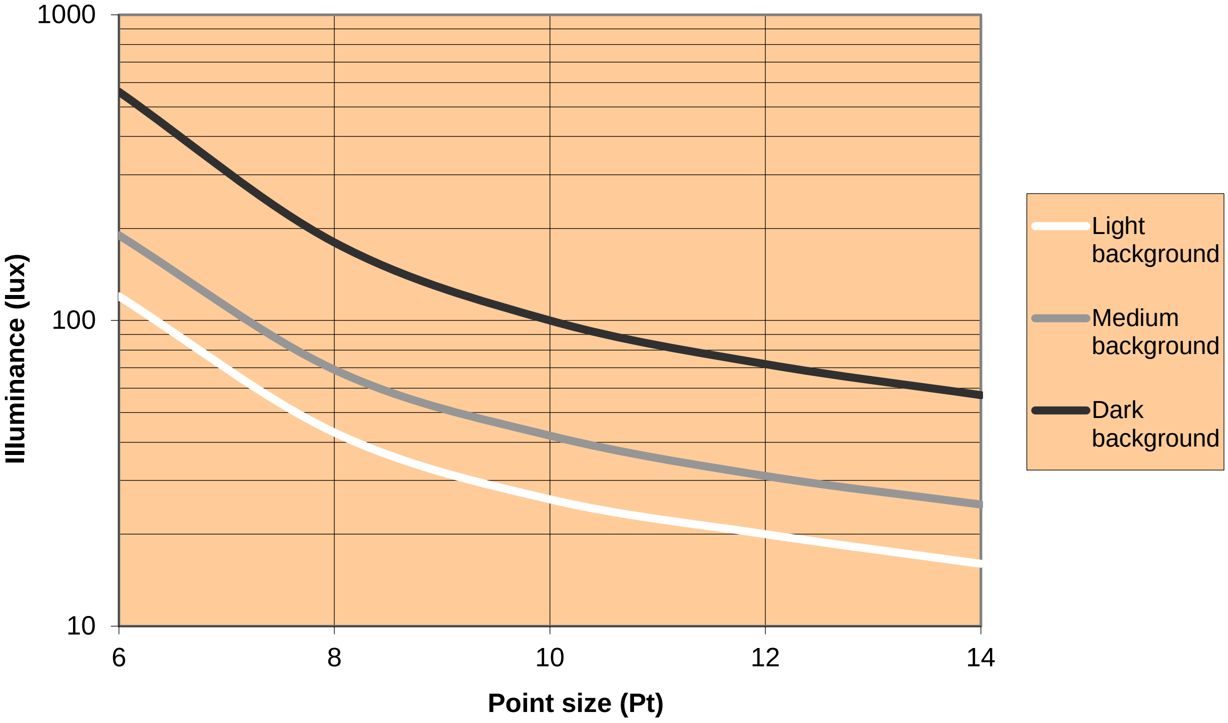

Figure 1. The task illuminance required to provide for relative visual performance RVP = 0.98 for a range of reading tasks. The reader is a normal-sighted 25 year-old with a viewing distance of 350mm. The reading matter is black print, ranging from 6- to 14-point size, on three types of paper: light (reflectance ρ=0.9); medium (ρ=0.6); and dark (ρ=0.3).

If this is not enough, we should not lose sight of the fact that indoor spaces in which reading tasks (or tasks of similar visual difficulty) are prevalent are not the universal norm. There are far more spaces that we pass through, or in which we engage in social or recreational activities, where our visual needs are much more simple, and often comprise nothing more than the ability be able to navigate through a furnished space freely and safely. How much light do we need to do this? Fortunately there has been some good research into this topic.

In a study of emergency egress from buildings, Dr P.R. Boyce conditioned subjects to 500 lux in an open-plan office before plunging them into low, or very low, illuminance levels, with the instruction that they were to find their way out. As well as timing them, he had installed infra-red cameras so he could monitor their progress, and he concluded:

> *At a mean illuminance of 1.0 lux on the escape route people are able to move smoothly and steadily through the space at a speed very little different from that achieved under normal room lighting.*[3]

The outcome of this brief survey of human lighting needs arrives at findings that contrast starkly with the purported purpose of lighting standards. It is evident that in indoor spaces where reading tasks are prevalent, such as offices, classrooms and libraries, we commonly provide illuminance levels that are between 15 and 25 times as much as people actually need for high levels of visual performance; and in spaces where finding one's way is the foremost demand on our visual faculties, which would include interiors such as shopping malls and airport terminals, we over-provide by several hundred fold. These are colossal differences between the illuminance levels required for the visual performance criteria that standards are claimed to ensure, and the levels that the standards specify. We need to look further into this.

Lighting for human need, or something else?

I have to hand a copy of the *Illuminating Engineer* published by the IES of Great Britain in October 1911; exactly 100 years ago to the month of this Convention. The journal includes a report "Illumination requirements for various purposes" with a table listing 34 activities along with corresponding illuminance values based on several field surveys. Regarding the aforementioned tasks; reading (ordinary print) is listed at 3.0 foot candles (30 lux); and schoolrooms are also at 3.0 fc; commercial offices are 4.0 fc; and libraries range from general, 1.5 fc; to bookshelves, 2.5 fc; and reading tables, 5.0 fc. Admittedly none of the indoor activities go as low as the 1 lux (0.1fc) finding from the emergency egress research, but broadly, if allowance is made for the fact that these field measured values precede not only photocopiers and laser printers but also any visual performance studies, it can be seen that general lighting practice of one hundred years ago showed substantial agreement with the data presented in Figure 1. In short, we need have little doubt in concluding that at that time (100 years ago) the illumination levels provided by general lighting practice were appropriate for meeting human visual needs.

Why, then, are the levels demanded for current lighting practice so substantially in excess of those levels? No serious proposition could be mounted on the basis of deteriorating human visual abilities, or on increasing difficulty of visual tasks. The answer is blatantly obvious. If any modern buildings were illuminated to such levels, people would choose to avoid them. If such lighting were to be imposed upon employees, or some other captive group, there would be outrage. Public opinion would be united that nobody should have to tolerate such dismal, gloomy conditions. And that is just the point. It is nothing to do with the speed and accuracy with which people are able to detect the critical detail of visual tasks. It is a matter of meeting people's expectations that, here in the 21st century, the variety of spaces that we all pass through, occupy, and engage in for recreational, social, and work activities, should appear to be adequately illuminated. During the past 60 years, we have made the transition from providing for visual needs to meeting human expectations.

Perceived adequacy of illumination

Do the elevated illuminance levels of current practice mean that the standards have adapted to changing expectations and that the present situation is quite satisfactory? This question brings us to the crux of this paper. The current standards specify lighting quantity in terms of visual task illuminance, and as we have seen, this is generally interpreted as the average illuminance of the horizontal workplane. It follows that for lighting to be efficient, economical, and purposeful, the lamp lumens must be directed onto the workplane with high optical efficiency. Furthermore, to direct light onto walls, ceilings, or other features which might catch the eye is deemed inefficient and wasteful. The evidence of this rationale is all around us in general lighting practice, and lighting designers can expect to encounter increasing pressure to follow this trend as providing a specified workplane illuminance (lux) with minimal lighting power density (W/m^2) is widely recognized as pursuing the holy grail of sustainability.

As has been mentioned, there has been a recent tendency among specifying bodies to add 'lighting quality' criteria to their stipulations, but this is simply trying to contain a hemorrhage with a *band-aid.* What is needed is a fundamental re-evaluation of whether or not the users of a space are likely to judge it to appear adequately illuminated, or to put it another way, what is the photometric correlate to the *perceived adequacy of illumination?*

Mean room surface exitance

The author has introduced[4] the concept of *mean room surface exitance* (MRSE) as a metric that serves as an indicator of typical assessment of the brightness of illumination of an indoor space. It is, within the volume of the room, the average density of lumens (lm/m^2) emerging from all of the surrounding room surfaces. It is shown to be both simple to calculate and practical to measure as it represents a typical level of exposure of an observer's eye to reflected light from the surrounding room surfaces.

To understand the concept of exitance, keep in mind that while illuminance is concerned with the density of luminous flux *incident* on a surface, exitance concerns the flux *exiting*, or emerging from, a surface. In an enclosed space, this is flux available for vision, and so MRSE is measured at the eye (ie, not on visual task planes) and includes only light that has undergone at least one reflection (ie, direct light is excluded). It may be thought of as an indicator of the level of the light that brightens the view of indoor surroundings, and which is independent of any effects of bright luminaires or windows.

It has been proposed[6] that MRSE may be applied as an indicator for perceived adequacy of illumination, PAI, which is a binary assessment, that is to say, in a given situation, the illumination may be perceived as either adequate or inadequate, so that PAI would be specified by a single MRSE value. However, we must suppose that a MRSE level that may be judged adequate in a waiting room or an elevator lobby could be considered inadequate in a workplace or a fast food outlet. Definition of the adequate/inadequate boundary, related to context, is the unresolved component of a workable system of lighting standards based on providing for human satisfaction.

Precursors for change

The system that underlies the range of worldwide lighting standards evolved gradually and comprises not merely the standards themselves, but everything from experience-based recommended practice guidance to computerized ‘design’ programs, and these in turn have generated firmly established mindsets. To overthrow all of this would seem to require nothing short of a revolution. Nonetheless, the *status quo* does not stand up to examination. It cannot survive.

It is, in fact, quite remarkable that the profession has for so long accepted without demur the imposition of standards that are so obviously unfounded and irrelevant. From the oft-quoted office workers propped up in front of self-luminous and near-vertical computer screens who have to be provided with several hundred lux uniformly distributed over the horizontal workplane that runs through their partitioned cells, to bedridden patients in hospital wards whose recovery is supposed to require a minimum daylight factor value, measured on the horizontal plane at bed level, we are confronted with such improbable scenarios that it is hard to believe that anyone has ever taken these demands seriously. It seems that once a concept has gained the hallowed status of Standard, it moves into a sphere where it is beyond critical examination.

The first hurdle to be overcome is lack of research. MRSE has been proposed as a suitable metric, but that needs to be tested. The aim must be to establish a scale of context-related values that provides an acceptably reliable indication of whether or not people will be satisfied that an indoor space appears to be illuminated to a level that is appropriate for its function. There will need to be procedures for predicting the values by calculation, and for measuring them for verification. The developing field of high dynamic range imaging, HDRi, would seem to be well suited for such measurements, as illustrated in Figure 2(a) and (b).

Such a change in the standards would incur a radical change in thinking about lighting. Room surfaces would be seen to be as much part of the lighting installation as the luminaires. The aim for the initial light distribution (by luminaires or fenestration) would be to distribute light onto light reflecting (or translucent diffusing) surfaces, with the objective of delivering reflected light to the eye, treating the room as a second luminaire. We would move on from the notion that the purpose of lighting is to provide for human need (RVP) to providing for human satisfaction (PAI). Lighting controls would respond to room brightness, as do people, and efficient electrical energy usage would be achieved through light being applied for visual effectiveness. Education

Figure 2(a). This high dynamic range image has been generated from a series of differently exposed images using a calibrated digital full-field camera to provide a data file specified in photometric units.

Figure 2(b). Sources of direct light may be identified for glare calculations, or eliminated, in which case what is left is room surface exitance.

programmes would be revised to direct all who are concerned with lighting provision, from services engineers to interior designers, to recognize that the appropriate distribution of light for an indoor space is determined as much by the arrangement of the room surfaces and their reflection properties as by the activities that the space houses. There would be a shared understanding of light distribution that would give designers scope to explore lighting design objectives and energy efficiency options. But first, what is needed is that the symptoms of dissatisfaction with the *status quo* become impossible to ignore.

Acknowledgments

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6. FOURTH SUBMITTED PUBLICATION

Cuttle C, 2012. A Shared Purpose for the Lighting Profession. *Mondo*arc*, Aug/Sept 2012; 68: 125-128.

We have a divided profession. The first illuminating engineering societies, formed more than 100 years ago, set the initial agenda for professional involvement in lighting. The purpose for providing Illumination was seen to be to satisfy human need for visibility, and the aim was to optimize illumination provision for efficiency and economy through application of science-based principles. This approach is entirely logical and has been adopted in many countries throughout the world, where the members of national IES or equivalent societies have been strongly influential in establishing lighting standards. However, around the middle of the 20th century it became apparent that there was growing dissatisfaction with this agenda as it failed to include the professional activities of a newer breed of lighting designers, and this has led to the emergence of the IALD in the North America, and in Europe, of ELDA, now superseded by the PLDA. Defining the purpose for providing illumination as seen by these groups is less straightforward, but one thing would seem to be unarguable: rather than thinking of illumination as the medium that makes things visible, these designers see lighting principally in terms of how it influences the appearance of peoples' surroundings. This difference of *visibility* and *appearance* being envisioned as the purpose of lighting underlies the professional division that remains with us to this day.

Following a lively response to his paper at PLDC in Madrid earlier this year, Christopher 'Kit' Cuttle became convinced that he needed to address the design community more directly about his thoughts on the current state of the lighting profession. Here are those thoughts...

A SHARED PURPOSE FOR THE LIGHTING PROFESSION

We have a divided profession. The first illuminating engineering societies, formed more than 100 years ago, set the initial agenda for professional involvement in lighting. The purpose for providing Illumination was seen to be to satisfy human need for visibility, and the aim was to optimise illumination provision for efficiency and economy through application of science-based principles. This approach is entirely logical and has been adopted in many countries throughout the world, where the members of national IES or equivalent societies have been strongly influential in establishing lighting standards. However, around the middle of the 20th century it became apparent that there was growing dissatisfaction with this agenda as it failed to include the professional activities of a newer breed of lighting designers, and this has led to the emergence of the IALD in the North America, and in Europe, of ELDA, now superseded by the PLDA. Defining the purpose for providing illumination as seen by these groups is less straightforward, but one thing would seem to be unarguable: rather than thinking of illumination as the medium that makes things visible, these designers see lighting principally in terms of how it influences the appearance of peoples' surroundings. This difference of visibility and appearance being envisioned as the purpose of lighting underlies the professional division that remains with us to this day.

VISIBILITY AS THE PURPOSE OF LIGHTING

Rather than employing a scale of task visibility, lighting standards make reference to relative visual performance (RVP) to specify illumination levels appropriate for various activities. The validity of RVP has been demonstrated many times for critical viewing situations, such as nighttime illumination of roadway signs, but its application to indoor general lighting practice lacks rigour. Visual performance research has been based almost exclusively on subjects viewing two-dimensional, diffusely-reflecting reading tasks, and researchers have chosen this viewing situation as it enables visual performance to be expressed as a function of illuminance. This has led to the widespread misunderstanding that prescribed levels of visual performance for all manner of activities can be assured by specifying task illuminance values. For example, in 2008 the IES of North America published Guide to Designing Quality Lighting for People and Buildings, which states that "The foundation for lighting design is ensuring that people have enough light to safely, efficiently and accurately perform predominant visual tasks." From this statement it may be inferred that "enough light" is all that is required to ensure a prescribed level of RVP for a given activity, but the reality is far more complicated. This because the two-dimensional diffusely-reflecting task is a special case, whereas the general case includes visual tasks that may be three-dimensional and have quite different optical characteristics, so that predicting visibility has to take account of the form, texture, gloss, colour contrast, and perhaps, the transparency or translucency of the task materials. Application of RVP in everyday situations would require definition of both the eye-task geometry and the luminance distribution of the entire surrounding light field. To specify a lighting condition for a real visual task that will ensure satisfaction of a prescribed visual performance criterion is no mean undertaking, and for this reason, it is very seldom done outside a research laboratory.

If such measurements were to be conducted in actual workplaces, those who claim that the currently recommended (or sometimes mandated) illuminance levels must be provided to maintain workers' productivity and health would find themselves confronted by some challenging data. Figure 1 shows that, for the typical reading task of 12-pt type on white paper, it requires just 20 lux to provide for the relative visual performance criterion of RVP=0.98, this value being generally accepted as the highest practical RVP level for lighting applications. It can be seen that for the required illuminance to exceed 100 lux, the font size would have to be reduced to 6-pt, or alternatively, reduced to 10-pt but printed onto dark-coloured paper, which has the double effect of reducing the background luminance and the task contrast. However, even this value of 100 lux falls far short of the levels conventionally provided for applications where reading tasks are prevalent, which typically fall within the range 300 to 500 lux, and it is clear that such levels can be justified on the basis of visual performance only by presuming that either the users are partially visually defective, or that they are persistently required to cope with visual tasks equivalent to reading very small print with very low contrast on low reflectance backgrounds. It can be seen that for everyday reading tasks recommended illuminance values are far out of step with visual performance requirements. If we transfer our attention to real tasks involving complexities such as three-dimensional form, texture and gloss, the situation would be further confused and greater discrepancies could be expected. It needs to be recognised that the often-made claim that the illuminance schedules are research-based and must be enforced to maintain productivity levels is

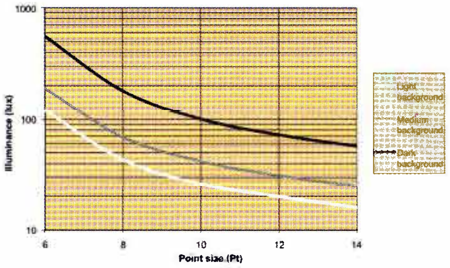

Figure 1: **The task illuminance required to provide for relative visual performance RVP = 0.98 for a range of reading tasks. The reader is a normal-sighted 25 year-old with a viewing distance of 350mm. The reading matter is black print, ranging from 6- to 14-point size, on three types of paper: light (reflectance p=0.9); medium (p=0.6); and dark (p=0.3).**

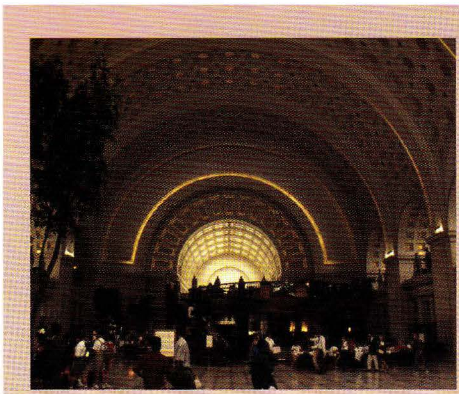

Figure 2: 'Focal glow' dominant. This photograph is offered as an example of the first of Richard Kelly's "three elemental kinds of light effect". Grand Union Station, Washington DC, USA. Lighting design: William M.C. Lam.

Figure 3: 'Ambient luminescence' dominant; the second of Kelly's kinds of light effect. Samslung Essel, Klosterneuberg, Austria. Architect: Heinz Tessar.

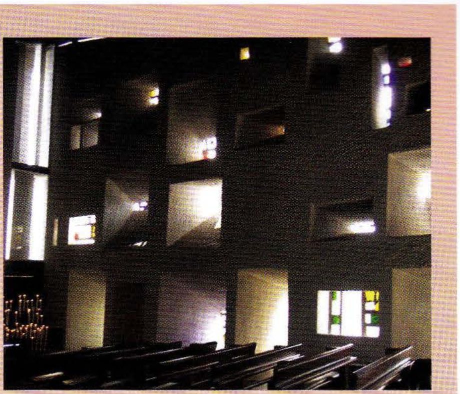

Figure 4: 'Play of brilliants' dominant; the third of Kelly's kinds of light effect. Notre Dame du Haut, Ronchamp, Franche-Comté, France. Architect: Le Corbusier.

false.

APPEARANCE AS THE PURPOSE OF LIGHTING

While the first illuminating engineering society had been founded in 1906 in New York, it was also in that part of the world that the first clear signs of an alternative faction emerged. In the years following World War II, leading architects were turning to a new breed of lighting professionals. Often these were individuals who had acquired their skills as stage lighting designers and who found themselves able to establish close rapport with architects. The pioneers of this development are now legends; designers such as Richard Kelly, Abe Feder, and Stanley McCandless in the USA, and J.M. Waldram in the UK; and architects who sought to arouse emotional responses in people entering their buildings found that they were able to communicate readily with these designers. They responded to the architects' expectations and had the ability to bring the magic of theatrical experiences into their creations. It was a symbiosis, and it is important to recognise that it was not that these designers raised the standard or quality of lighting design: they redefined its purpose.

In 1952, Richard Kelly set out his design philosophy in a lecture delivered at a joint meeting of The American Institute of Architects, the Society of Industrial Designers, and the Illuminating Engineering Society, in Cleveland, Ohio[1]. He identified "three elemental kinds of light effect"; these he described as: ambient luminescence, focal glow, and a play of brilliants. If any words could be said to have initiated the emergence of lighting design as a profession distinct from illumination engineering, it surely has to be these. Up to his death in 1977, Kelly developed close, almost intimate, working relationships with several of the leading architects of the era and was acknowledged to have made significant contributions to a number of major architectural projects.

It may be asked to what extent can the balance of these three kinds of light effect be applied for describing current lighting practice? Contemporary photographs of Kelly's work mostly comprise rather grainy half tones, so I have reviewed my own collection of photographs for examples which, I think, characterise dominance of each of the effects, even though Kelly had no connection with any of them. They appear as Figures 2 to 4.

Since that time there has been an uneasy relationship between lighting designers who see themselves to be involved in the process of architectural design, and those who design lighting installations to comply with all current standards and recommendations for best practice. For the remainder of this paper we will refer to these two types of lighting practitioner as 'architectural' designers and 'best practice' designers. No pejorative is intended by these terms: they are proposed only to describe two legitimate approaches to designing lighting installations. Of course there are other individuals who plan lighting installations without ever rising to the standards of either of these categories, but that is another issue. It might seem that the difference between these two designer groups is irreconcilable, but the aim of this paper is to suggest an alternative outcome.

'ARCHITECTURAL' LIGHTING DESIGNERS AND 'BEST PRACTICE' LIGHTING DESIGNERS

When we look at attitudes towards lighting standards, which are taken here to include the whole range of codes and recommended practice documents, the differences between these two types of practitioner become starkly apparent. The 'architectural' designers find it quite absurd that illuminance uniformity should be cited as a measure of lighting quality, and that in order to satisfy demands for energy efficiency they should be required to focus light output onto the horizontal workplane. Howard Brandston, who started in lighting as Stanley McCandless's assistant, has produced his own rule, "Rules are a substitute for thinking", to which he has added, "Codes and standards can distract us from lighting practice."[2] Such designers resent the very existence of lighting standards. Meanwhile, the 'best practice' designers depend on lighting standards in order to do their job. It is their role in life to devise installations that are fully-compliant and which thereby represent the best of current lighting practice. For the past few decades, illuminance schedules have been maintained at their current levels, which could be described as saturation levels, and standards have responded by increasing their scope to include additional rules relating to other aspects of lighting. These range from 'lighting quality' factors, such as glare control, to others concerned with health, safety and sustainability. This added complexity has had the effect of raising the authority and self-assurance of 'best practice' designers.

We need a total change of attitude towards standards. 'Best practice' designers need to come to terms with the fact that the illuminance schedules that form basis of lighting standards have escalated way beyond levels that can be justified on the basis of visibility, and new thinking is needed on what is meant by "enough light". 'Architectural' designers need to recognise that lighting standards are not going to go away, and for there to be standards that specify "enough light" in ways that achieve that objective but do not "distract [them] from lighting practice", they will need to become involved in the process of making standards. This could lead to a shared purpose for all lighting designers.

A SHARED PURPOSE

Look again at Kelly's description of three kinds of light effect. He was not describing the lighting installation, or the appearance of the lit scene, but rather the potential of the illumination (whether daylight or electric lighting) to interact with physical environments to create various types of visual experience. In his words, "Focal glow draws attention, pulls together diverse parts, sells merchandise, separates the important from the unimportant, helps people to see." (See Figure 2) This says everything about visibility that the 'best practice' designers could have been saying if they had not been sidelined by the simplistic notion of workplane illuminance. Kelly again, "Play of brilliants excites the optic nerves, and in turn stimulates the body and spirit, quickens the appetite, awakens curiosity, sharpens the wit. It is distracting or entertaining." (See Figure 4) Now we are into a region of lighting design where only 'architectural' designers should dare to tread. The last sentence is profound. While the 'best practice' designers aim to eliminate distraction (which they classify as glare), the 'architectural' designers seek to entertain with brilliants.

The other one of Kelly's three kinds of light is quite different in nature. Of this he says, "Ambient luminescence produces shadowless illumination. It minimizes form and bulk. It minimizes the importance of all things and people. It suggests the freedom of space and can suggest infinity. It is usually reassuring. It quiets the nerves and is restful." (See Figure 3) He adds that "Visual beauty is perceived by an interplay of all three kinds of light, though one is usually dominant." This brings us to the central proposal of this paper. Where Kelly would have described ambient luminescence to be dominant, this would be a situation where the illumination at the eye would be due mainly to diffusely reflected light from the surrounding environment. A high level of this ambient illumination within the volume of the space would correspond with the perception of a brightly lit space, and conversely, a low level with a dimly lit one. It is proposed here that this concept provides a sensible basis for illumination standards.

A NEW CRITERION FOR INDOOR LIGHTING

Recently the author has proposed perceived adequacy of illumination as the criterion on which indoor lighting standards should be based, leading to illumination schedules being specified in terms of a metric that relates to peoples' assessments of whether or not a space appears to be adequately illuminated.[3,4] Mean room surface exitance (MRSE) is proposed as such a metric, this being the average level of lumens per square metre reflected from the surrounding environment, or in other words, the density of light that the space (not the light sources) makes available at the eye. Procedures for calculation and measurement have been explained, and the proposal being advanced here is that the workplane illuminance schedules in the current standards be replaced with schedules of MRSE, specified in lumens per square metre. The difference is that MRSE includes only light that has undergone at least one reflection, and instead of being a measure of light incident on things to be seen, it refers to reflected light at the eye.

The recommended MRSE values will generally be lower than the current illuminance schedule values because they exclude direct light from luminaires and windows, but that does not mean that task illuminance values should be correspondingly reduced. It will be up to the lighting designer to identify the things that are visually important and to apply direct light to achieve appropriate emphasis and visibility. An identified object may be a sheet of printed paper; or a product on an assembly line; or a retail display; or a marble sculpture. Whichever, the direct illuminance should be related to the ambient level, indicated by the MRSE value, according to the emphasis required, and the distribution of direct light should be chosen according to the surface properties of the object. While there would, of course, always be some situations where it would be quite appropriate to direct most of the luminaire outputs onto the horizontal workplane, this would occur as the result of a decision, and not as a matter of course. The nonsense of acting as if all visually important objects are invariably to be found uniformly arrayed on the horizontal workplane would become too obvious to ignore. Lighting efficiency would be seen to be strongly influenced by the reflectances of room surfaces receiving direct illumination, and this would lead to a complete reevaluation of some familiar lighting techniques. Indirect lighting, or uplighting, and wall washing have long been recognised as attractive ways of lighting non-working spaces, but far too inefficient general use. Whether designing for compliance with MRSE specifications or for meeting expectations for a pleasantly lit space, these lighting distributions would be found to be visually effective and capable of achieving high efficiency where the distribution of direct light has been sensibly related to the room proportions and surface reflectances. Alternative light distributions for libraries, art rooms, recreation centres, and so on would spring to mind and gradually all lighting designers would settle down to thinking about how light may be distributed within any space to suit the light reflecting surfaces, and how the combination of direct and reflected illumination within the space would affect the appearance of the three-dimensional objects within it.

In this way, design thinking would progress quite naturally from ambient luminescence to focal glow, and ahead would lie the play of brilliants. While nobody should contemplate incorporating these latter two aspects of lighting into standards, the perceived adequacy of illumination criterion does offer a basis for a shared concept of the purpose of lighting. Making it happen would require some changes of attitude. 'Best practice' designers would need to accept that the basic criterion for "enough light" has to change, and 'architectural' designers would need to apply themselves to the process of creating standards. The objective would be lighting standards that specify "enough light" without restricting how direct light is to be distributed. With that common ground, 'architectural' and 'best practice' lighting designers should find that there is quite a lot that they can learn from each other.

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7. FIFTH SUBMITTED PUBLICATION

Cuttle C, 2015. Lighting Design: A perception-based approach. Abingdon: Routledge. 136pp, 2015.

This book takes a unique approach to the design of lighting installations for indoor spaces. The theme is that lighting does not simply make things visible: it influences the appearance of everything we see. This notion leads to identification of several perception-based concepts, and using these, a designer is able to discuss lighting design proposals with clients and other professionals in terms that relate their own visual experiences. These concepts are then able to be translated into illumination metrics, and using spreadsheets to automatically perform the necessary calculations, appropriate luminaire performance requirements are determined. The objective is for the designer to be able to specify lighting equipment layouts and control strategies with confidence that the illumination distributions provided will create envisaged appearances of selected objects and the spaces that enclose them. The spreadsheets can be downloaded from the publisher’s website.

LIGHTING DESIGN

By reading this book, you will develop the skills to perceive a space and its contents *in light*, and be able to devise a layout of luminaires that will provide that lit appearance.

Written by renowned lighting expert Christopher (Kit) Cuttle, the book:

- explains the difference between vision and perception, which is the distinction between providing lighting to make things visible, and providing it to influence the appearance of everything that is visible;
- demonstrates how lighting patterns generated by three-dimensional objects interacting with directional lighting are strongly influential upon how the visual perception process enables us to recognise object attributes, such as lightness, colourfulness, texture and gloss;
- reveals how a designer who understands the role of these lighting patterns in the perceptual process may employ them either to reveal, or to subdue, or to enhance the appearance of selected object attributes by creating appropriate spatial distributions of light;
- carefully explains calculational techniques and provides easy-to-use spreadsheets, so that layouts of lamps and luminaires are derived that can be relied upon to achieve the required illumination distributions.

Practical lighting design involves devising three-dimensional light fields that create luminous hierarchies related to the visual significance of each element within a scene. By providing you with everything you need to develop a design concept – from the understanding of how lighting influences human perceptions of surroundings, through to engineering efficient and effective lighting solutions – Kit Cuttle instils in his readers a new-found confidence in lighting design.

Christopher 'Kit' Cuttle, MA, FCIBSE, FIESANZ, FIESNA, FSLL, is visiting lecturer in Advanced Lighting Design at the Queensland University of Technology, Brisbane, Australia, and is author of two books on lighting (*Lighting by Design, 2nd edition, Architectural Press*, 2008; and *Light for Art's Sake, Butterworth Heinemann*, 2007). His previous positions include Head of Graduate Education in Lighting at the Lighting Research Center, Rensselaer Polytechnic Institute, Troy, New York; Senior Lecturer at the Schools of Architecture at the University of Auckland and the Victoria University of Wellington, both in New Zealand; Section Leader in the Daylight Advisory Service, Pilkington Glass; and Lighting Designer with Derek Phillips Associates, both in the UK. His recent awards include the Society of Light and Lighting's Leon Gaster 2013 Award for his LR&T paper 'A New Direction for General Lighting Practice', and the Lifetime Achievement Award presented at the 2013 Professional Lighting Design Conference in Copenhagen.

LIGHTING DESIGN

A perception-based approach

Christopher Cuttle

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The contents of this book have grown from the Advanced Lighting Design course that I have taught every year since 2005 at the Queensland University of Technology in Brisbane, Australia, for which I thank the programme coordinator, Professor Ian Cowling, and also the succession of lively and enquiring CPD (continuing professional development) students who have caused me to keep the curriculum in a state of continual revision.

While many people have contributed to the development of the ideas contained in this book, whether they realised it at the time or not, three former colleagues with whom I have maintained email contact have responded to specific issues that I encountered in preparing the text. They are, in no particular order, Joe Lynes and Professors Mark Rea and Peter Boyce. My thanks to each of them.

Those who have given permission for me to reproduce figures are acknowledged in the captions, but I want to make particular mention of Edward Adelson, Professor of Vision Science at the Massachusetts Institute of Technology, who not only permitted me to reproduce his Checker Shadow Illusion (Figure 1.1), but also two of my own modified versions of his brilliant figure.

INTRODUCTION

The aim of this book is to enable people who are familiar with the fundamentals of lighting technology to extend their activities into the field of lighting design. While the text is addressed primarily to students, it is relevant to professionals working in the fields of building services, interior design and architecture.

The premise of this book is that the key to lighting design is the skill to visualise the distribution of light within the volume of a space in terms of how it affects people's perceptions of the space and the objects (including the people) within it. The aim is not to produce lighting that will be noticed, but rather, to provide an envisioned balance of brightness that sets the appearance of individual objects into an overall design concept.

This is different from current notions of 'good lighting practice', which aim to provide for visibility, whereby 'visual tasks' may be performed efficiently and without promoting fatigue or discomfort. It is also quite different from some lighting design practice, where spectacular effects are achieved by treating the architecture as a backdrop onto which patterns of coloured light, or even brilliant images, are projected.

Several perception-based lighting concepts are introduced to enable distributions of illumination to be described in terms of how they may influence the appearance of a lit space. These descriptions involve perceived attributes of illumination, such as illumination that brings out 'colourfulness', or has a perceived 'flow', or perhaps 'sharpness'. It is shown that the three-dimensional distributions of illumination that underlie this understanding of lighting can be analysed in quantitative terms, enabling their characteristics to be measured and predicted. The principles governing these distributions are explained, and spreadsheets are used to automatically perform the calculations that relate perceived attributes to photometric quantities.

The objective is to enable a lighting designer to discuss lighting with clients and other professionals in terms of how illumination may influence the appearance of spaces and objects. When agreement is reached, the designer is then able to apply procedures that lead to layouts of luminaires and strategies for their control, and to do this with confidence that the envisioned appearance will be achieved.

1

THE ROLE OF VISUAL PERCEPTION

Chapter summary

The Checker Shadow Illusion demonstrates a clear distinction between the processes of vision and perception, where vision is concerned with discrimination of detail and perception involves recognition of surface and object attributes. The role of lighting in this recognition process involves the formation of lighting patterns created by interactions between objects and the surrounding light field. Confident recognition comprises clear perception of both object attributes and the light field. Three types of *object lighting patterns* are identified, being the shading, highlight, and shadow patterns, and it is by creating light fields that produce controlled balances of these three-dimensional lighting patterns that designers gain opportunities to influence how room surface and object attributes are likely to be perceived.

The evidence of your eyes

Figure 1.1 shows the Checker Shadow Illusion, and at first sight, the question has to be, where is the illusion? Everything looks quite normal. The answer lies in squares A and B: they are identical. That is to say, they are the same shade of grey and they have the same lightness, or to be more technical, they have the same reflectance (and thereby luminance) and the same chromaticity.

Do you find this credible? They certainly do not look the same. Now look at Figure 1.2, which shows a white sheet drawn over the figure with cut-outs for the two squares. Seen in this way they do look the same, and if you take a piece of card and punch a hole in it, you can slide it over the previous figure and convince yourself that the two squares are in fact identical and as shown in Figure 1.2.

This raises a question: how is it that, when the images of these two identical squares are simultaneously focussed onto the retina, in one case (Figure 1.2) they appear identical and in the other (Figure 1.1) they appear distinctly different?

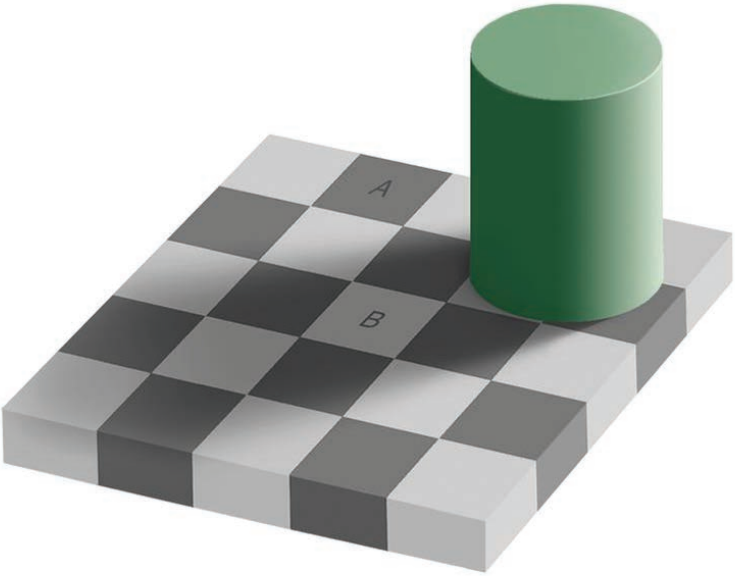


FIGURE 1.1 The Checker Shadow Illusion. Squares A and B are identical. They are presented here as related colours, that is to say, they appear related to their surroundings. The lighting patterns that appear superimposed over the surrounding surfaces cause a viewer to perceive a 'flow' of light within the volume of this space, and which leads to the matching luminances of A and B being perceived quite differently. *(Source: en.wikipedia.org/wiki/Checker_shadow_illusion.html, downloaded January 2013)*

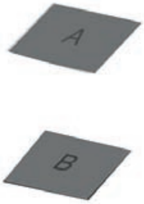


FIGURE 1.2 A white sheet has been drawn over the Checker Shadow Illusion, with cut-outs for squares A and B, and now they appear to be identical. In this case they are presented as unrelated colours.

Related and unrelated colours

The essential difference is that in Figure 1.1 the two squares are presented as *related colours*, that is to say, colours are perceived to belong to surfaces or objects seen in relation to other colours, and in Figure 1.2, they are shown as *unrelated colours*, meaning they are seen in isolation from other colours (Fairchild, 2005). As unrelated colours (grey is a colour), they are perceived to comprise nothing more than rectangular coloured shapes on a plain white background, but when they are set into the context of Figure 1.1, they are perceived as solid elements in a three-dimensional scene that have recognisable object attributes. It is this change in the way they are perceived that causes them to appear differently.

So what are the components of the surrounding scene that make this illusion so effective? Ask yourself, why is the cylindrical object there? Does it contribute something? In fact, it is a vital component of the illusion. So, what colour is it? Obviously, green. Is it uniformly green? Well, yes ... but look more carefully at the image of the object and you will see that both its greenness and its lightness vary hugely. The image is far from uniform, so how did you suppose the object to be uniformly green? The answer is that you perceived a distinctive lighting pattern superimposed over the uniformly green object. In Figure 1.3, the area enclosed by the object outline is shown as uniformly green and it appears as nothing more than a formless blob.

The solid, three-dimensional object perceived in Figure 1.1 is observed to be interacting with a directional 'flow' of light, which causes a *shading pattern* to be generated, and this appears superimposed over the green object surface. Note also that the cylinder's surface is not perfectly matt, and there is just a hint of a *highlight pattern* due to a specular component of reflection that is apparent at the rounded rim of the cylinder's top edge. These lighting patterns inform you about the object's attributes (Cuttle, 2008).

Now look at the checker board surface. Again we have a pattern due to the lighting, but in this case it is a *shadow pattern*, which has a different appearance from the shading

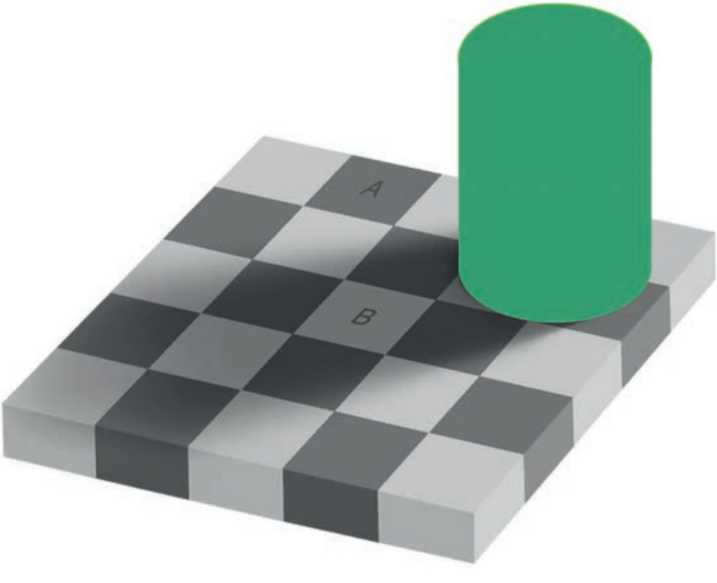


FIGURE 1.3 Previously the cylindrical object appeared to be uniformly green. Now it is uniformly green, but it does not look like a cylinder. That is because it is now lacking the lighting pattern due to interaction with the 'flow' of light.

and highlight patterns, but nonetheless is quite consistent with our perception of the overall 'flow' of light within the volume of the space. It will be obvious to you that if two surfaces have the same lightness (which also means they have the same reflectance) and one occurs within the shadow pattern and one outside it, they will have different luminance values. The creator of this brilliant illusion, Edward H. Adelson, Professor of Vision Science at the Massachusetts Institute of Technology, has carefully set it up so that squares A and B have the same luminance value, which means of course, that their images on your retina are identical. However, the function of the visual process is to provide information to the visual cortex of the brain, and here your perceptual process is telling you that, although these two squares match for luminance, they cannot have the same lightness. The one in the shadow must be lighter, that is to say, it must have higher reflectance, than the one in full light. You hold this innate understanding of lighting in your brain, and you cannot apply your conscious mind to overrule it.

In this way, it can be seen that the image focussed onto the retina is simply an optical projection of the visual scene that corresponds directly with the luminance and chromaticity values of the elements within the external scene. Since its inception, the study of lighting has concentrated on the visual process and how illumination may be applied to provide for visibility, later defined in terms of visual performance, but the role of vision is to serve the process of perception, and this occurs not at the retina, but in the visual cortex of the brain. What we perceive is not a pattern of brightness and colour, but a *gestalt*, this being a psychological term that describes the holistic entity that enables us to recognise all the forms and objects that make up our surroundings (Purves and Beau Lotto, 2003). Consciously, we are aware of three-dimensional spaces defined by surfaces and containing objects, but in order to make this much sense of the flow of information arriving through the optic nerve, we have to be subconsciously aware of a light field that fills the volume of the space. This is how we make sense of squares A and B. Seen in this way, it becomes obvious why attempts to analyse scenes in terms of luminance and chromaticity were bound to lead to frustration.

The role of ambient illumination

For most of the time, we live in a world of related colours. We are surrounded by surfaces and objects which, providing the entire scene is adequately illuminated, our perceptual faculties reliably recognise and make us aware of, sometimes so that we can cope with everyday life, and sometimes to elevate our senses to higher levels of appreciation, as when we encounter artworks or beauties of nature. Recognition involves identifying object attributes associated with all of the things that make up our surrounding environments, and our innate skill in doing this is truly impressive. Scientists working on artificial intelligence have tried to program super computers to perform in this way, but so far their best efforts fall far short of what human perception achieves every moment throughout our waking hours.

Provided that ambient illumination is sufficient, we are able to enter unfamiliar environments, orientate ourselves, and go about our business without hesitating to question the reliability of the perceptions we form of the surrounding environment. It is clear that substantial processing has to occur, very rapidly, between the retinal image and formation of the perception of the environment. There is no good reason why our perceptions of elements of the scene should show in-step correspondence with their photometric characteristics. Visual perception may be thought of as the process of making sense of the flow of sensory input through the optic nerve to the brain, where the purpose is to recognise surfaces and objects, rather than to record their images. Colours are perceived as related to object attributes, and effects of illumination are perceived as lighting patterns superimposed over them. As we recognised the cylinder in Figure 1.1 to be uniformly green with a superimposed shading pattern, so we also recognised the identical squares to differ in lightness because of the superimposed shadow pattern.

There will, however, be situations where we are confronted with elements seen in isolation from each other, and this is particularly likely to occur in conditions of low ambient illumination. When we find ourselves confronted by dark surroundings, reliance upon related colours and identification of object attributes may give way to perception of unrelated colours, and when this occurs, our perceptions do not distinguish lightness and illuminance separately, and luminance patterns dominate. That is to say, the appearances of individual objects within the scene relate to their brightness and chromaticity values, rather than upon recognition of their intrinsic attributes.

Figures 1.4 and 1.5 show two views of the same building. In Figure 1.4, we see a view of this magnificent cathedral in its setting, and we readily form a sense of its substantial mass and the materials from which it is constructed. Also, even if we are not conscious of it, we perceive the entire light field that generates this appearance. In Figure 1.5, our perception of this building is quite different. We have no notion of a natural light field, and the building seems to float, unattached to the ground. It is revealed by a glowing light pattern that does not distinguish between materials, and actually makes the building appear self-luminous. The building's appearance is dominated by brightness, and object attributes are not discernible. These two views show clearly the difference between related colours, in the daylight view, and unrelated colours in the night-time view. They also give us due appreciation of the role that lighting may play in bringing about fundamental differences in our perceptions.

Under normal daytime lighting, two-way interactions occur that enable our perceptual processes to make sense of the varied patterns of light and colour that are continuously being focussed onto our retinas. Working in one direction, there is the process of recognising object attributes that are revealed by the lighting patterns, while at the same time, and working in the opposite direction, it is the appearance of these lighting patterns that provides for the viewer's understanding of the light field that occupies the entire space.

FIGURE 1.4 The object attributes of this building are clearly recognisable, and the ambient illumination provides amply for all elements to appear as related colours. (Chartres Cathedral, France.)

FIGURE 1.5 The same building, but a vastly different appearance. Low ambient illumination provides a dark backdrop against which the cathedral glows with brightness. Object attributes are unrecognisable in this example of unrelated colours.

Perception as a basis for lighting design

From a design point of view, lighting practice may be seen to fall into two basic categories. On one hand, for illumination conditions ranging from outdoor daylight to indoor lighting where the ambient level is sufficient to avoid any appearance of gloom, we live in a world of related colours in which we distinguish readily between aspects of appearance that relate to the visible attributes of surfaces and objects, and aspects which relate to the lighting patterns that appear superimposed upon them.

On the other hand, in conditions of low ambient illumination, where we have a sense of darkness or even gloom, whether indoors or, most notably, outdoors at night, we typically experience unrelated colours and this may lead to the appearances of objects and surroundings dominated by brightness patterns that may offer no distinction between object lightness and surface illuminance.

The implications of this dichotomy for lighting design are profound. Outdoor night-time lighting practice, such as floodlighting and highway illumination, is based on creating brightness patterns that may bear little or no relationship to surface or object properties. Alternatively, for situations where ambient illumination is at least sufficient to maintain an appearance of adequacy (apart from outdoor daylight, this may be taken to include all indoor spaces where the illumination complies with current standards for general lighting practice) we take in entire visual scenes including object attributes, and involving instant recognition of familiar objects and scrutiny of unfamiliar or otherwise interesting objects. The identification of object attributes may become a matter of keen interest, as when admiring an art object or seeking to detect a flaw in a manufactured product, and we depend upon the lighting patterns to enable us to discriminate and to respond to differences of object attributes.

Between these two sets of conditions is a range in which some uncertainty prevails. We have, for example, all experienced ‘tricks of the light’ that can occur at twilight, and generally, recommendations for good lighting practice aim to avoid such conditions. Perhaps surprisingly, it is within this range that lighting designers achieve some of their most spectacular display effects. By isolating specific objects from their backgrounds and illuminating them from concealed light sources, lighting can be applied to alter the appearance of selected object attributes, such as making selected objects appear more textured, or colourful, or glossy. All of this thinking will be developed in following chapters.

Before we close this chapter, ask yourself, why do we call Figure 1.1 an illusion? If the page is evenly illuminated, squares A and B will have the same luminance and so they stimulate their corresponding areas of our retinas to the same level. The fact that these equal stimuli do not correspond to equal sensations of brightness is cited as an illusion. The point needs to be made that vision serves the process of perception, and perception is not concerned with assessing or responding to luminance. Its role is to continually seek to recognise object attributes from the flow of data arriving from the eyes. When we are confronted with Figure 1.1 in a condition of adequate illumination, our perception process performs its task to perfection. A is correctly recognised as a dark checker board square, and B as a light square. Rather than labelling Figure 1.1 as an illusion, perhaps we should refer to it as an insight into the workings of the visual perception process.

However, the real purpose for examining this image has been to show how perception depends upon and is influenced by the lighting patterns that objects and surfaces generate through interactions with their surrounding light fields. These lighting patterns may have the effects of revealing, subduing, or enhancing selected object attributes, and it is through control of light field distributions that lighting designers influence people's perceptions of object attributes. Skill in exercising this control, particularly for indoor lighting, is the essence of lighting design and the central theme of this book.

References

Cuttle, C. (2008). *Lighting by Design, Second Edition.* Oxford: Architectural Press.

Fairchild, M.D. (2005). *Color Appearance Models, Second Edition.* Chichester: Wiley.

Purves, D. and R. Beau Lotto (2003). *Why we see what we do: An empirical theory of vision.* Sunderland, MA: Sinauer Associates.

2

AMBIENT ILLUMINATION

Chapter summary

The perception of ambient illumination concerns whether a space appears to be brightly lit, dimly lit, or something in between. At first this might seem a rather superficial observation until we consider all of the associations that we have with 'bright light' and 'dim light', at which point ambient illumination becomes a key lighting design concept. It provides a basis for planning lighting based on the perceived difference of illumination between adjacent areas, or spaces seen in sequence as when passing through a building. A thought experiment is introduced which leads to the conclusion that mean room surface exitance (MRSE) provides a useful indicator of ambient illumination, where MRSE is a measure of inter-reflected light from surrounding room surfaces, excluding direct light from windows or luminaires. The Ambient Illumination spreadsheet facilitates application of this concept.

The amount of light

An important decision in lighting design is, 'What appearance of overall brightness (or dimness) is this space to have?' General lighting practice gives emphasis to the issue of how much light must be provided to enable people to perform the visual tasks associated with whatever activity occurs within the space and, of course, this must always be kept in mind. In a banking hall, for example, we need to ensure that the counters are lit to an illuminance that is sufficient to enable the tellers to perform their work throughout the working day without suffering strain. While that aspect of illumination must not be overlooked, there is an overarching design decision to be made, which is whether the overall appearance of the space is to be a bright, lively and stimulating environment, or whether a more dim overall appearance is wanted. The aim of a dim appearance may be to present a subdued, and perhaps sombre, appearance, or alternatively, to create a setting in which illumination can be directed onto selected targets to present them in high contrast relative to their surroundings. Of course, the surroundings cannot be made too dim as illumination must always be sufficient for safe movement, but there is substantial scope for a designer to choose whether, in a particular situation, the overall impression is to be of a bright space, or of a dim space, or of something in between. Clearly, the impressions that visitors would form of the space will be substantially affected by the designer's decision.

This raises a question. If we are not lighting a visual task plane for visibility, but are instead illuminating a space for a certain appearance of overall brightness, how do we specify the level of illumination that will achieve this objective? All around the world, lighting standards, codes, and recommended practice documents specify illumination levels for various indoor activities in terms of illuminance (lux) and a uniformity factor. If someone states that 'This is a 400 lux installation', that means that illuminance values measured on the horizontal working plane, usually specified as being 700mm above floor level and extending from wall to wall within the space, should average at least 400 lux, and furthermore, at no point should illuminance drop to less than 80 per cent of that average value.

The reasons for this are historical. It was in the late nineteenth century that the practice of measuring illumination emerged, and for indoor lighting, the prime purpose was to enable working people to remain productive for the full duration of the working day, despite daylight fluctuations. While the recommended illuminance levels have increased more than tenfold since those days, the measurement procedures are essentially unchanged even though light meters have undergone substantial development. The two specified measures, an average illuminance and the uniformity factor, are the means by which lighting quantity is specified, and more than that, they govern how people think about illumination quantity. Perhaps the worst feature of these specifications is that they have the effect of inhibiting exploration of different ways in which the light might be distributed in a space, and how lighting may be applied to create a lit appearance that relates to a space and the objects it contains. For lighting designers, these aspects of appearance are all-important, and in fact, it may be said that they form the very basis of what lighting design is all about. To be obliged to ensure that all lighting is 'code compliant' is nothing short of a denial to pursue the most fundamental lighting design objectives.

A thought experiment

We are going to conduct a thought experiment as a first step to exploring how lighting does more than simply make things visible, and in fact, we are going to explore how lighting affects the appearance of everything we see. To start, you need to get yourself into an experimental mindset. The first requirement is to forget everything you know. Then, imagine an indoor space where the sum total of ceiling, wall and floor areas add up to 100m^2, as shown in Figure 2.1.

Then, into this space is added a luminaire that emits a total a luminous flux, F, of 5000 lumens (Figure 2.2).

How brightly lit will the space appear? This might seem to be a difficult question to answer, which is as it should be because a vital piece of information is lacking. Until the room surface reflectance values are specified, you have no way of knowing how much light there is in this space.

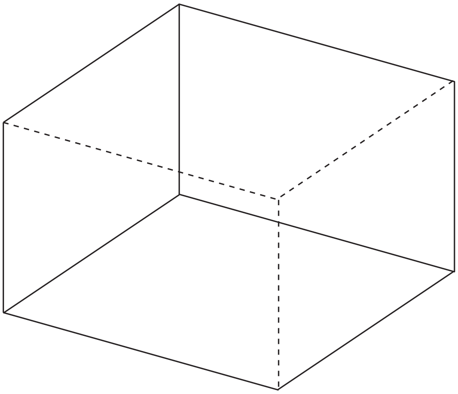


FIGURE 2.1 To start the thought experiment, imagine a room for which the sum of ceiling, walls, and floor area is $100m^2$.

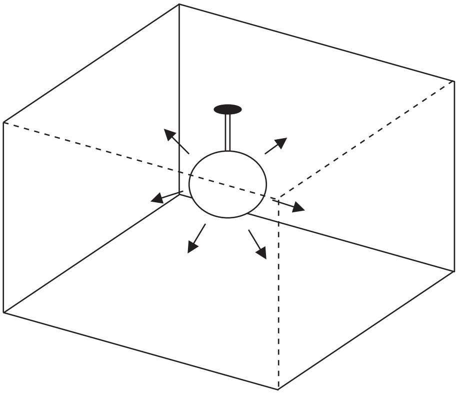


FIGURE 2.2 To the room is added a luminaire with a total flux output F = 5000 lumens.

To keep life simple, we will specify that all room surfaces have a reflectance value, ρ_{rs}, of 0.5, that is to say, 50 per cent of incident lumens are absorbed and 50 per cent are reflected (Figure 2.3). Now we can work out how many lumens there are in the space.

How much light do we have?

	addition	*total*
Initial flux (F)	5000	5000
First reflection	2500	7500
Second reflection	1250	8750
Third reflection	625	9375

and so on …

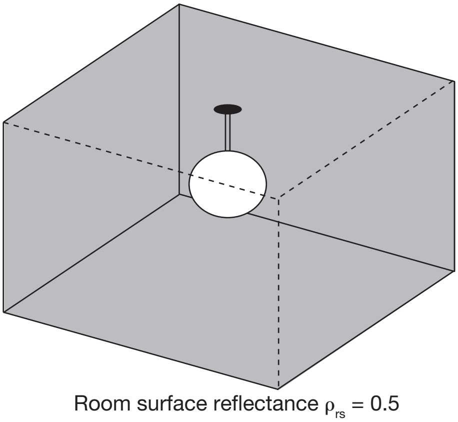


FIGURE 2.3 All room surfaces are given a neutral grey finish so that $\rho_{rs} = 0.5$.

All of the initial 5000 lumens from the luminaire are incident on room surfaces that reflect 50 per cent back into the space, so the first reflection adds 2500 lm, bringing the total luminous flux in the space up to 7500 lm. These reflected lumens are again incident on room surfaces, and the second reflection adds another 1250 lumens to the total. The process repeats, so that you could go on adding reflected components of the initial flux until they become insignificantly small. Alternatively, the effect of an infinite number of reflections is given by dividing the initial flux by (1 - ρ), so that:

$$\begin{aligned}\text{Total flux} &= F/(1 - \rho)\\ &= 5000/(1 - 0.5)\\ &= \textit{10,000 lumens}\end{aligned}$$

An interesting point emerges here. We have surrounded the luminaire with surfaces that reflect 50 per cent of the light back into the space, and this has doubled the number of lumens. Keep this point in mind. Now we divide the total flux by the total room surface area to get the average room surface illuminance:

$$\begin{aligned}E_{rs} &= 10{,}000/100\\ &= 100 \text{ lux}\end{aligned}$$

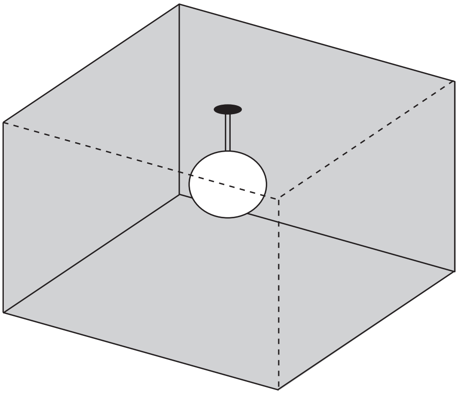
At last we have a measure we can understand. This would be enough light for us to see our way around the space, but not enough to make the room appear brightly lit. Let's suppose that we want a reasonably bright appearance. Well, we could fit a bigger lamp in the luminaire, but before we take that easy option, let's think a bit more about the effect of room surface reflectance. We have seen that it can have a quite surprising effect on the overall amount of light in the space.

What would be the effect of increasing ρ_{rs} to 0.8, as shown in Figure 2.4? Combining the expressions we used before, it follows that the mean room surface illuminance:

$$E_{rs} = \frac{F}{A(1-\rho)}$$

$$= \frac{5000}{100(1-0.8)}$$

$$= \underline{250 \text{ lux}}$$



Room surface reflectance ρ_{rs} = 0.8

FIGURE 2.4 Room surface reflectance is increased so that $\rho_{rs} = 0.8$.

This deserves some careful attention. We increased ρ_{rs} from 0.5 to 0.8, which is a 60 per cent increase, and the total flux increased two-and-a-half times! How can this be so? Think about it this way. It is conventional to refer to surface reflectance values, but try thinking instead of surface absorptance values, where $\alpha = (1 - \rho)$. What we have done has been to reduce α_{rs} from 0.5 to 0.2, and that is where the 2.5 factor comes from.

As this is a thought experiment, think about what would happen if we could reduce α_{rs} to zero. Well, the lumens would just keep bouncing around inside the room. When you switched on the luminaire, the total flux would keep on increasing. If you did not switch off in time, the room probably would explode! If you did switch off in time, the light level would remain constant. You could come back a month later and it would be undiminished, until you open the door and in a flash all the lumens pour out and the room would be in darkness. Thought experiments really can be fun. Now think about going in the opposite direction.

What would be the effect of reducing ρ_{rs} to zero? How brightly lit would the room appear? The question is of course meaningless. The only thing visible would be the luminaire, as shown in Figure 2.5. If you were sufficiently adventurous, you could feel your way around the room and you could use a light meter to confirm the value of the mean room surface illuminance:

$$E_{rs} = \frac{F}{A(1-\rho)}$$

$$= \frac{5000}{100(1-0)}$$

$$= \underline{50 \text{ lux}}$$

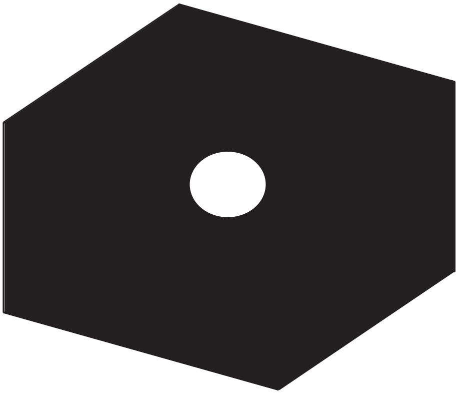


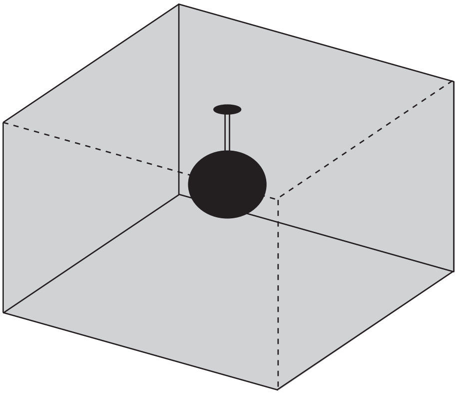
FIGURE 2.5 Room surface reflectance is reduced to zero, so $\rho_{rs} = 0$.

The meter would respond to those 50 lux, but your eye would not. Here is another important point. The direct flux from the luminaire has no effect on the appearance of the room. It is not until the flux has undergone at least one reflection that it makes any contribution towards our impression of how brightly, or dimly, lit the room appears. To have a useful measure of how the ambient illumination affects the appearance of a room, we need to ignore direct light and take account only of reflected light.

Let's think now about a general expression for ambient illumination as it may affect our impression of the brightness of an enclosed space. The luminaire is to be ignored, and so in Figure 2.6, it is shown black. Admittedly, a black luminaire emitting 5000 lm is rather more demanding of the imagination, but bear with the idea. To take account of only light reflected from room surfaces, we need an expression for *mean room surface exitance, MRSE*, where exitance expresses the average density of luminous flux exiting, or emerging from, a surface in lumens per square metre, lm/m^2.

$$\text{MRSE} = \frac{F\rho}{A(1-\rho)} \tag{2.1}$$

$$= \frac{\text{FRF}}{A\alpha} \tag{2.2}$$



A black luminaire emits F lumens in a room
of area A and reflectance ρ

FIGURE 2.6 The final stage of the thought experiment. A black luminaire emits F lm in a room of area A and uniform surface reflectance ρ, and mean room surface exitance, MRSE, is predictable from Formulae 2.1 and 2.2.

The upper line of Formula 2.2 is the *first reflected flux FRF*, which is the initial flux after it has undergone its first reflection. This is the energy that initiates the inter-reflection process that makes the spaces we live in luminous. More descriptively, it is sometimes referred to as the 'first bounce' lumens.

The bottom line is the *room absorption, Aα*. One square metre of perfectly black surface would comprise 1.0m^2 of room absorption; alternatively, it may comprise 2.0m^2 of a material for which $\alpha = 0.5$, or again, 4.0m^2 if $\alpha = 0.25$. It is a fact that when you walk into a room, the ambient illumination reduces because you have increased the room absorption. You could minimise that effect by wearing white clothing, but that is unlikely to catch on among lighting designers. My own observation is that if lighting designers can be said to have a uniform, it is black. It seems we aspire to be perfect light absorbers!

The MRSE concept

Of course, real rooms do not have uniform reflectance values, but this can be coped with without undue complication.

On the top line of Formula 2.1, Fρ is the First Reflected Flux, FRF, which is the sum of 'first bounce' lumens from all of the room surfaces, such as ceiling, walls, partitions and any other substantial objects in the room. It is obtained by summing the products of:

- direct illuminance of each surface $E_{s(d)}$
- surface area A_s
- surface reflectance ρ_s

So, in a room having n surface elements:

$$\mathrm{FRF} = \sum_{s=1}^{n} E_{s(d)} \cdot A_s \cdot \rho_s \tag{2.3}$$

On the bottom line of Formula 2.1, $A(1 - \rho)$ is the Room Absorption, indicated by the symbol $A\alpha$, and it is a measure of the room's capacity to absorb light. As it is conventional to describe surfaces in terms of reflectance rather than absorptance;

$$A\alpha = \sum_{s=1}^{n} A_s(1-\rho_s) \tag{2.4}$$

The general expression for mean room surface exitance, Formula 2.2, may be summarised as:

> *The mean room surface exitance equals the first bounce lumens divided by the room absorption.*

MRSE has three valuable uses:

1 The MRSE value provides an indication of the *perceived brightness or dimness of ambient illumination*. Table 2.1 gives an approximate guide for the two decades of ambient illumination that cover the range of indoor general lighting practice. These values are based on various studies conducted by the author and reported by other researchers, and it should be noted that ambient illumination relates to a perceived effect, while MRSE is a measurable illumination quantity, like illuminance, but not to be confused with working plane illuminance.

TABLE 2.1 Perceived brightness or dimness of ambient illumination

Mean room surface exitance (MRSE, lm/m^2)	*Perceived brightness or dimness of ambient illumination*
10	Lowest level for reasonable colour discrimination
30	Dim appearance
100	Lowest level for 'acceptably bright' appearance
300	Bright appearance
1000	Distinctly bright appearance

2 The MRSE ratio for adjacent spaces provides an index of the *perceived difference of illumination*. Table 2.2 gives an approximate guide for this perceived difference as one moves from space to space within a building, or to the appearance of differently

TABLE 2.2 Perceived differences of exitance or illuminance

Exitance or illuminance ratio	*Perceived difference*
1.5:1	Noticeable
3:1	Distinct
10:1	Strong
40:1	Emphatic

illuminated surfaces or objects within a space. There is more about this perceived difference effect in the following chapter.

3 It may provide an acceptable measure of the total *indirect illuminance* received by an object or surface within the space, so that for a surface S, the total surface illuminance may be approximately estimated by the formula:

$$E_s = E_{s(d)} + \text{MRSE} \tag{2.5}$$

where $E_{s(d)}$ is the direct illuminance of surface S. Procedures for predicting direct illumination are explained in Chapter 6.

Before we examine how MRSE may be applied in the design process, I am conscious that some readers may be finding the exitance term unfamiliar, as it often is customary to refer to illuminance as the metric for incident light, and luminance for reflected light. To see where exitance fits in, take a step back. Illuminance is a simple concept. It refers to the density of luminous flux incident on a surface, either at a point or over an area, in lux, where 1 lux equals 1 lumen per square metre (lm/m^2). Exitance is also a simple concept. It refers to the density of flux exiting, or emerging from, a surface in lm/m^2. (It should be noted that the lux unit is defined as the unit of illuminance, and so should not be used for exitance. Actually, keeping these units distinct for incident and exiting flux helps to avoid confusion.) Now consider luminance. This is not a simple concept. As simply as I can express it, it is the luminous flux due to a small element in a given direction, relative to the area of the element projected in that direction and the solid angle subtending the flux, measured in candelas per square metre (cd/m^2). It needs to be recognised that there are times when it is necessary to use the luminance metric, as for visual task analysis where the contrast of the critical detail has to be defined, but to refer to the average luminance of a wall or a ceiling really is meaningless without a defined view point. After all, what is the average projected area of one of these elements? Readers who are not familiar with the exitance term are strongly advised to make themselves acquainted with it. Not only is it a much more simple concept than luminance, but when we are concerned how illumination affects the appearance of room surfaces, it is the correct term to use. Seen in this way, MRSE is the measure of the overall density of inter-reflected light within the volume of an enclosed space.

Applying the ambient illumination concept in design

Room surface reflectances are so influential upon both the appearance of indoor spaces and the distribution of illumination within them that, in an ideal world, lighting designers would take control of them. The reality is that generally someone else will make those decisions, but lighting designers must persist in making these decision makers aware of the influence they exert over ambient illumination and the overall appearance of the illuminated space.

The creativity of a lighting designer is largely determined by the ability to perceive a space and its objects *in light*, and as we have seen, the perceived light is reflected (not direct) light. A room in which high reflectance surfaces face other high reflectance surfaces is one in which inter-reflected flux persists, and it is this inter-reflected flux that provides for our sense of how brightly or dimly lit the space appears.

To initiate this inter-reflected flux, direct light, which travels from source to receiving surface without visible effect, has to be applied. The essential skill of a lighting designer may be seen as the ability to devise an invisible distribution of direct flux that will generate an envisaged distribution of reflected flux.

Large, high reflectance surfaces enable the direct light to be applied efficiently and unobtrusively, and where high MRSE levels are to be provided, the availability of large, light-coloured surfaces that can be washed with light becomes an important consideration for both appearance and energy efficiency. Conversely, where the aim is to keep MRSE low, perhaps to provide high contrasts for display lighting, dark-coloured room surfaces reinforce the visual effect by absorbing both spill light (display lighting that misses the display) and 'first bounce lumens' reflected from the displays.

Estimating surface reflectance values is not straightforward. The Munsell Value (MV) scale orders surface colours on a 10-step scale according to lightness assessments, where MV0 appears to be a perfect black, and MV10 a perfect white. Unlike reflectance, lightness is a subjective scale, and while it relates to reflectance, the relationship is far from linear. A value of MV5 is perceptually mid-way between black and white and so it might be expected to have a reflectance around 0.5, but as Figure 2.7 shows, its actual value is

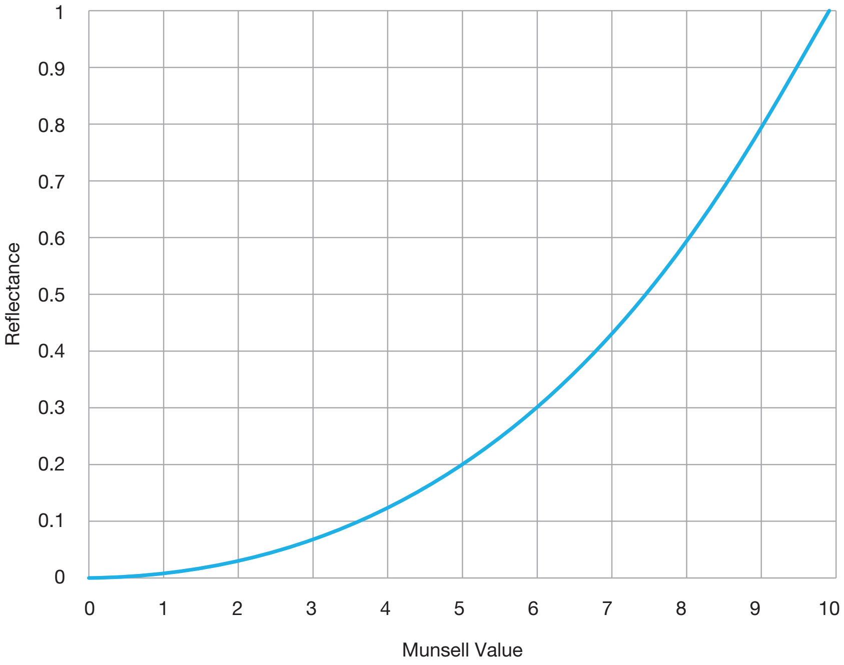


FIGURE 2.7 Reflectance plotted against Munsell Value, where a surface of MV0 would be assessed as a perfect black and MV10 as a perfect white. Perceptually MV5 is mid-way between these extremes and might be expected to have a reflectance of 0.5, but actually, it has a reflectance of approximately 0.2.

approximately 0.2. Furthermore, it can be seen that a surface having a reflectance of 0.5 has a MV of approximately 7.5, and that puts it perceptually three-quarters of the way towards perfect white. The practical implication of this pronounced non-linearity is that inexperienced designers are inclined to substantially overestimate reflectance values. A reasonably reliable procedure is to fit an internally blackened tube over an illuminance meter as shown in Figure 2.8 and to take two readings, one for the surface, R_S and one for a sheet of good quality white paper which has been slid over the surface, R_P. It is reasonable to assume that the paper has a reflectance of 0.9, so that for a measure of surface reflectance, $\rho_S = 0.9\, R_S/R_P$. Patterned as well as plain surfaces can be dealt with in this way, but care needs to be taken to avoid specular reflections, particularly for glossy surfaces. Also, it should not be assumed that shiny surfaces have high reflectance. These surfaces simply reflect without diffusion, so that if the meter is exposed to specular reflection, what is being measured is an image of a light source rather than the overall reflection of light from the surface.

FIGURE 2.8 Using an internally blackened tube mounted onto a light meter to obtain a measurement of surface reflectance. Two measurements are made without moving the meter, one of the surface as shown, and a comparison reading with a sheet of white paper in the measurement zone.

The effects of this tendency to overestimate reflectance values are compounded by the impact of surface reflectance values on MRSE. It can be seen from Formula 2.1 that MRSE is proportional to the ratio of room surface reflectance to absorptance, ρ/α. Figure 2.9 plots the value of this ratio relative to reflectance, and again it can be seen that the impact of room surface reflectance increases exponentially with reflectance, and could lead to grossly inflated MRSE values being predicted where reflectance values have been overestimated. We can see here the effects of reflectance that were observed in the thought experiment, and while these effects are real, they will not be realized unless reflectance values have been accurately assessed.

These considerations suggest an initial sequence for applying these concepts:

1. Decide upon the level of MRSE, taking account of design considerations concerning the perceived brightness or dimness of ambient illumination, and referring to Table 2.1 and the discussion in the section entitled 'The amount of light'.
2. Calculate the room absorption, $A\alpha$, referring to Formula 2.4.
3. Determine the level of first reflected flux, turning Formula 2.2 around to $FRF = MRSE \times A\alpha$
4. Determine a distribution of direct flux to provide the FRF value. At this point, we come to a central design issue: how to distribute the direct flux, $F_{s(d)}$, or in other words, how to choose the surfaces onto which flux will be directed. To explain this issue we will consider two cases.

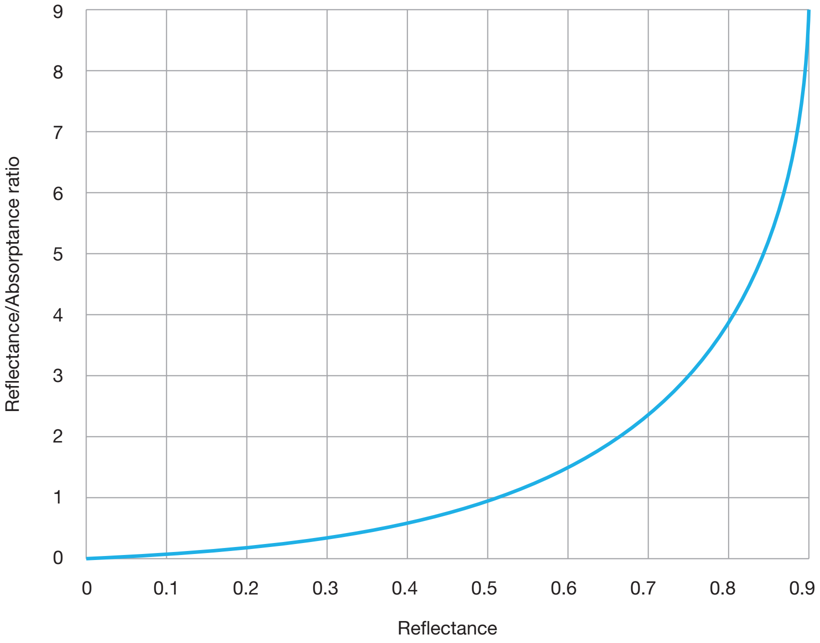


FIGURE 2.9 The value of the reflectance/absorptance ratio is proportional to mean room surface exitance, MRSE. Note how values increase exponentially at higher reflectance values.

Throughout this book we will be making use of spreadsheets to facilitate calculations, and their outputs are shown in the Boxes alongside the text. Readers are strongly encouraged to follow the instructions for downloading the spreadsheets so they can then follow the applications described. Boxes 2.1 and 2.2 show two outputs of the Ambient Illumination Spreadsheet, but the real benefit of doing calculations in this way is not that it all happens so quickly and easily (although that undoubtedly is a benefit) but that, once a situation has been set up, the user is able to explore alternative solutions with instant feedback. Readers are strongly encouraged to follow these examples, and then to go beyond them by asking, ‘What if …?’

BOX 2.1

AMBIENT ILLUMINATION
140117

Project Case 1
MRSE 150 lm/m^2

Room Dimensions

Length	Width	Height
12	9	3 m

Surface	As	ρs	Aαs	Direct Flux (%)	$F_{s(d)}$	E_s	E_s/MRSE
Ceiling	108	0.85	16.2	75	24437	376	2.5
Walls	126	0.5	63	15	4887	189	1.3
Floor	108	0.25	81	10	3258	180	1.2
Object 1	0	0	0	0	0	0	0.0
Object 2	0	0	0	0	0	0	0.0
Object 3	0	0	0	0	0	0	0.0

Room absorption Aα	160.2 m^2
First reflected flux (FRF)	24030 lm
Total luminaire flux (F)	32583 lm

Key

ρs	Reflectance of surface S
Aαs	Absorption of surface S (m^2)
As	Area of surface S (m^2)
E_s	Illuminance of surface S (lx)
$F_{s(d)}$	Direct flux incident on surface S (lm)
MRSE	Mean room surface exitance (lm/m^2)

Notes

Enter data only in cells shown in red – all other data are calculated automatically.
Direct Flux (%) is the direct flux incident on S as a percentage of total luminous flux.

Envisage an indoor space measuring 12m long, 9m wide, and 3m high. To keep life simple, we will not get too specific about the function of this room. For Case 1 we will work on the basis that the aim is to provide a fairly bright overall appearance, where everything appears adequately lit but no objects are to be selected for particular attention, and what is called for is a well-diffused, overall illumination. Decisions have been made for surface finishes, and it has been agreed that ceiling reflectance, ρ_{clg}, is to be 0.85, ρ_{wall} to have a value of 0.5, and ρ_{flr} will be 0.25, and Box 2.1 shows the dimensions and the reflectances entered on the Ambient Illumination Spreadsheet.

After giving due consideration to the points discussed in 'The amount of light', we decide upon a MRSE level of 150 lm/m^2. This value is entered on the spreadsheet, noting that data are to be entered only into cells marked in red. To fully understand the procedure, the reader is advised to check the calculation on paper using the aforementioned formulae.

The FRF value shown in Box 2.1 is the number of lumens reflected from all of the room surfaces required to provide the moderately bright overall appearance that we have set as our goal. Now we address the first really important design issue: how to distribute the direct flux? The aim is to achieve a well-diffused illumination, and to do this without creating distinctly bright zones suggests a lighting installation that distributes illumination evenly over large surfaces. The only remaining red values are in the Direct Flux (%) column, and this is the column where the designer experiments with direct flux distributions. Two values have been entered: 15 per cent of total luminaire output is to be directed onto the walls, and 10 per cent onto the floor. As no objects have been entered, that leaves 75 per cent onto the ceiling. The next column, $F_{s(d)}$, shows the number of lumens of direct flux required on each room surface; next, the E_s column shows the illuminance (including indirect flux) on each surface; and in the final column, the ratios of surface illuminance to ambient illuminance, E_s/MRSE. Below these columns are the values of $A\alpha$, FRF and the total luminous flux, F, to be emitted by the luminaires.

Ways of predicting luminaire layouts for direct light distributions are explained in Chapter 6, but before that, this spreadsheet gives the designer opportunity to explore the implications of flux distribution. To experience this, download the Ambient Illumination spreadsheet and click the Box 2.1 tag. Try changing the walls and floor flux percentages, and if you like, you can add a few objects, such as furniture items. You will see that every time you add more room absorption or direct more flux onto surfaces of lower reflectance, up goes the luminaire flux. For optimum energy efficiency, set the walls and floor direct flux percentages to zero so that the direct ceiling flux becomes 100 per cent, and you will see the luminaire flux drop to just over 28,000 lm. This would be the most energy efficient solution for achieving the MRSE target in this location, but when this happens, the value of E_s/MRSE climbs to 2.7, and this may be a cause for concern.

If the aim is to achieve the ambient illumination without any surface appearing noticeably more strongly lit than any other surface, then as indicated in Table 2.2, the aim should be to keep values of E_s/MRSE below 1.5. A value of 2.7 for the ceiling indicates that this surface will appear distinctly more strongly lit than any other surface or object in this space, and in fact, for the case shown in Box 2.1, where some flux is directed onto the walls and floor, the E_s/MRSE value is only slightly reduced to 2.5, so the appearance of the direct illumination onto the ceiling would certainly be 'noticeable', even if not 'distinct'. We could try adjusting the percentage values on the spreadsheet to achieve a less pronounced effect, but watch the value of the total luminaire flux, F. As more luminaire flux is directed onto lower reflectance surfaces, so the flux required to provide the MRSE value goes up. It should not pass notice that this flies in the face of conventional practice. All around the world, lighting standards for illumination sufficiency for indoor activities are specified in terms of illuminance applied onto the horizontal working plane, from which it follows that 'efficient' lighting takes the form of a grid layout of luminaires that directs its output directly onto that plane. While it is widely acknowledged that indirect ceiling lighting installations can achieve pleasant effects, the way the standards are specified causes them to be classified as inefficient. When a designer is satisfied that a satisfactory distribution of direct flux has been achieved, a copy of the spreadsheet would be saved onto the design project file.

Now turn attention to Case 2, for which we have a quite different aim. Again, we will not get too specific about the situation, but this time the aim is that a few selected objects are to be presented for display, and these are to become the 'targets' for the lighting with the intention that they will catch attention by appearing brightly lit in a dim setting. The revised output for the Ambient Illumination spreadsheet is shown in Box 2.2, and it shows that most of the direct flux is to be directed onto these targets. Even so, this is a space that people would need to be able to find their way through, so a background of inky blackness would not be acceptable. This brings us face-to-face with a tricky design decision. On one hand we aim to achieve a luminous environment that is dark enough to provide for effective display contrasts, while on the other hand it needs to be light enough for people to find their way through safely, and, at least as important, we need to create an entry to the space that people find welcoming. We should keep in mind that in order to attract people to enter this dim space, at least part of the displayed material should be positioned so that it is visible to someone approaching the entrance to the space.

As shown in Box 2.2, we have opted for a MRSE level of 10 lm/m^2, and at this stage we enter into discussion with the design team. It is agreed that both ρ_{clg} and ρ_{flr} are to be kept down to a level of 0.15, although to provide a slightly lighter background to the displays, a wall finish with a reflectance value of 0.25 is chosen. The displayed objects have a total surface area of 20m^2 with an average reflectance of 0.35, but it would be unrealistic to suppose that we will be able to direct 100 per cent of the luminaire flux onto them. It has been assumed that there will be 10 per cent spill light, half of it onto the walls and half onto the floor, and based on all these inputs, the spreadsheet shows that we need a total luminaire flux of 8690 lumens. That luminous flux, appropriately directed, will provide a display illuminance of 401 lux, and, referring again to Table 2.2, the visual effect will be 'emphatic', as it will provide a E_s/MRSE value of 40. Note that in order to achieve this dramatic effect we did not start by setting the target illuminance, but rather, we set the ambient illuminance and then determined the flux distribution. To provide a higher level of target illuminance would have the effect of raising the ambient illumination above the design value without adding to the E_s/MRSE ratio.

From these two cases it can be seen that in order for lighting to exert its potential for influencing the appearance of everything we see, control over room surface reflectance values is as important as being able to control direct flux distributions. Between these two quite extreme cases, many options exist for designers to control ambient illumination level to support chosen lighting design objectives. The Ambient Illumination Spreadsheet is a useful tool for achieving this control.

BOX 2.2

AMBIENT ILLUMINATION SPREADSHEET

140117

Project	Case 2
MRSE	10 lm/m^2

Room Dimensions

Length	Width	Height
12	9	3 m

Surface	As	ρs	Aαs	Direct Flux (%)	$F_{s(d)}$	E_s	E_s/MRSE
Ceiling	108	0.15	91.8	0	0	10	1.0
Walls	126	0.25	94.5	5	435	13	1.3
Floor	108	0.15	91.8	5	435	14	1.4
Object 1	20	0.35	13	90	7821	401	40.1
Object 2	0	0	0	0	0	0	0.0
Object 3	0	0	0	0	0	0	0.0

Room absorption Aα	291.1 m^2
First reflected flux (FRF)	2911 lm
Total luminaire flux (F)	8690 lm

Key

ρs	Reflectance of surface S
Aαs	Absorption of surface S (m^2)
As	Area of surface S (m^2)
E_s	Illuminance of surface S (lx)
$F_{s(d)}$	Direct flux incident on surface S (lm)
MRSE	Mean room surface exitance (lm/m^2)

Notes

Enter data only in cells shown in red – all other data are calculated automatically.

Direct Flux (%) is the direct flux incident on S as a percentage of total luminous flux.

3

ILLUMINATION HIERARCHIES

Chapter summary

Where ambient illumination is sufficient for illuminance and lightness (which is related to reflectance) to be perceived separately, as typically occurs for conventional indoor lighting practice, lighting may be planned in terms of illuminance (rather than luminance) distributions. Local concentrations of illumination can be applied to direct attention, to give emphasis and identify objects that the designer deems to be visually significant. The notion of ordered distributions of illumination leads to the concept of illumination hierarchy, whereby illumination distributions are structured as a principal means by which the designer may express his or her design intentions. Such distributions are planned as changing balances of direct and indirect illumination, and are achieved by specifying *target/ambient illuminance ratio* (TAIR) values. The Illumination Hierarchy spreadsheet facilitates application of this concept.

Ordered illumination distributions

Most forms of life are attracted towards light, and humans are no exception. Phototropism is the process by which attention is drawn toward the brightest part of the field of view. It can be detrimental, as when a glare source creates a conflict between itself and what a person wants to see, and in general lighting practice much attention is given to avoiding such effects. However, for lighting designers it is a powerful tool, enabling us to draw attention to what we want people to notice and away from things of secondary or tertiary significance. An ordered illumination distribution is the underpinning basis for structuring a lighting design concept.

It is important to spend some time looking carefully at how our perceptions of space and objects are influenced by selective illumination. It was noted in Chapter 1 that colours that make up an overall scene are generally perceived as *related colours,* and as long as illumination is sufficient to ensure photopic adaptation, we have no difficulty in recognising all the surrounding surfaces and objects that make up our environments. The process of recognising the multitude of 'things' that may, at any time, comprise our surroundings falls within the topic of perceptual psychology, but without getting involved in that field of learning it is sufficient here to acknowledge that this recognition process involves discriminating differences of object attributes such as lightness, hue and saturation, from which we form perceptions of spaces, people, and objects. We achieve this without conscious effort throughout our waking hours over a very wide range of 'adequate' lighting conditions. In this context, the onset of dimness may be thought of as the borderline of reliable recognition of object attributes.

However, with ordered illumination distributions we can go beyond simply providing for object recognition. Retailers long ago worked out that if an object that is small in relation to its surroundings receives selective illumination, particularly without the source of light being evident, people's perceptions of that object's attributes can be significantly affected. Whether or not it appears more brightly lit, it is likely to appear more colourful, and perhaps more textured or more glossy, than it would appear without selective illumination. Lighting designers have at their disposal the means to establish hierarchies of visual significance in illuminated scenes, and means for achieving this in an ordered manner is the content of this chapter.

Illuminance ratios

When we place an attractive object, such as a vase of flowers, beside a window to 'catch the light', we are exploiting the potential for a pool of local illumination to identify this object as having been selected for special attention. Similarly, electric lighting can provide a planned gradation of illumination that expresses the designer's concept of layers of difference. Hard-edged contrasts can give emphasis to such effects, but alternatively, a different but equally striking effect may be achieved by a build-up of illuminance that leads the eye progressively towards the designer's objective. High drama requires that surroundings are cast into gloom, but in architectural situations, safety requirements generally require surroundings to remain visible, although perhaps distinctly dim, at all times. Planning such distributions is more than simply selecting a few objects for spotlighting. It involves devising an ordered distribution of lighting to achieve an *illumination hierarchy*.

The concept of a structured illumination distribution was pioneered by J.M. Waldram (1954). Working from a perspective sketch of the location, he would assign an 'apparent brightness' value to each significant element of the view, and then he would convert those subjective values into luminance values so that he could apply illumination engineering procedures to determine a suitable flux distribution. Waldram's notion of creating an ordered brightness distribution related to luminance would seem to be valid for low adaptation situations, such as occur in outdoor lighting, but not for situations where surface lightness is readily recognised, such as in adequately illuminated indoor scenes. As has been noted, for these situations our perceptions distinguish illumination differences more or less independently of surface reflectance values.

J.A. Lynes (1987) has proposed a design approach based on Waldram's method with the difference that the designer develops a structured distribution of surface illuminance values. Lynes introduces his students to the topic through an exercise in perceived difference of illumination, and his simple procedure is illustrated in Figure 3.1. He stands in front of his class with a spotlight shining onto a white screen. Point 0 is the brightest spot, and from this point a numbered scale extends across the screen. Each student completes a score card, and starts by indicating the scale value that, in his or her assessment, corresponds to the point along the scale at which a 'noticeable difference of brightness' occurs. This is the student's 'N' value, and would be followed by a 'D' value for a distinct difference, an 'S' value for a strong difference and an 'E' value for an emphatic difference. The cards are then gathered, average values calculated and consensus values for N, D, S and E are marked on the screen. After that, Lynes measures the illuminance level at each point, from which illuminance ratios are calculated for each perceived difference.

The author has conducted this exercise with students on numerous occasions. Perhaps the first surprise is to find how easy it is to obtain consensus, and the second is how well the results are repeated year after year. The data presented in Table 2.2 is typical, and while this simple procedure may not qualify as 'good science', it is well worth going through the procedure. It calls for thoughtful observation, and, perhaps surprisingly, it provides useful guidance for lighting design. Not only students, but anyone interested in designing lighting should go through the process of making these illumination difference assessments at least once during their lifetime.

Whereas in Chapter 2 we discussed how initial responses to a space may be influenced by ambient illumination, now we turn attention to the perceived effects that can be

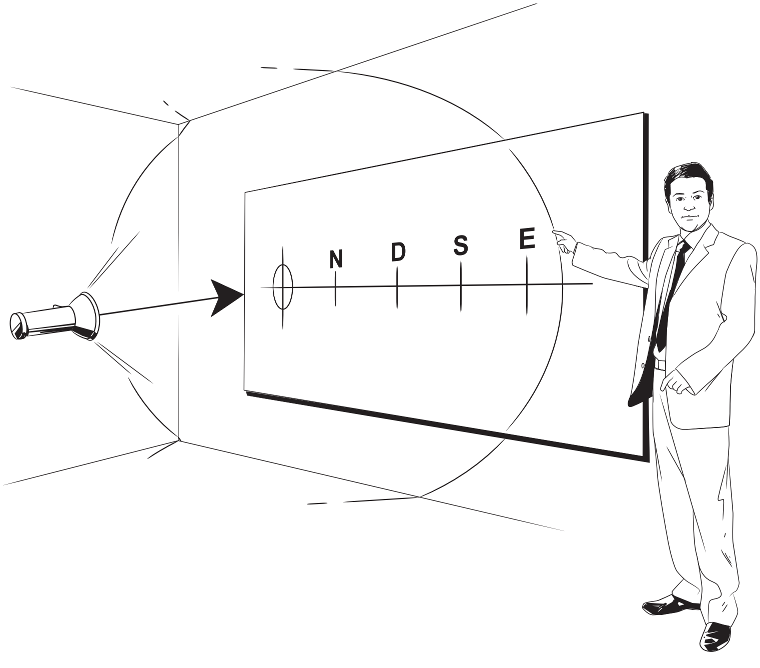


FIGURE 3.1 Demonstration set-up for gaining assessments of noticeable, distinct, strong and emphatic illumination differences.

created by controlling the distribution of illumination within a space. From Table 2.2 it can be seen that where the aim is to achieve a difference that is sufficient to be noticed, you can forget about 10 or 20 per cent differences. Unless a difference of at least 1.5:1 is provided, people will not notice the illumination to be anything different from uniform. To achieve differences that are likely to be described as 'distinct' or 'strong', it is necessary for the designer to be purposeful and deliberate in how they achieve such pronounced visual effects. Illumination distributions will have to be carefully controlled and, preferably, surrounding reflectances kept low. An 'emphatic' difference is quite difficult to achieve other than in a theatre or similar setting, and as was noted towards the end of Chapter 2, raising the target illumination unavoidably raises the ambient illumination. Where the aim is to achieve high illuminance differences, target objects need to be small in relation to their surrounding space, or more specifically, to the room absorption of the surrounding space.

We will return to this last point, but before moving on, let it be repeated that making assessments of the appearance of illumination differences is a revealing exercise in observation. Actually doing it, and measuring one's own assessments of perceived difference, is instructive. Then following up with observation and measurement in real locations is enormously valuable. The meter tells you nothing useful until you have related its readings to your own experience. The data in Table 2.2 is typical, but a designer needs to be able to visualise these illuminance ratios. It is by having in mind the perceived effect of illuminance ratios that a designer is able to specify values that reflect observation-based experience.

Target/ambient illuminance ratios

While the perceived adequacy of illumination (PAI) criterion is concerned with ensuring adequate inter-reflected flux (MRSE) within a space, the *illumination hierarchy* criterion is concerned with how the direct flux from the luminaires may be distributed to create an ordered pattern of illumination that supports selected lighting design objectives, which may range from directing attention to the functional activities of the space to creating aesthetic or artistic effects. For all of this, we make use of the *target/ambient illuminance ratio, TAIR,* where target illuminance is the sum of direct and indirect components, and TAIR relates target illuminance to the ambient illumination level. The designer selects target surfaces and designates values according to the level of perceived difference of illumination brightness to be achieved both between room surfaces, and between objects and the surroundings against which they are seen. As the point has been made that illumination is not visible until it has undergone its first reflection, it may be wondered why we are now dealing with incident target illumination, which comprises both direct and indirect illumination. The answer is that as both components undergo reflection at the same surface, it makes no difference whether we take the ratio of the incident or reflected values.

MRSE provides the measure of ambient illumination within a space, and except where there are obvious reasons to the contrary, it is reasonable to assume that the incident illumination on each target surface *tgt* will be the sum of direct illuminance and MRSE, so the total illuminance on a target surface:

$$E_{tgt} = E_{tgt(d)} + MRSE \tag{3.1}$$

and the target/ambient illuminance ratio:

$$TAIR = E_{tgt} \,/\, MRSE \tag{3.2}$$

The TAIR concept provides a basis for planning a distribution of direct flux from the luminaires that will achieve an envisioned illumination distribution within a space. It follows that for any chosen target surface, the direct illuminance:

$$E_{tgt(d)} = MRSE(TAIR - 1) \tag{3.3}$$

Designing an illumination hierarchy involves designating *TAIR* values for selected surfaces or objects to signal noticeable, distinct, or strong perceived differences of illumination, again referring back to Table 2.2, and there really is no limit to the situations for which this procedure may be applied. A designer may choose to target a substantial proportion of the total room surface area, and examples of this would include lighting a mural covering a whole wall, or an architectural icon, or a library reading area, or perhaps, the horizontal work plane of an industrial assembly shop. Alternatively, the target area may be a single object that comprises a small proportion of the total surface area, such as a solitary sculpture, or a featured retail display, or the preacher in his pulpit; or it may comprise a number of even smaller items, such as display of coins, or individually lit items of glassware. Whatever the situation, the designer first needs to decide upon the *MRSE* level to achieve the required ambient illumination for the space, and then to decide upon the *TAIR* for each target surface for the differences of illumination brightness. This enables Formula 3.3 to be applied to draw up the distribution of direct target illuminance values.

This puts the designer in the position of being able to determine the distribution of direct light to be applied throughout the space in order to achieve the envisioned distribution of reflected light. The total indirect flux provided by first reflections from all surfaces receiving selective target lighting:

$$F_{ts(i)} = \sum E_{tgt(d)} A_{tgt} \rho_{tgt} \tag{3.4}$$

Note that the suffix *tgt* indicates an individual target surface, and *ts* refers to all target surfaces within the space. This value of $F_{ts(i)}$ indicates the extent to which all of the selective target lighting will contribute towards the first reflected flux required to achieve the ambient illumination MRSE. The usefulness of this formula becomes apparent in the following section.

It may be noted in passing that, unlike MRSE, TAIR is not proposed as a suitable metric for lighting standards. TAIR is a tool that enables pursuit of chosen lighting design objectives, which may range from very simple through to distinctly complex in nature, and its application involves objectives that are beyond the scope of standards, whether advisory or mandatory.

Illumination hierarchy design procedure

Without wishing to give the impression that creative lighting design can be achieved by following a step-by-step procedure, the concepts previously described imply a sequence for logical decision making. The flowchart shown in Figure 3.2 should be referred to while following this procedure.

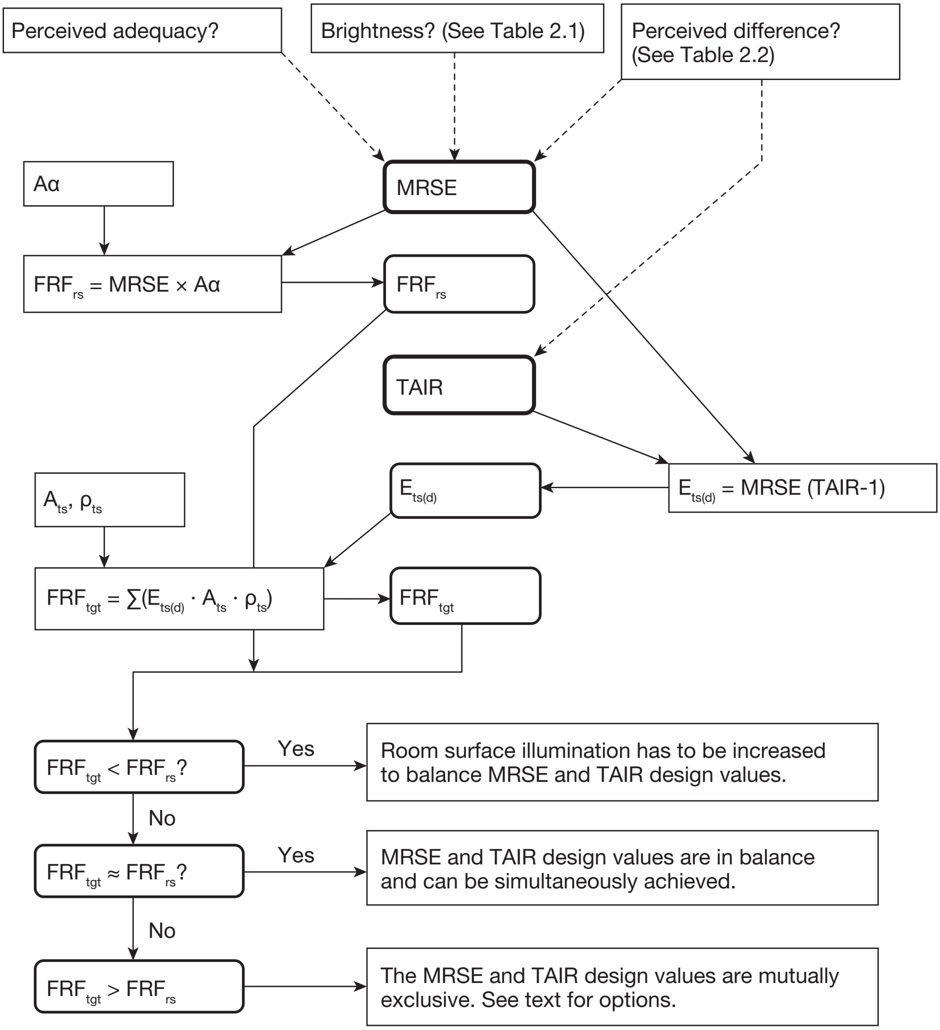


FIGURE 3.2 Flowchart for achieving mean room surface exitance, MRSE, and task/ambient illumination, TAIR, design values.

1 For a design location, consider a level of MRSE that would provide for an appropriate appearance of overall brightness or dimness. Codes or standards specified in task plane illuminance are unlikely to be helpful. Should there be a published MRSE value relevant to the location, it probably relates to the perceived adequacy of illumination (PAI) criterion and specifies the minimum value of MRSE to be provided. Consider whether a higher level to give a brighter appearance would be appropriate, referring to Table 2.1 for guidance, and taking into account the immediately previous brightness experience of a person entering this space. Consider whether it is to appear brighter or dimmer than the previous space, and if so, by how much, this time referring to Table 2.2 for guidance. Where no minimum levels are specified, designing for an appearance of dimness becomes an option providing safety concerns are kept in mind.

2 Decide upon the design value of MRSE, this being the overall density of inter-reflected flux to be provided within the volume of the space, and enter this value into the Illumination Hierarchy spreadsheet (see Box 3.1, and use your own downloaded copy of the spreadsheet).

3 Estimate the area and reflectance value for each significant surface S within the room, making sure to include any surfaces or objects that you might decide to highlight with selective lighting, and enter these onto the spreadsheet. The spreadsheet calculates the room absorption value, $A_{\alpha(rs)}$, and the total first reflected flux, FRF_{rs}, required to provide the MRSE value.

4 Consider the illumination hierarchy that the light distribution is to create in this space. Think about which objects or surface areas you want to highlight with selective lighting, and by how much. You will provide direct light onto these target surfaces, while surrounding areas will be lit mainly, or perhaps entirely, by reflected light.

5 Enter your design value of TAIR for each target area, taking account of how the appearance of the selected objects or surfaces will be affected by localised direct illumination. This listing of TAIR in Column 5 of the spreadsheet becomes the record of your illumination hierarchy for the space.

6 The spreadsheet completes the calculations, giving the first reflected flux to be provided by light reflected from the targets, FRF_{ts}, and the difference between this value and the total FRF required to provide the MRSE value, $FRF_{rs} - FRF_{ts}$.

Then:

- If the first reflected flux from the targets is less than the total first reflected flux required, that is to say, if $FRF_{ts} < FRF_{rs}$, then in addition to the light directed onto the target areas, the surrounding room surfaces will need some direct illumination to make up for the difference, $FRF_{rs} - FRF_{ts}$. This is needed to ensure that the MRSE design value will be achieved. The direct illumination onto the room surfaces does not need to be applied uniformly, and often the most effective way will be to spread light over large, high-reflectance surrounding surfaces such as ceiling and walls. Concentrating this light onto small areas may cause them to compete visually with the target areas, as has been discussed in Chapter 2. There is plenty of scope for ingenuity in devising ways of raising the overall illumination brightness without detracting from the selected targets.

- If $FRF_{ts} \approx FRF_{rs}$, the target illumination alone will provide for the design values for both MRSE and TAIR. This is because reflected light from the target surfaces will both provide the design level of ambient illumination and achieve the intended balance of target/ambient levels. A serendipitous outcome.
- If $FRF_{ts} > FRF_{rs}$, the proposed balance of MRSE and TAIR values cannot be achieved in this situation. The reason is that if the direct target illuminance is applied, the reflected flux will raise MRSE above the design level, and reduce TAIR values below the design levels. Usually the most effective remedial action will be to reduce the total target area, such as by concentrating the objects to receive direct light into more restricted areas. Otherwise, it will be necessary to reduce either, or both, ρ_{ts} and ρ_{rs}, but unfortunately, lighting designers seldom have much influence over reflectance values. A compromise may be inevitable, but at least the outcome will not come as an unwelcome surprise.

Example: a banking premises

Box 3.1 shows a worksheet from the Illumination Hierarchy spreadsheet, and again, readers are strongly recommended to experience the use of these design tools. Room surface data have been entered for a banking premises, so take a moment to familiarise yourself with the location.

A bright and business-like appearance is wanted, and a MRSE level of 200 lm/m^2 is proposed. This value has been entered, and as previously, data shown in red are input by the user and all other values are calculated automatically. Column 4 gives the computed room absorption values, and the bottom line shows that 39,096 lumens of first reflected flux from the room surfaces is required to provide the MRSE level. Next the designer enters a TAIR value for selected target surfaces. This is the vital component of this stage of the design process, and Column 5 forms the statement of the designer's initial intent for illumination hierarchy. At the bottom of the final column it is shown that 20,899 lm of the required FRF will be provided from the target surfaces, so that the difference of 18,197 lm will need to be made up by applying additional direct light onto room surfaces.

This is the information that the designer needs to determine the balance of direct and indirect illumination. Various options for providing the deficit *FRF* may come to mind, but a simple and efficient solution would be uplighting. The required direct ceiling illuminance is:

$$\begin{aligned} E_{clg(d)} &= FRF_{clg} / (A_{clg} \cdot \rho_{clg}) \\ &= 18197 / (113.3 \times 0.75) = 214 \text{ lux} \end{aligned}$$

This direct illuminance added to the MRSE value of 200 lm/m^2 would give a total ceiling illuminance E_{clg} of 414 lux, giving a TAIR value of just over two. Table 2.2 indicates that this would correspond to a perceived difference that would appear somewhere between noticeable and distinct, and so would create a visible effect that might compete with the planned distribution of TAIR values. This effect could be reduced by applying less illumination onto the ceiling and making up for the deficiency by adding some direct light onto other surfaces, particularly the walls.

It is at this point that the attraction of using the spreadsheet becomes evident. By treating selected room surfaces as targets, alternative strategies may be readily examined. As the wall surfaces have lower reflectance values than the ceiling, it will take more direct

BOX 3.1

ILLUMINATION HIERARCHY SPREADSHEET

Date: 140119

Project Name: Banking Hall Initial design

MRSE 200 lm/m^2

Room Surface	As m^2	ρs	Aαs	TAIR	$E_{tgt(d)}$ lx	FRF_{tgt} lm
Ceiling	113.3	0.75	28.3	1	0	0
Wall 1	19.8	0.65	6.9	1	0	0
Mural, wall 1	29.7	0.35	19.3	3	400	4158
Wall 2	40.3	0.65	14.1	1	0	0
Wall 3	24.8	0.65	8.6	1	0	0
Blinds, wall 3	24.8	0.8	4.9	1	0	0
Wall 4	28.2	0.65	9.8	1	0	0
Blinds, wall 4	12.1	0.8	2.4	1	0	0
Floor, public	51	0.25	38.2	1.5	100	1275
Floor, private	45.3	0.15	38.5	3	400	2718
Counter top	17	0.55	7.6	5	800	7480
Counter front	21.4	0.3	14.9	3	400	2568
Display panels	3	0.5	1.5	10	1800	2700

Aαrs	195 m^2	**FRFts**	20899 lm
FRFrs	39096 lm	**FRFrs – FRFts =**	18197 lm

Symbols

As, Aαs	area of surface S, room absorption of S (m^2)
E	illuminance (lux)
FRF	first reflected flux (lm)
MRSE	mean room surface exitance (lm/m^2)
ρ, α	reflectance, absorptance
s, rs	individual surface, all room surfaces
TAIR	target/ambient illuminance ratio
tgt, ts	individual target surface, all target surfaces

lumens to bring the FRF_{rs} value up to the required level, but the light-coloured blinds in walls 3 and 4 could receive selective wallwashing, and this might create an attractive appearance. However, the effectiveness of this solution would depend upon the staff pulling down the blinds during hours of darkness. It would be necessary to enquire whether this could be relied upon, and after all, this is the way that lighting design happens. It is part of the reason why no two designers would come up with identical schemes.

Box 3.2 shows a design proposal. The TAIR values in Column 5 have been adjusted to provide various levels of unnoticeable, noticeable, distinct and strong perceived

BOX 3.2

ILLUMINATION HIERARCHY SPREADSHEET

Date: 140119

Project Name: Banking Hall Final design proposal

MRSE 200 lm/m^2

Room Surface	As m^2	ρs	Aαs	TAIR	$E_{tgt(d)}$ lx	FRF_{tgt} lm
Ceiling	113.3	0.75	28.3	1.25	50	4248
Wall 1	19.8	0.65	6.9	1.25	50	643
Mural, wall 1	29.7	0.35	19.3	4	600	6237
Wall 2	40.3	0.65	14.1	1	0	0
Wall 3	24.8	0.65	8.6	1.25	50	806
Blinds, wall 3	24.8	0.8	4.9	2.5	300	5952
Wall 4	28.2	0.65	9.8	1.25	50	916.5
Blinds, wall 4	12.1	0.8	2.4	2.5	300	2904
Floor, public	51	0.25	38.2	1.5	100	1275
Floor, private	45.3	0.15	38.5	3	400	2718
Counter top	17	0.55	7.6	5	800	7480
Counter front	21.4	0.3	14.9	3	400	2568
Display panels	3	0.5	1.5	10	1800	2700
		Aαrs	195 m^2	**FRFts**		38449 lm
		FRFrs	39096 lm	**FRFrs – FRFts =**		647 lm

Symbols

As, Aαs	area of surface S, room absorption of S (m^2)
E	illuminance (lux)
FRF	first reflected flux (lm)
MRSE	mean room surface exitance (lm/m^2)
ρ, α	reflectance, absorptance
s, rs	individual surface, all room surfaces
TAIR	target/ambient illuminance ratio
tgt, ts	individual target surface, all target surfaces

differences, and by adding more target surfaces in this way, the $FRF_{rs} - FRF_{ts}$ difference has been reduced to a negligible value. This means that the first reflected flux from the targets will provide the required 200 lm/m^2 of mean room surface exitance, and with the exception of the blinds, the visible effect of this additional illumination will not be bright enough to be noticed. In this way, the original design intent will be maintained. It can be seen not all surfaces are to receive direct light.

Column 6 shows the direct illuminance to be provided onto each target surface. All that is left now is to apply some straightforward illumination engineering, and procedures for determining luminaire layouts to distribute direct flux to achieve specific illuminance values are explained in Chapter 6.

References

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4

SPECTRAL ILLUMINATION DISTRIBUTIONS

Chapter summary

Various ways in which human perception of a lit space is influenced by the spectral power distribution (SPD) of illumination are reviewed. Distinction is made between assessment of light for visibility and for brightness, and alternative response functions for indoor spaces are examined. The effects of SPD upon the perception of illumination colour (colour appearance) and coloured materials (colour rendering) are examined, along with various proposals for identifying how both SPD and illumination level influence the appearance of lit spaces. These include perceived attributes of illumination, such as the whiteness, naturalness and colourfulness of illumination, as well as some non-visual effects. It is concluded that people have different daytime and night time expectations and needs for lighting.

Luminous sensitivity functions

Before 1924, the only way of measuring light was to make comparisons with a familiar light source, which led to metrics such as the candle power and the foot candle, but in that year the CIE (International Commission on Illumination) introduced the V(λ) luminous sensitivity function which defines the relative visual response, V, as a function of the wavelength of radiant power, λ, as shown in Figure 4.1. This was a significant breakthrough that required innovative research, and it enabled luminous flux, F, to be defined in terms of lumens from a measurement of spectral power distribution:

$$F = 683\Sigma P(\lambda)V(\lambda)\Delta_{\lambda} \tag{4.1}$$

where:

P(λ) = spectral power, in watts, of the source at the wavelength λ
V(λ) = photopic luminous efficiency function value at λ
Δ_λ = interval over which the values of spectral power were measured

It can be seen from Figure 4.1 that V(λ) has its maximum value of 1.0 at 555nm, and so the luminous efficiency of radiant flux at this wavelength is equal to the value of the constant in Formula 4.1, 683 lm/W. At 610nm, where the value of V(λ) is approximately 0.5, the luminous efficiency reduces to half that value.

So by defining the V(λ) function, the CIE made it possible for the output of a light source to be specified in terms of the lumen, while at the same time enabling light itself to be defined in terms of radiant power within the waveband 380–780 nanometres (nm). To this day, lighting standards and recommended practice documents, as well as the calibration of all light meters, are based on V(λ), and in fact, it continues to be quite appropriate for measuring illumination in situations where photopically-adapted viewers are fixating upon visual tasks. Examples range from a library reading room to a hospital operating theatre, and for these, as well as for most task-based applications in between, this luminous sensitivity function continues to serve us well. There is, however, more to human response to light than this, and for designers to be able to apply lighting knowingly and effectively in the range of situations encountered in general lighting practice, we could benefit from metrics that take account of a wider range of human interactions with radiant flux.

Formula 4.1 assumes a human observer operating within the range of photopic vision, and this means that error is incurred whenever V(λ) is applied for mesopic or scotopic conditions. Also, the researchers who established the V(λ) function had their subjects observing a quite small luminous patch that subtended just 2 degrees at the eye, so that it

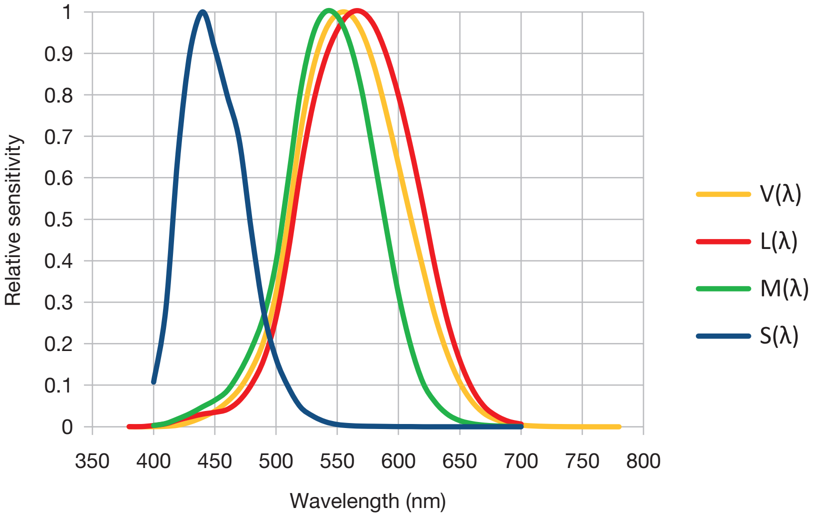


FIGURE 4.1 Relative sensitivity functions for V(λ), and the three cone types; long-, medium- and short-wavelength; L(λ), M(λ) and S(λ). It can be seen how closely V(λ) represents the responses of the L and M cones, and ignores the S cone response.

was illuminating only the foveal regions of the subjects' retinas. The photoreceptors in these central regions are only long- and medium-wavelength responsive cones, which are often (but inaccurately) referred to as the red and green cones, and their luminous sensitivity functions are shown in Figure 4.1 as L(λ) and M(λ) respectively. It should be noted how similar are the responses of these two cones, particularly when it is borne in mind that it is the difference in response of this pair of two cone types that enables colour discrimination on the red–green axis, and also, how closely similar they are to V(λ). The responses of the short-wavelength (blue) cones, shown as the S(λ) function, as well as all of the rods, are simply not taken into account by the V(λ) function.

For a photopically-adapted viewer, the S(λ) function does not affect acuity for a fixated task, but it does affect assessments of the brightness of the surrounding field, and this occurs to an extent that changes with field luminance. The Bezold-Brücke hue shift describes the effect of perceived colour differences on the blue–yellow axis increasing relative to those on the red–green axis with increasing luminance, and this affects brightness assessments. Rea *et al.* (2011) have proposed a luminous sensitivity function for brightness:

$$B(\lambda) = V(\lambda) + g.S(\lambda) \tag{4.2}$$

where the value of *g* is related to field luminance. In this way, a variable allowance for the response of the short-wavelength cones can be added to the long- and medium-wavelength cones dominated V(λ), and Mark Rea has tentatively suggested that for the range of luminous environments discussed in this book, for which 10 <MRSE <1000 lm/m^2, a *g* value of 3.0 would be appropriate. The resulting luminous sensitivity function, indicated as V_{B3}(λ), is shown in Figure 4.2. It is proposed that applying this function for predicting or measuring MRSE would give more reliable results, in terms of better matching metrics to assessments, than using conventional lumen-based metrics.

Meanwhile the CIE has given attention to other deficiencies of V(λ) by defining additional luminous sensitivity functions, the most notable being the V′(λ) function introduced in 1951, which defines the relative response of the rod photoreceptors, and so relates to scotopically-adapted vision (Figure 4.3). This function shows substantially greater sensitivity for shorter wavelength (blue) radiant flux, but while research scientists are able to recalculate luminous flux according to the viewing conditions, this does not happen in general lighting practice. The notion that the lumen output of a lamp might depend on the circumstances of its use is a complication that the lighting industry would not welcome, and so the 1924 V(λ) function persists. Until lighting practice comes to terms with this discrepancy, some level of mismatch between measured or predicted lighting performance and human response is inevitable. For designers, it becomes a matter of how we balance simplicity and convenience against actually providing what we have promised.

It may be noted that the visual field has to become distinctly dark, with adaptation luminance less than 0.001 cd/m^2, for vision to become entirely due to the rod photosensors. When this occurs, scotopic conditions prevail and the V′(λ) luminous sensitivity function applies, so that scotopic luminous flux:

$$F' = 1700\Sigma P(\lambda)V'(\lambda)\Delta_\lambda \tag{4.3}$$

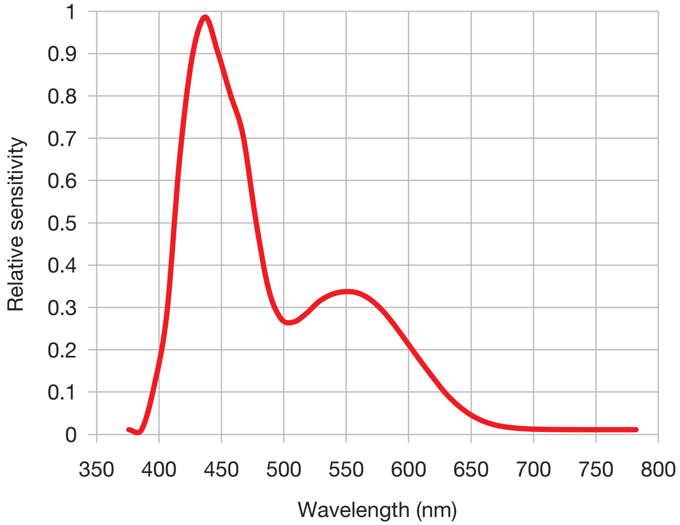


FIGURE 4.2 The $V_{B3}(\lambda)$ spectral sensitivity of brightness function for daytime light levels, where the contribution of the S cones relative to $V(\lambda)$ is high ($g = 3$). After Rea (2013).

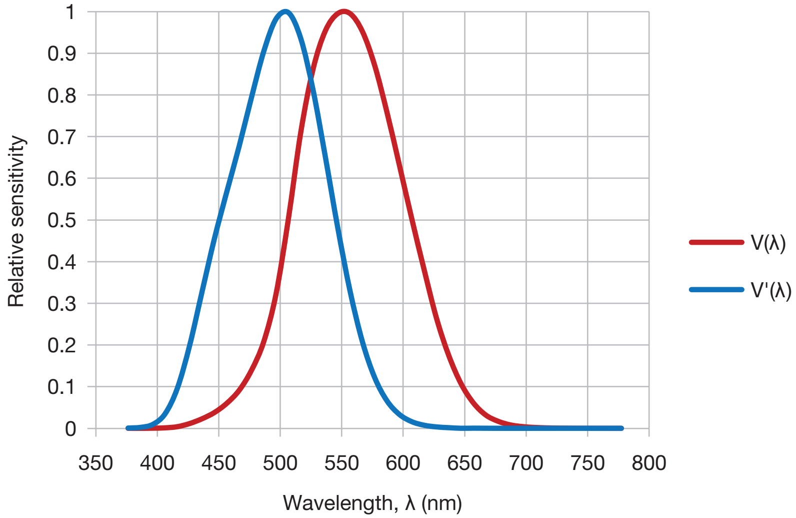


FIGURE 4.3 The $V(\lambda)$ and $V'(\lambda)$ relative luminous efficiency functions relate to photopic and scotopic adaptation respectively.

In this way, while the photopic luminous flux, F, for a given source is determined by application of Formula 4.1, its scotopic lumens, F′, could be determined by application of Formula 4.3. Note the increased value of the constant in this formula to reflect the high sensitivity of dark-adapted rods. It follows that if the value of F′/F, referred to as the S/P (scotopic/photopic) ratio, is high, then at low light levels, where the rods are active, the visual response will be underrated. Sources rich at shorter wavelengths, such as metal halide lamps, will, for the same lumens, generate stronger visual responses than lamps rich at longer wavelengths, such as sodium lamps.

Some other visual and non-visual responses

While it would seem quite straightforward that F′ should be used as the measure for luminous flux for scotopic conditions, these conditions are in fact so dim that nobody actually provides illumination to achieve them. Lighting practice for outdoor spaces, such as car parks, roadways and airport runways, aims to provide conditions in the mesopic range, which extends from 0.001 cd/m^2 up to the lower limit of the photopic range, at 3 cd/m^2. Within this substantial adaptation luminance range, spectral sensitivity undergoes transition between scotopic and photopic adaptation, and where we are concerned with brightness assessments, this means transition between the very dissimilar $V'(\lambda)$ and $V_{B3}(\lambda)$ functions, which makes accurate assessment of the likely visual response problematic (Rea, 2013). This is a real issue for providing illumination at outdoor lighting levels.

For indoor lighting at photopic levels, there are some different issues that concern researchers. It has been established that, at the same luminance levels, pupil size is smaller for higher S/P illumination, and this led to the assumption that pupil size is determined by the response of the rod photoreceptors, even at photopic levels. Berman *et al.* (1993) conducted a series of laboratory studies for tasks close to the visual threshold (the point at which there is a 50/50 probability of accurate detection) and showed that performance was better for higher S/P sources. It might seem odd that reduced pupil size, which must reduce the amount of light reaching the retina, should give increased performance, but the explanation offered was that reducing the lens aperture would improve the quality of the retinal image. As with a camera, smaller lens aperture gives increased depth of field, which is an advantage for anyone whose refractive correction is less than perfect. It also occurs that rays passing through the peripheral zones of the eye's lens tend to undergo aberrations, as the lens of the eye is, in fact, of no more than moderate optical quality, so that reducing observers' pupil sizes is likely to cause them to experience improved image resolution. It was claimed that these advantages would more than compensate for the reduced retinal illuminance.

Application of the S/P findings to lighting practice has recently been the subject of both research and debate. The notion that visual performance could be maintained at lower illuminance levels offers opportunities for significant energy savings, and this certainly has aroused interest, but it has been pointed out that the higher performance demonstrated for threshold visual tasks would be unlikely to apply for the much more usual condition of suprathreshold tasks. General lighting practice aims to ensure that tasks are performed with high rates of accuracy, meaning that they are to be illuminated to well above their threshold levels, so that advantages that may occur in an experiment where the probability of error is high probably would not occur in practical situations (Boyce, 2003). A recent field study by Wei *et al.* (2014) of office workers found not only that any advantages attributable to high S/P sources were too small to be worthwhile, but also that the people working in those conditions disliked the high S/P lighting. Among the research community there now seems to be a lack of interest in pursuing this topic, but that has not stopped some unscrupulous suppliers from making claims that are exaggerated, and even downright false, for high S/P lamps. It may be noted in passing that since the original investigations, researchers have become aware that pupil size response is more complex than simply responding to the level of rod cells stimulation, and seems to involve the recently discovered ipRGC response (see following paragraph).

Humans exhibit various non-visual responses to light, and the most important, at least from our point of view, is the circadian response, being the 24-hour cycle that we experience along with most living things on this planet. With the onset of circadian night, a hormone named melatonin is released from the pineal gland into the bloodstream, and this is associated with the sleep/wake cycle that is said to be regulated by a hypothetical biological clock that each one of us carries inside us. Researchers had noted that the melatonin response to light exposure displays a spectral sensitivity that does not match that of any of the retinal photoreceptors, but it was not until 2002 that the mystery was solved. The answer lies in the complex pattern of connections within the retina that link the photoreceptors to the optic nerve for communication to the brain. Retinal ganglion cells were known to play major roles in this process, but what had not been suspected was that some of these cells actually contain a photopigment, which has been named melanopsin, and the light response of these intrinsically photosensitive retinal ganglion cells (ipRGCs) connects not to the visual cortex, but to the endocrine gland, and on to the pineal gland. The peak sensitivity of these cells due to the melanopsin photopigment occurs at 460 nm, which is substantially shorter than the peak responses of any of the retinal photocells.

Rea (2013) has proposed a spectral sensitivity function, $V_C(\lambda)$, for the human circadian response, which is shown in Figure 4.4. This is rather different from the other functions

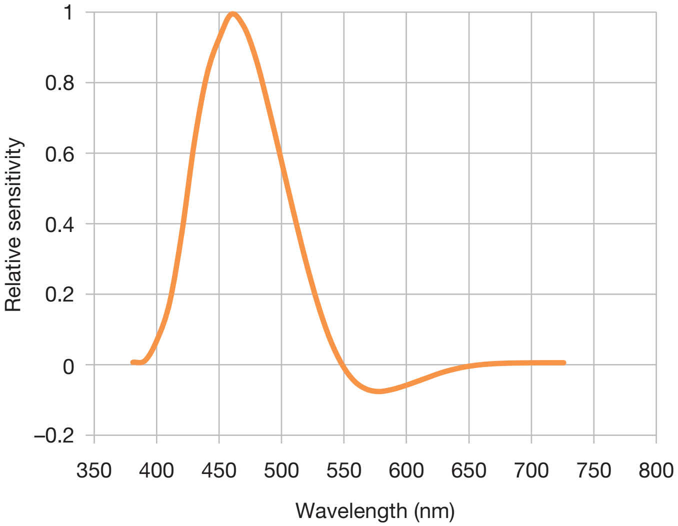


FIGURE 4.4 Rea's proposed $V_C(\lambda)$ function for the relative circadian response (After Rea, 2013).

discussed so far in that it is not the response of a cell, but of a system. A large part of the response is additive, meaning that light at these wavelengths will have the effect of dispersing melatonin from the blood, and part is subadditive, which means that for a broad-spectrum source, energy at these wavelengths will have a negative effect, but if the total sum for the whole spectrum is negative, the response should be assumed to be zero.

Taking account of this function calls for a quite different way of thinking about the impact of light exposure. Before the invention of electric lighting, illumination after sunset was either absent, or it was of low intensity and biased toward longer wavelengths, so that circadian cycles were largely undisturbed by after-dusk light exposure. While we all applaud the benefits of electric lighting, a consequence has been a substantial growth in nocturnal light exposure, and while many find this lifestyle choice attractive, health studies of people who engage in it over long periods, such as shift workers and airline staff, are a cause for concern. There is reason to suppose that daytime exposure to illumination that scores highly on the circadian spectral sensitivity function, followed by night time exposure to reduced levels of low scoring illumination, would be conducive to long-term health.

While these human responses to light represent concerns that lighting designers can never ignore, there are two principal concerns for the spectral distribution of illumination that must always be at the forefront of a lighting designer's mind. These are how the colour appearance of the illumination relates to the design concept of the space, and how the colours of illuminated objects within the space will be rendered by the illumination.

Colour appearance of illumination

It is common experience that some materials can be heated to the point where they become incandescent, starting from a dull red, increasing with temperature through bright crimson to brilliant white-hot. Most materials would melt or evaporate if the temperature was to be further increased, but the theoretical 'black-body' does not have this limitation and its temperature can be raised until it becomes 'blue-hot'.

When lamp makers discovered how to step beyond the restrictions of producing light by incandescence, that opened up opportunities to produce light with different spectra, including light that was not far removed from white but which was distinctly different from the warm, yellowish light emitted by a hot metal filament. In fact, it became possible to produce light that matched the appearance of different phases of daylight illumination, but this raised the question of how to describe these variation of 'white' light in a way that would make sense to people choosing, or specifying, these new-fangled discharge and fluorescent lamps.

The answer they came up with was to define the colour appearance of all types of nominally 'white' light sources in terms of correlated colour temperature (CCT), this being the temperature of a black-body, specified in degrees Kelvin, that most closely matched the appearance of the source in question. In Figure 4.5, the 'black-body locus' defines the change in chromaticity of emitted light from the black-body as its temperature is varied, and it can be seen that this corresponds to the commonly experienced change of colour of emitted light when materials are heated. The invention of the halogen cycle enabled

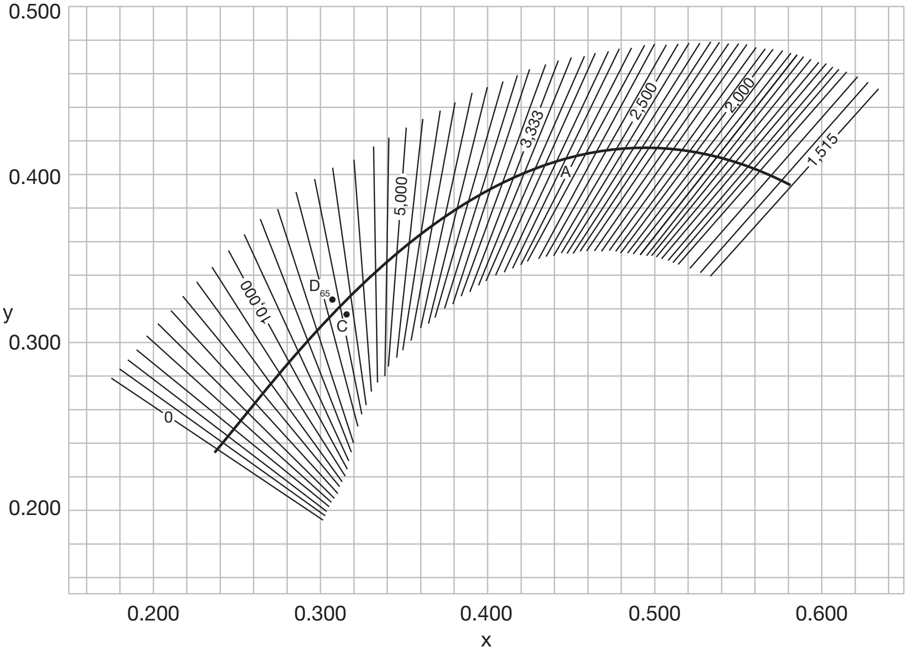


FIGURE 4.5 The black-body locus (solid line) plotted on the CIE 1931 (x,y) chromaticity chart with intersecting lines of constant correlated colour temperature indicated in degrees Kelvin. Also shown are the chromaticity coordinates of CIE Standard Illuminants, A, C, and D65 (from IESNA 2000).

incandescent filaments to be maintained at temperatures of up 3300K, and CCT described the appearance of the emitted light quite reliably. However, the real need for being able to indicate the colour appearance of illumination was the developing market for fluorescent lamps, where spectral distribution has nothing to do with temperature. There was demand for light sources that could provide 'white hot', and even 'blue-hot', illumination colours, as well as the colours of daylight illumination, and fluorescent lamps made all of this possible. Figure 4.6 shows CCT values for some familiar lamp types related to colour appearance. The confusing ways in which the CCT scale associates low colour temperatures with warm colour appearance and high colour temperatures with cool colour appearance, and that intervals on this scale are quite out of step with perceived differences, are both neatly overcome by the reciprocal mega Kelvin scale (MK^{-1}). While lamp makers have recognised the usefulness of this scale, it has not come into general use and, in any case, it has the disadvantage that it associates the chromaticity of a black-body with whiteness, and this has had unfortunate consequences that have been shown up by recent research.

Rea and Freyssinier (2013) have reported a study in which subjects described the appearance of different lighting chromaticities, and it was found that there is an extended range of chromaticities that may appear 'white', or with minimum perceived 'tint', and importantly, these chromaticities do not follow the line of the black-body locus. Figure 4.7 shows a section of the black-body locus crossed by lines of constant colour

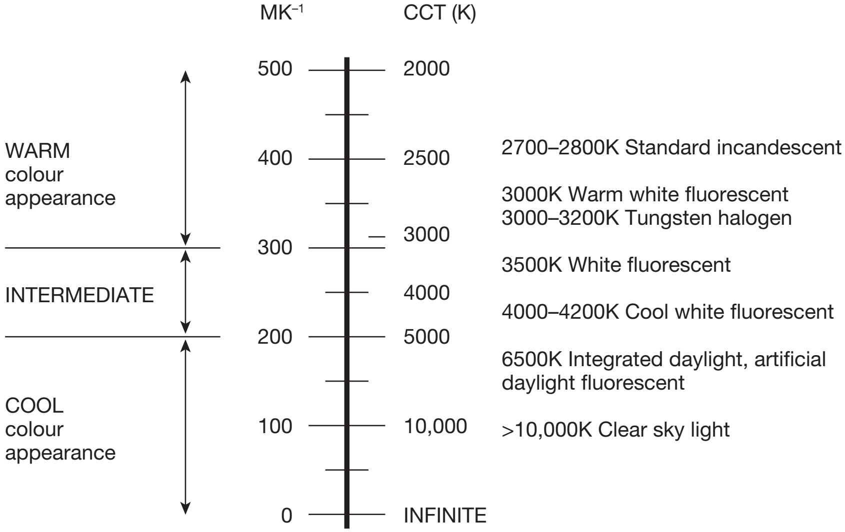


FIGURE 4.6 The reciprocal mega Kelvin scale (MK^{-1}) compared with the Kelvin (K) scale, and with typical assessments of colour appearance and CCTs of some familiar light sources.

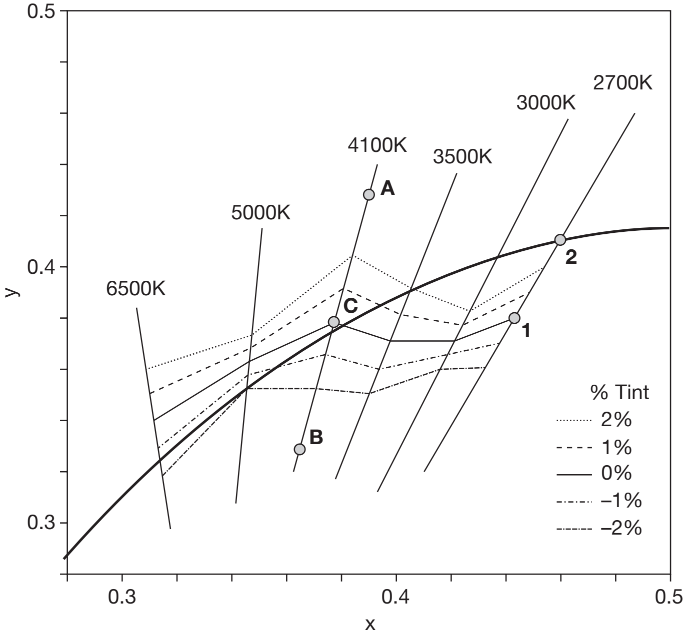


FIGURE 4.7 Contours of perceived level of tint. The solid line is the black-body locus plotted on the CIE 1931 chromaticity chart. The line of 0% tint is the contour of source chromaticities perceived to have minimum tint at that colour temperature, and these are referred to as ‘white’ sources, with other lines showing increasing levels of perceived tint. See text for more explanation (from Rea, 2013).

temperature (see Figure 4.5), and superimposed over these are lines of perceived level of tint. The 0% line is the experimentally-derived contour of 'white' sources. This does not mean that source chromaticities on this contour appear identical, but rather that at a given colour temperature, any source chromaticity on this contour is perceived to be with minimum tint. While sources A, B, and C all have the same colour temperature of 4100K, they will be perceived quite differently. In fact, source C will appear more similar to source 1 than to either A or B, as both C and 1 appear to be with minimum tint. Departures above (+ive) or below (-ive) this contour incur increasing perceived tint, where for different points along this contour, positive tint may appear slightly yellow, chartreuse or green, and negative may appear slightly pink, purple or blue (Rea, 2013). It should be noted that this 'white' source locus departs significantly from the black-body contour, being above it for CCTs above 4000K, and below it for CCTs below 4000K.

Seen in this way, it becomes obvious why conventional light sources around 4000K have been described as 'white', and lower colour temperature light sources are perceived to be yellowish-white and are said to appear 'warm', and higher colour temperature sources are perceived to be bluish-white and are said to appear 'cool'. The notion of the 'black-body' being the standard reference source is ingrained to the point that as the lighting industry has developed newer technologies, such as compact fluorescent lamps and now LED sources, repeatedly their aim is to match the characteristics of traditional sources. At the time of writing, examples are occurring of lighting companies advertising new LED sources by claiming that the illumination is indistinguishable from halogen lighting. There is, however, at least one LED manufacturer that is promoting its product as departing from the black-body locus, but even so, it may be some while before we have opportunities to experience tint-free 'white' illumination of different colour temperatures in spaces that enable us to properly assess their appearance.

Illuminance and illumination colour preference

It was way back in 1941 that A.A. Kruithof, a lamp development engineer with Philips Lighting in the Netherlands, wrote an article describing the fluorescent lamp. This lamp had been introduced in the USA only three years earlier, and despite the turmoil of the Second World War, it was finding its way into Europe. Among the many unfamiliar aspects of this new technology that Kruithof described was that it would be possible to select the CCT of lighting. This had not been possible previously, and to provide guidance on how to do this, he included the diagram reproduced in Figure 4.8. This figure is possibly the most reproduced diagram in the history of lighting. The white zone indicates acceptable combinations of illuminance and CCT, and within the lower shaded zone, which includes combinations of low illuminance and high CCT, Kruithof described the effect as 'cold and harsh', while in the upper shaded zone, which includes combinations of high illuminance and low CCT, he described the effect as 'unnatural' (Kruithof 1941).

The article gives little information on how this diagram was derived, but Kruithof has told the author that it was a 'pilot study' based entirely on the observations by himself and his assistant. For low colour temperatures, incandescent lamps were switched from series to parallel, but as the halogen lamp had not been invented, those conditions would have

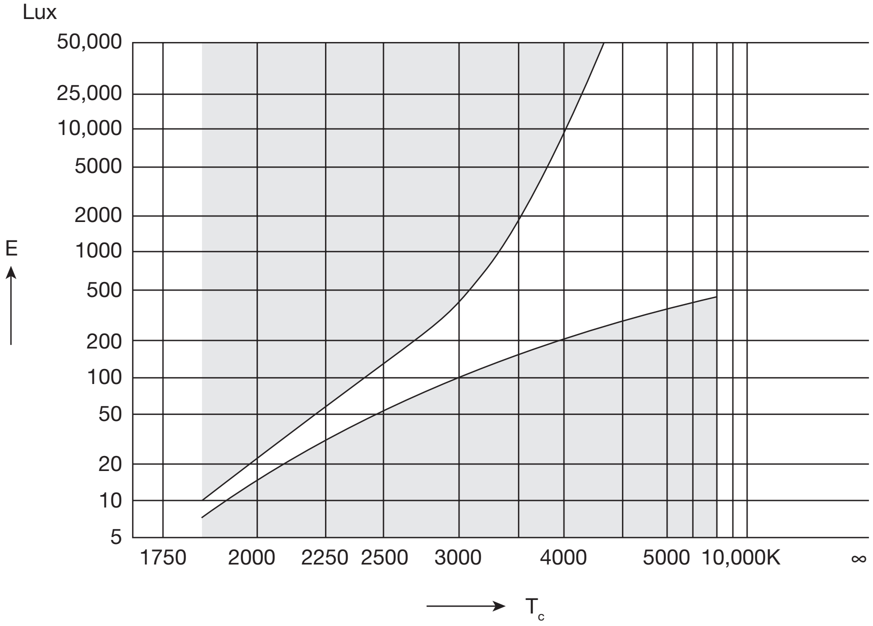


FIGURE 4.8 Kruithof's chart relating correlated colour temperature (T_C) and illuminance (E) to colour appearance. The white zone is described as 'preferred', while the lower shaded zone appears 'cold and harsh' and the upper zone appears 'unnatural' (from Kruithof, 1941).

been limited to 2800K. For higher CCTs, they used some 'special fluorescent lamps' that were currently under development, but even with the resources of the Philips research laboratories at that time, the range of phosphors available would have been restricting. For some parts of the diagram, Kruithof relied on a common sense approach. It is obvious that outdoor daylight with a CCT of 5000K at an illuminance of 50,000 lux is very acceptable, so he extrapolated to that point. It was in this way that the diagram of the 'Kruithof effect' was put together.

Since that time, several researchers have sought to apply scientific method to defining a sound basis for this phenomenon, but this has proved an elusive goal. However, the 'Kruithof effect' lives on. Lighting designers continue to refer to it with reverence, and perhaps more convincingly, you are unlikely to find opportunities to carry out observations of lighting installation that occur in the shaded areas of the diagram. You will find that the higher lighting levels provided in commercial and industrial locations, whether by fluorescent or high intensity discharge lamps, tend to make use of CCTs corresponding to the intermediate or cool ranges shown in Figure 4.6. Even where CCTs higher than 5000K are used, if the illuminance also is high (say more than 1500 lux), the effect is more inclined towards a bright and colourful appearance reminiscent of daylight, rather than a noticeably 'cool' effect. Conversely, where lighting is deliberately dim, the low CCTs of incandescent lamps, or even candles, are likely to be the chosen light sources. If you practise observation coupled with measurement, you are likely to find ample confirmation of the Kruithof effect.

Illumination colour and 'flow' of light

There is an interesting dimension of colour contrast that has been routinely exploited by stage lighting designers, and which has the potential to be influential in architectural lighting design. People are sometimes surprised by the appearance of colour photographs taken outdoors in sunny conditions. Areas in sunlight appear to have a yellow cast, and particularly for snow scenes, shadows appear noticeably blue. While our visual response tends to obscure this naturally occurring colour difference, if you look for it you can see it, and many artists, particularly the impressionists, have recorded their observations of this 'sun and sky' lighting effect.

Stanley McCandless incorporated the effect into his method for stage lighting (McCandless 1958). An essential feature of his approach is that all objects on stage are to be illuminated from opposite sides, with the light from one side having lower CCT to give a sunlight effect, and the light from the other side having higher CCT, perhaps of lower intensity, to give a skylight effect. In this way, a distinct and coherent 'flow' of light is achieved without strong shadows being cast. This means that an actor can remain clearly visible while having his face in the shadow.

When you are aware of this 'sun and sky' lighting effect, it is surprising how often you can find examples of it in retail display lighting. Car showrooms can achieve very effective displays by flooding the space with diffuse light using relatively efficient 'daylight' lamps which might have a CCT of more than 5000K, while providing highlighting from spotlights having CCT close to 3000K. Clothing stores often use lower CCT spotlights to strongly highlight selected items that are arranged as vertical eye-catching displays, while relying on the cooler appearance of general fluorescent lighting to reveal the daylight colours of the merchandise that the customers handle. Blue is a frequently used colour for the internal surfaces of display cabinets that have internal spotlights, and of course, it gives the sky effect to the shadows. Everybody sees 'flow' of light effects of this sort, but it takes a lighting designer to observe the visual effect and to understand how it can be provided.

Colour rendering of illumination

Among the more spectacular developments within the lighting industry during the past half century has been progressive improvement in colour rendering, being the influence that lighting has on the perceived colours of objects and materials. In fact, for most everyday lighting applications, colour rendering really has ceased to be a problem. Users have a choice of light sources that are quite satisfactory for industrial and office lighting applications, as well as for general lighting for retail, recreational, and social activities. It has not always been so, and when the Colour Rendering Index (usually abbreviated to CRI, but note also the use of scientific symbol R_a below) was introduced in 1965, it was a useful tool for sorting out the good, the indifferent and the plain ugly.

CRI continues to appear in codes, standards and specifications, where statements such as 'CRI shall be not less than 85' is a simple formula for avoiding lamp types that would cause unsatisfactory user responses. However, for the applications where colour rendering is an important factor, CRI fails to provide reliable guidance. Art gallery and museum directors have learned the hard way that simply specifying a high CRI value does not ensure excellent, or even acceptable, appearance of displays.

There have been several proposals over the years to make CRI more useful, or to replace it with something better. The following sections review some of these proposals and offers guidance on coming to terms with colour rendering.

The CIE Colour Rendering Index

The International Commission on Illumination (CIE) defines colour rendering as the 'effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant' (CIE, 1987).

The supposition here is that the observer is fully adapted to the same lighting that illuminates the objects, and that the colour appearance of the objects would be natural, and therefore optimal, if the lighting was provided by a reference source. The concept of a reference source is central to any discussion of colour rendering as it provides the basis for the comparison that is contained in the definition. It is an inherent assumption that the perceived colours of objects lit by the appropriate reference source would appear entirely acceptable, and that any departure from this appearance would be detrimental.

As the brightness and the colour of the ambient illumination in our environment changes, the response of our visual system adapts to the ambient condition. CRI assumes photopic adaptation and makes no adjustment for brightness, while the observer's state of chromatic adaptation is assumed to be determined by the chromaticity of the actual light source. The corresponding reference source is accorded a colour temperature that matches the correlated colour temperature (CCT) of the light source. For CCTs less than 5000K the reference source is the black-body, and for 5000K and above it is a CIE standard daylight distribution defined by its CCT. Getting these assumptions in mind is essential for understanding CRI.

The CRI values for a test source are determined by the Test Colour Method (CIE, 1994). Fourteen test colour samples (TCS), listed in Table 4.1, are defined by individual spectral reflectance curves. For each TCS, u,v chromaticity coordinates on the 1960 UCS (Uniform Chromaticity Scale) chart are calculated for both the test source and its reference source, and a colour adaptation transform is applied to allow for chromatic adaptation differences between the two sources. After that, colour differences in UCS space are calculated for each TCS under both sources. Each difference is defined by a vector that specifies the colour shift for viewing the TCS alternatively under the reference source and under the test source, allowing for adaptation to each source. The magnitude of each vector ΔE_i enables the Special Colour Rendering Index R_i for each TCS to be calculated:

$$R_i = 100 - 4.6\,\Delta E_i \tag{4.4}$$

From only the first eight TCS values, the General Colour Rendering Index R_a is calculated:

$$R_a = 1/8 \sum_{i=1}^{8} R_i \tag{4.5}$$

TABLE 4.1 The 14 CIE TCS (Test colour samples). TCS 1–8 comprise the original set of moderately saturated colours representing the whole hue circle, and these are the only samples used for determining CRI. The other six have been added for additional information, and comprise four saturated colours, TCS 9–12, and two surfaces of particular interest. Regrettably, details of colour shifts for these TCS are seldom made available

No.	*Approximate Munsell notation*	*Colour appearance under daylight*
1	7.5R 6/4	Light greyish red
2	5Y 6/4	Dark greyish yellow
3	5GY 6/8	Strong yellow green
4	2.5G 6/6	Moderate yellowish green
5	10BG 6/4	Light bluish green
6	5PB 6/8	Light blue
7	2.5P 6/8	Light violet
8	10P 6/8	Light reddish purple
9	4.5R 4/13	Strong red
10	5Y 8/10	Strong yellow
11	4.5G 5/8	Strong green
12	3PB 3/11	Strong blue
13	5YR 8/4	Light yellowish pink (human complexion)
14	5GY 4/4	Moderate olive green (leaf green)

This may seem complicated, but the CIE documentation includes a computer program that performs the task effortlessly. While this takes away the pain for the lamp manufacturer, it is necessary for us to understand what is being done so we can see how it might be done better. The program output for a standard Warm White halophosphate fluorescent lamp is shown in Figure 4.9.

There is plenty to ponder here. The lamp is, of course, an old-fashioned fluorescent lamp, and it is sobering to realise that when CRI was introduced in 1965, this was the standard lamp for general lighting practice. The program gives the *x,y* chromaticity coordinates, the CCT (T_c), and a measure of how far the chromaticity is off the black-body locus (dC). The CRI (R_a) is the average of R_i values for TCS 1–8, and it can be seen that these vary substantially. Referring to Table 4.1, colour shifts are relatively small for the yellow-green and violet TCSs, but become large in other zones. Then look at the strong colours, particularly the strong red, represented as TCS 9, for which the chromaticity shift is massive, but the value for this TCS was not, and still is not, taken into account by CRI. Human complexion (TCS 13) has a poor score, so it is no wonder that everybody was pleased to see the back of this lamp, and really, that has been the foremost achievement of CRI. Nobody would now dream of lighting an indoor space in which the appearance of people might be of some consequence with such an utterly dismal lamp.

```
        File:    WARMWT.EMI
        Path:    C:\DOCUME~1\CRI\
        Title:   WarmWhite  fluor. lamp; No 5

Coords:
        x=       0.4363
        y=       0.4111
        Tc=        3066 K
        dC=      2.85e-03

Reference colours:
        CIE standard colours (1–14)
        Ra calculated based on the first eight colours

Special Rendering Indexes:
No. 1 =          42.1
No. 2 =          69.3
No. 3 =          89.8
No. 4 =          39.8
No. 5 =          41.6
No. 6 =          53.6
No. 7 =          66.2
No. 8 =          11.8
No. 9 =        –116.7
No. 10 =         29.9
No. 11 =         21.5
No. 12 =         24.4
No. 13 =         46.9
No. 14 =         94.0

Ra =             51.77
```

FIGURE 4.9 Output from CIE13 3W.exe computer program to calculate CRIs, for a Warm White halophosphate fluorescent lamp. While this is an old-fashioned lamp, this example illustrates well the colour rendering issues that CRI was devised to cope with.

Problems with CRI

Despite this level of success, CRI has several problems, some of which may be evident from the previous section. The CIE specifies 14 TCSs, and calculates CRI from just eight of them, ignoring the other six. The reason for this is that originally only TCS 1–8 were specified, and they are all medium saturation colours, but people had noted that lamps that might perform reasonably well for these colours could fail badly for rendering strong colours. Also, the appearances of human complexion and foliage have special significance as people have clear notions of how they should appear, and so it was decided that these too should be added. This led to the addition of six more TCSs, but then, rather than change CRI, it was decided that they should be listed separately to provide users with additional information. However, while the program output gives these values, most users are completely unaware of them. Manufacturers claim that people would be confused by the additional data, but nonetheless, it needs to be recognised that colour rendering is too complicated an issue to be adequately defined by a single number.

To illustrate this point, if data for the additional six TCSs were to be provided, what interpretation should be placed upon them? A low value of R_i indicates that the appearance of this TCS will be distinctly different under the test and reference sources, but no indication is given of the nature of that difference. For example, the negative R_i value noted for the strong red TCS might indicate that the test source shifts it towards yellow, giving an orange tint, or towards blue, giving a mauve tint. Alternatively, it might appear less saturated, giving a pink tint, or it might appear more saturated, appearing as a vivid red. Not only does CRI give no indication of which of these differences occurs, but it treats all of them as being equally detrimental. There is good evidence to indicate that, within reason, people like lamps that make their surroundings appear more colourful, that is to say, which cause increased saturation. This challenges the central notion that a reference source provides optimal colour rendering.

Another issue is that it has for some while been acknowledged that the 1960 UCS chart is far from uniform in its spacing of chromaticity values, and since then there have been several proposals for more uniform definitions of colour space. To change the colour space would affect CRI values, so this has not been done, with the result that CRI continues to be calculated using a procedure that is known to evaluate colour differences unequally.

There are other problems. The CRI scale causes confusion, some users supposing it to be a percentage scale, so the fact that some lamps are shown to have negative values comes as a surprise. Also, because CRI has been so widely used by specifiers, manufacturers have developed lamps to achieve high CRI values, so that they have incorporated the shortcomings of CRI into their new products. It has become increasingly apparent that this approach has led to lamps being promoted for good colour rendering but which have distinctly less than optimal performance. These shortcomings of CRI became clearly evident with the development of tri-phosphor fluorescent lamps in the 1970s, and they are now seen to be a substantial hindrance to progress by companies working on development of white LED sources. It is high time for changes to be made to CRI.

What is being done about CRI?

There has been no shortage of suggestions over the years, with past proposals for a Colour Discrimination Index, and even a Flattery Index. While these may have attracted attention at the times when they were proposed, the CIE has set up a Technical Committee to revise CRI and this project has gained support from the US National Institute for Science and Technology. It has led to the development of the Colour Quality Scale (CQS) (Davis and Ohno, 2004), which is a substantial revision of CRI and involves a new set of 15 test colour samples of high chromatic saturation spanning the entire hue circle, and it makes the switch to 1976 CIELAB colour space, which assesses different types of colour difference more closely to how they appear. Shifts of hue or shifts to lower saturation are treated as being equally detrimental, but shifts to higher saturation incur no penalty. A weighting is placed on CCT, so that for CCTs less than 3500K or more than 6500K, scores are modified by a scaled multiplication factor. This would have the effect, for example, of reducing the domestic incandescent lamp's rating from 100 to 97. The scale itself is modified to eliminate negative values, with the effect that all of the very poorly performing lamps will have ratings between 0 and 20.

The single rating indicator with a maximum value of 100 is retained, and the overall weighting of CQS between 20 and 100 is not too different from CRI, although ratings for some lamp types do undergo significant changes. In particular, it may be expected that lamps with multiple narrow waveband emissions, such as LED combinations, will achieve more favourable CQS ratings than the ratings they gain under CRI. Finally, to overcome the effect of averaging, by which a lamp may gain a moderately high score while one or two test colours show large colour differences, individual scores are calculated as root mean square (RMS) values.

The retention of a single scale indicator of colour rendering suits specifiers, who would continue to be able to prescribe a minimum value for a given application, and while it should reduce anomalies, it will not provide lighting designers with guidance on how the colour appearance of illuminated objects will be affected by the light source. So while CQS falls short of providing lighting designers with all the information they need, it does go a long way towards overcoming the anomalies incorporated into CRI. It is, however, important to appreciate that while CQS has been published and discussion invited, at the time of writing it had not been endorsed by the CIE.

What is the current state of knowledge on colour rendering?

Researchers in the colour science field have achieved remarkable success during the past decade, which has led to the development of colour appearance models (CAMs). Two scientists had independently developed models for predicting how a typical observer perceives colours in the environment, each taking account of a range of variables and known visual phenomena. Dr R.W.G. Hunt, with the Kodak Corporation in the UK, had spent a lifetime working on coloured images and Dr Y. Nayatani of Japan developed his model to address concerns in illumination engineering and colour rendering. In 1997, the two models were merged to produce a single Colour Appearance Model, CIECAM97s. This was taken up with enthusiasm in a range of industries where colour is a critical aspect of quality control, particularly where imaging is involved, and soon the CIE Technical Committee concerned had available a wealth of feedback gained from practical application. This led to CIECAM02, which was actually published in 2004, and is considered likely to remain unaltered for some while as it is believed to be as good a model as can be produced from current knowledge. For a review of CIECAM02, see Fairchild (2004).

The input data required to apply CIECAM02 to predict the colour appearance of an element in the field of view include colorimetric data for the object (stimulus) and the light source (adapting stimulus), the absolute luminance and colorimetric data of the proximal field, including the background and surround to the stimulus. The success of this model lies in the variety of potentially influential factors that may be taken into account. In Chapter 1 we noted how the colour appearance of an object can be affected by whether colours are perceived as related or unrelated, and in CIECAM02, the effect of surrounding surfaces upon the perception of surface colours is predictable. This is just one of a range of colour appearance phenomena that have been observed and reported over the years, and which have subsequently been researched and quantified, and now have been combined into a single comprehensive model.

The spectral power distribution of the light source is one of the input variables, and so aspects such as how bright and colourful a specific object will appear in a given setting could be examined for alternative lamps. In terms of applied scientific knowledge, this undoubtedly would be a leap forward. However, we cannot use CIECAM02 in the way that we use CRI, that is to say, we cannot use it to describe the colour properties of a lamp, as it has to be applied to a specific viewing situation. Perhaps this will become possible one day. The spectacular advances in computer visualisation software that have occurred during the past decade might enable us to model the effect of different light sources upon colour appearance of a real or simulated scene, but meanwhile, we need to think about what the information is that would be useful to us now.

What do we want to know about colour rendering?

When we get down to meeting actual needs for presenting coloured objects for critical examination and assessment, it becomes apparent that those who put such objects on display have learned a lot about people's preferences for colour appearance. For confirmation of this, you need look no further than your local supermarket. The fresh produce displays use different lamp types for the meat, fish, fruit and vegetables, as well as for the 'deli' displays, all of which have been chosen for how they render the colours of that particular type of merchandise, and quite obviously, those choices have been made without reference to CRI. The way in which colour rendering is understood by the CIE experts is clearly indicated by the definition given at the beginning of this section, but it is apparent that the preferences shown by people making visual selections of fresh produce have nothing to do with making comparisons, conscious or subconscious, with appearance under a reference source.

It can be seen that the lamp type chosen for each of the fresh produce applications imparts a particular type of colour shift, and the store operators have made themselves aware of which type of colour shift suits each type of merchandise. For the lighting designer who encounters a situation that calls for a certain type of colour shift, the available lamp data fail to provide the necessary guidance. Manufacturers give the CCT and CRI values, and also they may show the spectral power distribution curve, but nobody should assume that there is a simple relationship between this curve and colour rendering properties. Even for an experienced lighting designer, an SPD curve comprising a combination of line spectra and broad-band emissions gives little or no useful guidance on colour rendering.

What is needed is a straightforward way of showing what a lamp will do to the colour appearance of the objects that it illuminates. A lighting designer does not need to be told what is good and what is bad. The information that the designer needs is to enable an informed decision on which lamp type will best suit his or her purpose for a particular application. This leads us to the colour-mismatch vector.

The colour-mismatch vector (CMV) method

In 1988, two lamp engineers at Philips Lighting in the Netherlands proposed a novel way of presenting colour rendering information (van Kemanade and van der Burgt, 1988). Figure 4.10(a) shows the chromaticity shifts for a set of 215 colours more or less equally spaced over the chromaticity chart, when illuminated by a reference source and then by a test source. The individual colour-mismatch vectors are plotted onto the CIELAB chart, and in this case, the test lamp is a halophosphate fluorescent lamp not very different from the one represented in Figure 4.9. Each vector indicates the extent and direction of the mismatch between the reference source and the test lamp. A vector pointing towards the centre of the chart indicates a chroma reduction, and a radial direction indicates a hue shift. It should be noted that the vectors are not randomly scattered but show a distinct flow pattern, and it should not come as a surprise that mismatches increase for higher chroma, that is to say, for TCS points further from the centre.

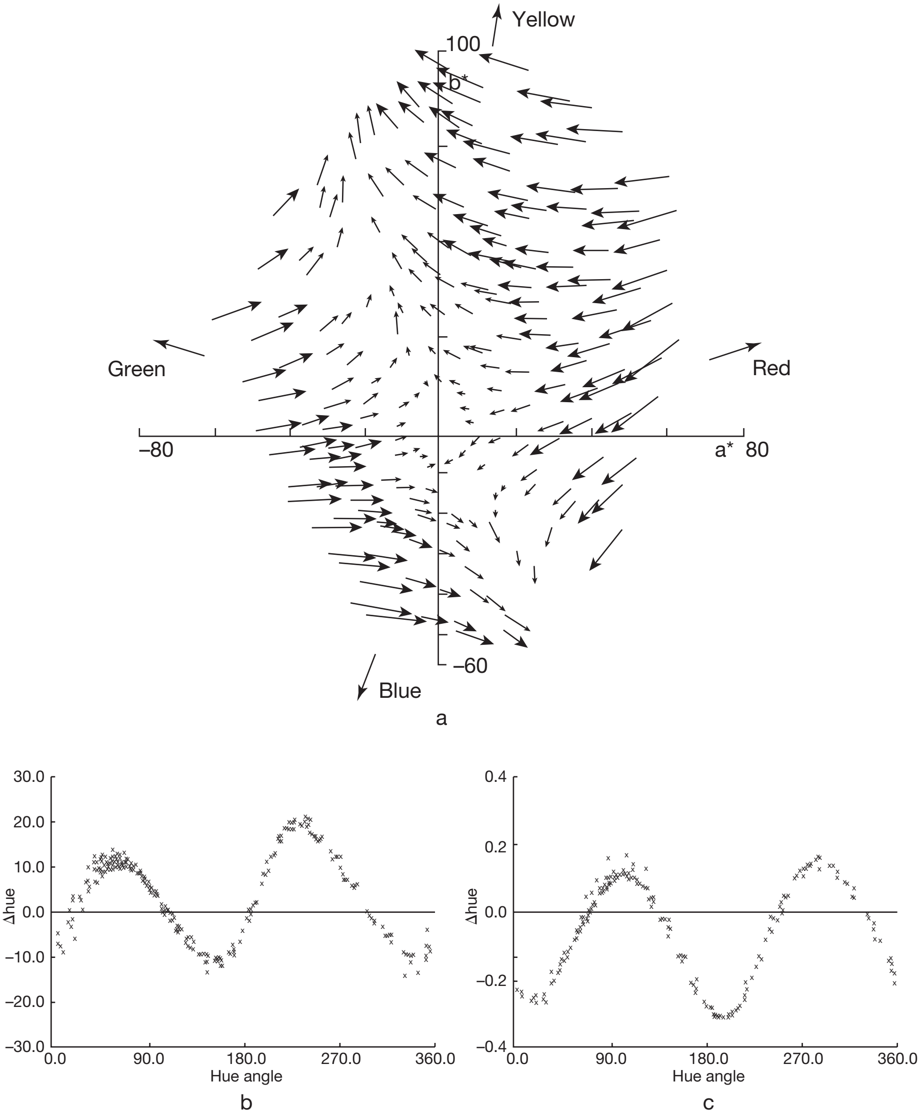
The main features of the flow pattern are expressed in Figure 4.10(b) and (c). The hue angle on these graphs is measured from a^* anticlockwise, so relationship to the unique hues can be read from Figure 4.10(a). It is clear to see whereabouts on the hue circle a test lamp introduces hue shifts or changes in chroma. The authors included more charts for fluorescent lamps with different colour rendering properties, and an interesting comparison of white SON and metal halide.

At first this type of chart may appear intimidating, but with a little practice, the wealth of information that it provides is easily extracted. There is still the comparison with a reference source, but instead of the system deciding what is good or bad, it is for the lighting designer to choose the colour rendering characteristics that will suit a particular application. Quite apart from those fresh produce supermarket displays, how else does a designer select the most suitable lamp for an indoor swimming pool, or a make-up mirror, or an orchid display, or an exhibition of antique manuscripts, or an ice-cold vodka bar? The CMV method enables designers to make informed lamp selections based on colour rendering characteristics. Unfortunately, lamp manufacturers are showing themselves to be reluctant to provide this information, particularly for the newer generation of light sources.

Colour gamut area

It might seem that an ideal light source would produce a CMV diagram in which every vector radiates outwards from the central point, creating a colourful world in which all colours appear more saturated, and there is evidence to indicate that people do prefer light sources that tend to increase colour saturation, at least to some extent.

A colour gamut is the polygon formed when the eight TCSs, illuminated by a given light source, are plotted onto the CIE UCS diagram. Equal distances between points on this diagram correspond approximately to equal perceived colour differences, so that the relative areas of the polygons formed by connecting the TCS points for a given source provide an indication of the 'colourfulness' associated with that source. Figure 4.11 shows the colour gamuts for a range of widely used light sources, and the general trend of



a

b

c

FIGURE 4.10 Colour-mismatch vector data for a halophosphate Cool White colour 33 fluorescent lamp (From van Kemenade and van der Burgt, 1988).

A) CMVs on the CIELAB chart for Opstelten's set of 215 test colour samples.

B) Hue component of CMV, where +ive ΔHue indicates shift to higher hue angles.

C) Relative chroma content of CMV, where $\Delta C^{\star}=\Delta\text{chroma}/\text{chroma}$, and +ive $\Delta C^{\star}$ indicates increase in saturation with respect to reference source.

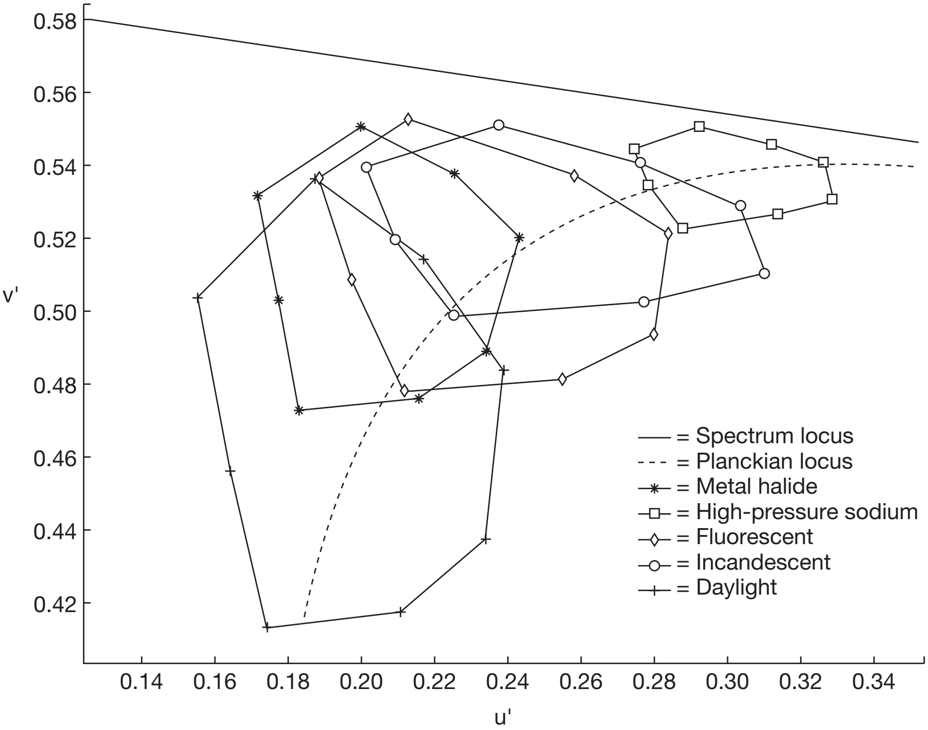


FIGURE 4.11 Gamut areas for some familiar light sources plotted on the CIE 1976 UCS (uniform chromaticity scale) diagram. Gamut area relates to the perceived 'colourfulness' associated with a light source (from Boyce, 2014).

increasing gamut areas with increasing CCT is clearly evident. Note the large area of the Daylight source, actually the CIE D65 daylight standard, and it becomes evident why this source is often regarded as the light source against which all others should be judged.

Boyce (2003) has noted a correspondence between gamut areas and findings from research studies into the phenomenon of 'visual clarity' (Bellchambers and Godby, 1972). Although this concept has never been precisely defined, a variety of studies have found that when subjects compare adjacent scenes and are instructed to adjust the light level in one 'so that the overall clarity of the scene is the same' as in the other, a lower illuminance is set in the scene with greater colour gamut area. Boyce's formula for predicting the illuminance ratio for matching appearance from the gamut area ratio is:

$$E_1 / E_2 = 1.0 - 0.61\ log_{10}(G_1 / G_2) \tag{4.6}$$

where E_1 and E_2 are the illuminance values and G_1 and G_2 are the gamut areas for the two light sources.

Quite separately, Rea (2013) has reported that CRI does not reliably predict people's colour preferences for fruit, vegetables, skin and other often-encountered natural objects, and has proposed that light source gamut areas should also be taken into account. The gamut areas calculated from the u', v' values of the UCS diagram produce very small values, leading him to propose a gamut area index:

$$GAI = 100(G_S / G_{ees}) \tag{4.7}$$

where G_S is the gamut area of light source S, and G_{ees} is the gamut area for an equal energy source, for which the value has been calculated to be 0.007354. The value of GAI may be more or less than 100 according to the gamut area of S, and Rea advises that for preferred appearance of natural objects, which, of course, includes other people, light sources should be 'high in CRI *and* high (but not too high) in GAI'. This leads to his proposal for 'Class A' colour for general illumination light sources, for which the chromaticity should lie on the 'white' source locus (Figure 4.7), *and* CRI should be equal to or more than 80, *and* GAI should be between 80 and 100 (Rea, 2013). For specification writers, a statement along the lines of 'All light sources shall be of Class A colour' could be expected to improve reliability.

Source spectrum and human response

At first sight, this review of how the spectral properties of illumination may influence people's responses to a lit scene might seem to comprise a bewildering array of disconnected factors, some of which have backgrounds of intensive research while others are based on not much more than casual observation. However, some introspection suggests an underlying pattern that gives some insight into how these factors are connected.

It is clear that when we are concerned with a brightness response rather than visibility, $V(\lambda)$ tends to underrate sources that are rich in the shorter visible wavelengths, that is to say, sources that are high in S/P ratio and CCT. While it has long been recognised that this occurs for scotopic conditions, the $B(\lambda)$ function (Formula 4.2) applies for photopic conditions as well. The $V_{B3}(\lambda)$ function (Figure 4.2) has been proposed as the appropriate illumination metric for indoor general lighting practice, but has yet to gain acceptance.

Illumination that has high luminous efficiency on the B3 metric would also provide well for circadian response, measured on the $V_C(\lambda)$ function (Figure 4.4), making it an appropriate source for daytime illumination. Light sources with CCT values around 4000K are commonly described as 'white' light sources, and it may be noted that this is the CCT value at which the 'white' source locus crosses the black-body locus (Figure 4.7), suggesting that higher CCT sources with chromaticities on the 'white' source locus might not attract the negative assessments accorded to the high S/P sources used in recent research studies. The usefulness of the high retinal image resolution associated with high S/P sources has been questioned, but it would seem reasonable to suppose that 'white' high S/P sources would gain any such advantages without incurring negative assessments for appearance.

McCandless' notion of 'sunlight and skylight' suggests options for attractive effects by adding low S/P highlights to overall high S/P illumination, and the Kruithof effect points to high S/P (or CCT) illumination gaining preference at high illuminance levels, in other words, high CCTs for daytime and low CCTs for night time. All of this fits in with providing illumination to coincide with the circadian cycle.

Rea's proposal that, for general lighting practice, the shortcomings of CRI may be largely overcome by specifying 'Class A' colour defines a basis for generally preferred colour rendering. Figure 4.11 shows clearly how, for high CRI sources, gamut area (related to colourfulness) tends to increase with CCT. While CRI relates to the 'naturalness' of colour appearance, Rea's proposal adds a new notion of 'whiteness', and, through including GAI in the criteria, the appearance of 'colourfulness'. This may, in turn, be seen to be consistent with the 'visual clarity' concept, and furthermore, with the other more anecdotal concepts observed by McCandless and Kruithof. In this way, the range of factors reviewed in this chapter may be seen as contributing towards a reasonable and consistent understanding of human response to light source spectrum.

Even so, a designer who wishes to have control over the appearance of a space, or selected targets within the space, is left in a difficult situation. He or she cannot avoid feeling poorly supported by the information currently available from the lighting industry, and it is perhaps ironic that efforts to improve this situation tend to be resisted by the industry on the grounds that such changes would cause confusion.

My own approach has been to equip myself with a *GretagMacbeth ColorChecker*, and to use this to make objective assessments of the colour characteristics of light sources. The *ColorChecker* comprises 24 matt-surfaced colour samples mounted on a stiff board, and some time needs to be spent examining it under mid-day daylight, as shown in Figure 4.12. The bottom row is a grey scale, from full-white to full-black, and in this viewing

FIGURE 4.12 The *GretagMacbeth ColorChecker* colour rendition chart being examined under daylight. A viewer who forms a clear memory image of the chart in this situation can then make comparisons with its appearance under other sources of illumination.

condition all the samples appear neutral (no hint of hue), and the steps between them appear equally spaced. The next row up comprises primary colours, with the additive primaries to the left and the subtractive primaries to the right, and all of them appear as fully saturated, clear colours. The two rows above are moderate colours, some with special significance. For example, starting from the left-hand end of the top row, the samples represent dark skin, light skin, blue sky, foliage and so on. Explanations are given on the reverse side.

Start by gaining experience of the appearance of the *ColorChecker* under daylight. This gives you a tool that enables you to objectively assess the colour characteristics of other light sources and illumination conditions, whether you are evaluating a sample of new type of light source or visiting a recent lighting installation. The appearance of the *ColorChecker* will quickly reveal to you how your perception of colours is influenced by the illumination. It is worth noting that under low light levels, all the colours will appear dull and the intervals between the grey samples will appear compressed towards the darker end. Providing that illumination is sufficient to ensure photopic adaptation, the appearance of the primaries can be particularly revealing. While you will be accustomed to all of these samples appearing saturated, certain light sources can cause some of them to appear unexpectedly bright. To understand this, think back to the discussion of lamps used to enhance the appearance of various types of food displays. More generally, look carefully at the appearances of the moderate colours, noting that people are particularly sensitive about skin colours. When people complain about colour rendering, the most commonly occurring comments are of the ‘They make you look awful!’ type.

It is in this way that a lighting designer may select lamp types for various applications with confidence that the effect on the appearances of coloured room surfaces and objects will be in accord with the overall design objectives. From the foregoing discussion, it is clear that people have different expectations for daytime and night time illumination, and where the aim is to satisfy those expectations, the designer should provide for coincidence with the circadian cycle. Of course, circumstances will occur where the intention is to achieve alertness and visual stimulation when people would naturally be inclined to restfulness, and for these applications the intensity and duration of bright light exposure needs to be given consideration. Meanwhile it is to be expected that developments in light source technology will provide designers with increased options, and it is to be hoped that the lighting industry will respond with more useful product information. In particular, that it will recognise that while the needs of specifiers may be best met by familiar, single figure values, designers’ needs are more complex. They need information that addresses the foregoing issues, and this is not met by catalogue pages presenting brightly coloured spectral power distribution curves.

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5

SPATIAL ILLUMINATION DISTRIBUTIONS

Chapter summary

The appearances of three-dimensional objects are influenced by the lighting patterns that are generated through interactions between the objects and the spatial distribution of illumination. As noted in Chapter 1, there are three types of these object lighting patterns; shading, highlight and shadow patterns; and they appear superimposed over each object's surface in response to the optical characteristics of the objects and the photometric characteristics of the surrounding light field. The light field is also examined in terms of perceived characteristics, and the concepts of the *'flow' and the 'sharpness' of illumination* are discussed. These characteristics may have the effects of revealing, or enhancing or subduing the appearance of selected object attributes. The perceived strength of the 'flow' of light relates to the vector/scalar ratio (VSR) and its perceived direction corresponds with the vector direction. The highlight contrast potential (HCP) gives an indication of the extent to which lighting may provide for perceived 'sharpness'.

Three-dimensional distributions of illumination

In Chapter 1, we noted that the green cylinder interacted with the illumination distribution to produce lighting patterns that appeared superimposed onto the surface of the cylinder and the checker board (Figure 1.1), and these patterns not only affected the cylinder's appearance, but they influenced our whole understanding of the surrounding light field and the objects within it. In this chapter we are going to look closely at these lighting patterns, and we are going to identify the three-dimensional characteristics of illumination that cause them.

The three object lighting patterns

The three objects shown in Figure 5.1 are all interacting with the same surrounding light field, but the object lighting patterns produced by those interactions are strikingly different. The matt white sphere has formed a graded *shading pattern* of varying surface illuminance related to surface orientation, and in this respect, the pattern follows from the cosine law of illumination. Completely different in appearance is the *highlight pattern* generated by the glossy black sphere, which is formed by specular images of the higher luminance elements in this space that are also the sources of illumination. Different again is the *shadow pattern* produced by the peg-on-a-disc, where the shadow cast by the peg is clearly revealed on the disc's surface (Cuttle, 1971).

Each of these lighting patterns tells us something different about the three-dimensional light field surrounding these objects. Look carefully at the matt white sphere. No part of its surface is unlit, but there is a distinct bias. If I could hand you a small arrow, you would be able to place it on the image to coincide with your perception of the direction of the 'flow' of light. It would not matter how many sources of illumination are present, always you would perceive just one 'flow' direction. You might also describe the apparent strength of the 'flow' as being distinct, but not strong. Now turn to the glossy black

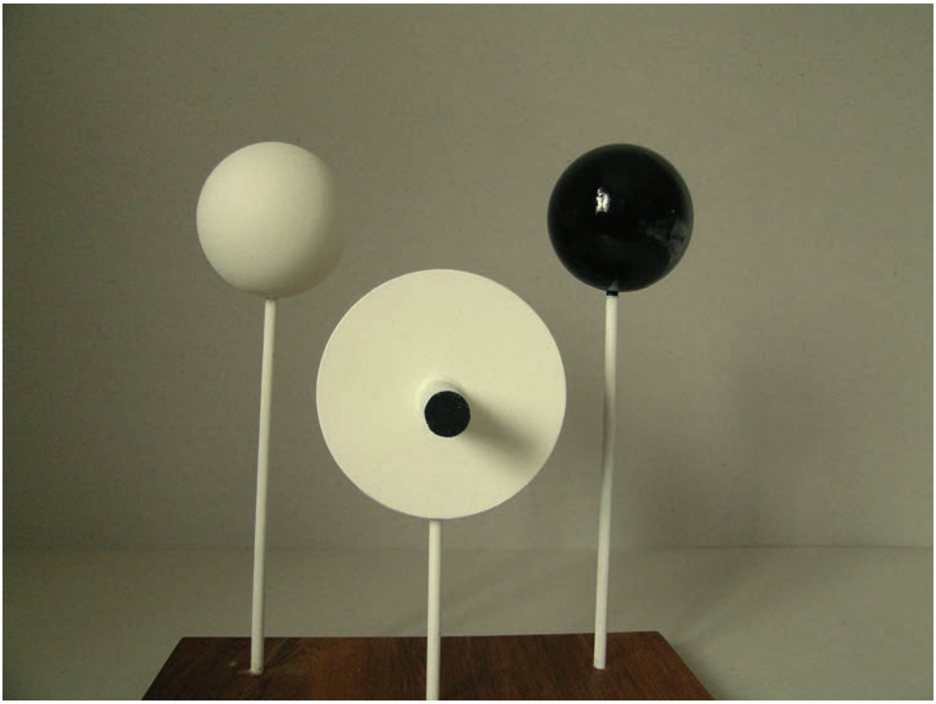

FIGURE 5.1 The triple object lighting patterns device. This device separates as far as possible the three object lighting patterns. The matt white sphere shows the shading pattern; the glossy black sphere shows the highlight pattern; and the peg-on-a-disc shows the shadow pattern.

sphere. Its appearance is dominated by a single 'highlight' image, and if you look carefully you will be able to make out the shape of this light source's outline and recognise that it is a window. No other light source is bright enough to register a noticeable 'highlight', and so you may conclude that the window is the sole source of direct illumination. Finally, look at the shadow pattern formed on the peg-on-a-disc. Its direction coincides with the appearance of the 'flow' direction, and like the shading pattern, it is only moderately strong. Also, it is quite softy defined, as this lighting lacks 'sharpness'.

You will have worked out by now that you have been looking at lighting patterns generated by the light field in a small, or moderately sized, room with fairly light (reflective) room surfaces, lit by a single side-window. This is a pretty detailed description of the location and the light field within it. What would be the effect if we leave the triple-object in its present position but change the lighting?

Figure 5.1 reappears as Figure 5.2(a), and below it, you see the effect of blanking off the window and introducing a spotlight in Figure 5.2(b), and then turning off the spotlight and adding six small display lights in Figure 5.2(c). The two columns of photos across to the right show the effects of these lighting conditions on the appearance of two groups of objects. The first column shows a group of familiar domestic items, and we should appreciate that, even for objects that we are unlikely to select for display treatment, their appearance can be substantially affected by lighting. In fact, the appearance of everything that we see, pick up and make use of is affected by the object lighting patterns formed by its surrounding light field. Figure 5.2(d) shows the garlic pot and two capsicums in the daylight situation, which has a distinct 'flow' of light without 'sharpness'. The effect of the single spotlight in Figure 5.2(e) is to reproduce quite closely the 'flow' direction while somewhat increasing the 'flow' strength, but the really noticeable change is the presence of 'sharpness', revealed by the highlight (even more noticeable in real life than it appears in this image) and shading patterns. In Figure 5.2(f), the 'flow' revealed by the shading pattern on the garlic pot has almost vanished, but the effect of 'sharpness' due to the lighting is still highly evident.

The second column of photos shows some objects that we might put on display to attract interest, and here the object attributes include transparency, iridescence, and dichromatic colours. These three figures, 5.2(g), (h) and (i), call for careful attention. How would you approach the task of providing display lighting for this group of objects? At first it might seem that almost anything could work, but it should be noted that the three object lighting patterns, being the shading, highlight and shadow patterns, are separately identifiable and it is the different balances of these patterns that determine the spatial lighting effects. Careful observation of these images shows how the attributes of any one of these objects may be revealed, enhanced or subdued by the balance of object lighting patterns created by their interactions with the light field.

To summarise, we have identified ***three object lighting patterns:***

> ***The Shading Pattern:*** Due to the interaction of an object's three-dimensional form with a 'flow' of light. The pattern is a variation of surface illuminance due to changing incidence of light with surface orientation which influences the appearance of object form and texture. The lighting metrics that relate to the 'flow' are the vector/scalar

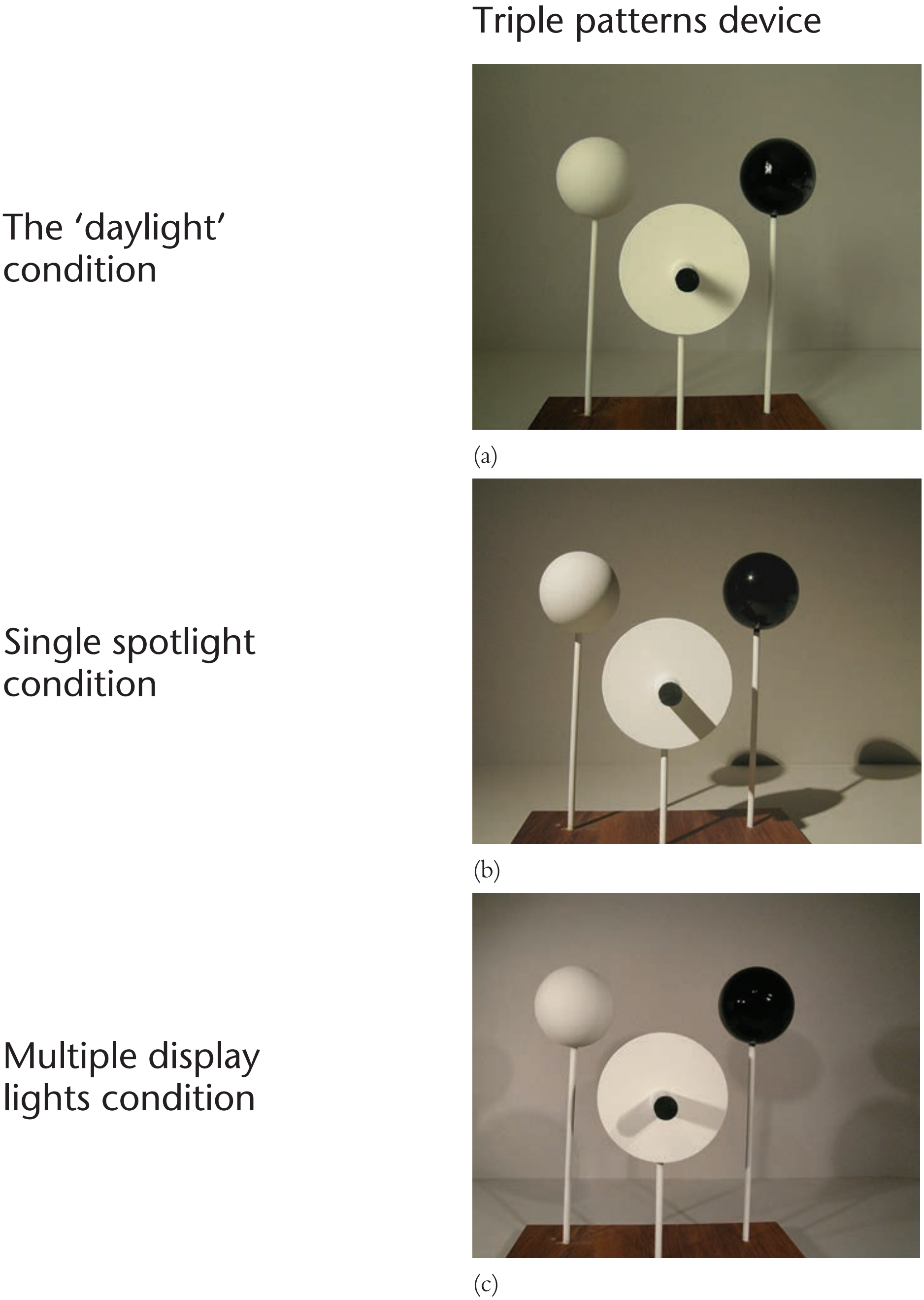

FIGURE 5.2 For the three lighting conditions described in the text; the first column of photos shows the lighting patterns formed on the triple lighting patterns device, and the next two columns show the lighting patterns on a group of domestic objects and a group of display objects.

(d)

(e)

(f)

(g)

(h)

(i)

> ratio (VSR), which corresponds with the perceived strength of 'flow', and the vector direction, which corresponds with the perceived direction of 'flow'.
>
> ***The Highlight Pattern:*** Due to specular reflections of relatively high luminance objects, particularly light sources, that appear superimposed on an object's surface. There has to be some level of surface gloss for a highlight pattern to be evident, and either polished metals or shiny, dark coloured surfaces give maximum effect. This pattern influences the appearance of gloss, sheen or lustre, and may be described as an aspect of the 'sharpness' of lighting. The metric that relates to these effects is the highlight contrast potential (HCP).
>
> ***The Shadow Pattern:*** Due to a shadow caster projecting a shadow onto a receiving surface in a directional light field. The appearance of this lighting pattern may be described in terms of both the strength and 'sharpness' of cast shadows, and it may influence the perception of object form, texture and/or location. Perceived shadow strength is associated with the VSR, and 'sharpness' with the HCP.

The concept of object lighting patterns is readily understood by non-lighting people and can form a useful basis for discussion when lighting designers are talking about how their proposals will affect the appearance of the various objects that will form significant components of the design. Designers are usually able to communicate their ideas using these concepts without going into details, such as explaining the precise difference between a shading pattern and a shadow pattern. However, while non-lighting people will perceive the lighting patterns entirely as a visual effect, for designers, there is a deeper insight. Every lighting pattern is recognised to be a three-dimensional interaction between a particular type of surface and a particular type of incident light. The understanding that there are just three types of object lighting patterns – shading, highlight and shadow – and two lighting characteristics of concern – 'flow' and 'sharpness' – provides powerful concepts for devising distributions of light that respond to space, form and material.

To appreciate how these concepts might be applied in the real world, we will take a look at the lighting for an up-market retail store. QELA offers high couture fashion in the setting of an exclusive art gallery, and is located in Doha, on the Pearl, which is a man-made archipelago off the coast of Qatar. The entrance from a shopping mall gives no view to the interior, giving a sense of entering into a private zone. The initial view of the central atrium, shown in Figure 5.3, with its freestanding staircase connecting the two floors, has been designed to create a strong visual impact. Here, selected displays of beautiful accessories are presented within the setting of an art gallery, and all of this contained by the curved forms of the architecture and the overarching domed ceiling.

The design brief had stated that "merchandise was to stand out from the ambient effect with highly controlled accent lighting". The lighting designers, Gary Campbell and Tommaso Gimigliano of dpa lighting design, proceeded to devise separate lighting solutions specifically for each aspect of the overall design. In the interests of controllability and energy efficiency, it was decided that lighting throughout the store was to be LED-based and dimmable, although some exceptions were made for the jewellery displays and decorative fittings.

FIGURE 5.3 The striking first view of the interior of the QELA boutique, Doha, where high quality accessories are presented in the setting of an art gallery, calling for a variety of lighting characteristics. Interior design by UXUS Design, Amsterdam; Photography by Adrian Haddad; Lighting by dpa lighting design.

The immediate impression is one of a bright and lively space. A MRSE level of at least 300 lm/m^2 is required to give this sense of a distinctly bright space, and it can be seen that while there are areas of white or near-white surfaces, overall reflectance values are varied and include some quite dark surfaces. Note particularly the floor, which although highly polished, is nonetheless highly absorptive, which will have the effect of increasing the perceived strength of the downward 'flow' of light. However, the high MRSE value requires a high level of first reflected flux (FRF), and to achieve this without wasting light calls for luminaire flux to be directed onto high reflectance (low absorptance) surfaces.

Taking a closer look at the central area, Figure 5.4 shows how direct flux is strongly concentrated onto the displays. This central zone is lit from the ceiling above the atrium, and this involves throws of nine or ten metres. The 'flow' of light is strongly downwards and its 'sharpness' creates glittering highlight patterns on the polished metals and richly glossy surfaces of the luxury goods on display, as well as crisp, sharply defined shadow patterns. These lighting patterns are set into contrast by the display podiums, which lack any surface features that respond to 'sharpness'. Their smooth, matt surfaces reveal shading patterns, but not highlight patterns.

A quite different lighting distribution is provided for the background to these displays, which is formed by the perimeter walls and the artworks supported on them. These are washed by angled overhead lighting, which delivers much of the FRF for the space. As for the domed ceiling, these are surfaces for which distinct lighting patterns are not wanted.

Moving into the smaller surrounding areas, even more strongly accentuated display lighting effects are achieved on the mannequins as a result of the much reduced ambient

FIGURE 5.4 QELA – The display lighting in the central area has strong downward ‘flow’, with ‘sharpness’ creating crisp shadow and highlight patterns, set against a background of artwork displays. Interior design by UXUS Design, Amsterdam; Photography by Adrian Haddad; Lighting by dpa lighting design.

illumination, as shown in Figures 5.5 and 5.6. ‘Flow’ directions are still vertically downwards, and this lighting creates particularly strong shading and highlight patterns.

Some subtle changes are revealed upon ascending the staircase to the upper level. Warm white illumination is used throughout the store, and, as shown in Figure 5.7, this sense of warmth is reinforced by the flames of simulated open fire. To the left of this view, the jewellery displays receive special treatment. The freestanding podiums include integrated fibre optic downlights in the slim polished chrome ring at the top, and these are powered by metal halide projectors adjustable for both intensity and colour. ‘Sharpness’ is essential for the strong highlight patterns that give jewellery its sparkle, and cool white illumination is best for viewing silver and diamond pieces.

LED sources, ceiling recessed and track mounted, are used extensively, and all may be dimmed by remote devices. In addition, staff can adjust display luminaires for direction, both pan and tilt, as well as for intensity, from an iPad, giving them free rein to achieve creative lighting effects.

Clearly the ability to envisage lighting in three dimensions is crucial to understanding how to evolve design proposals to create light fields to interact with the surfaces and objects that make up our surroundings. The three lighting patterns provide a useful basis not only for describing visual effects that a proposed lighting distribution will achieve, but also for thinking through the characteristic of lighting that will do the job. For those proposals to be effective, they need to have photometric validity.

FIGURE 5.5 QELA – In this display area, which is adjacent to the central area, the lower mean room surface exitance (MRSE) level has the effect of strengthening the shading patterns. Interior design by UXUS Design, Amsterdam; Photography by Adrian Haddad; Lighting by dpa lighting design.

FIGURE 5.6 QELA – In this display area, the mannequin appears isolated by the strong shading pattern generated by the selective lighting. Interior design by UXUS Design, Amsterdam; Photography by Adrian Haddad; Lighting by dpa lighting design.

FIGURE 5.7 QELA – On the upper floor, the 'fire' on the right matches the warm white illumination used throughout the boutique, except for the jewellery display area on the left, where the colour temperature as well as the intensity of the display lighting can be adjusted to suit the items on display. Interior design by UXUS Design, Amsterdam; Photography by Adrian Haddad; Lighting by dpa lighting design.

Three-dimensional illumination distributions

There are distinct differences between measuring illumination at a point on a surface and at a point in space. The CIE (International Commission on Illumination) defines illuminance in terms of incidence at a point on a surface, and the familiar cosine-corrected illumination meter is designed specifically for measuring that quantity. The CIE definition simplifies illumination into a two-dimensional concept, but this has not been achieved without consequence.

It is conventional for illumination to be measured, calculated and specified in terms of illuminance on two-dimensional planes, such as visual task planes and wall-to-wall horizontal working planes, and this is severely limiting for design options (Lam, 1977). Conversely, the 'flow' of light is a three-dimensional concept, and it involves quite different thinking about lighting. Instead of planes, think of the volume of a space comprising a light field that fully occupies the space, and three-dimensional objects within the space interacting with the light field to generate object lighting patterns that appear superimposed on their surfaces. The appearance of 'flow' is made evident by shading patterns and by the strength of shadow patterns, and may be perceived to vary in both strength and direction throughout the space. Leaving aside 'sharpness' for the moment, we need to be able to measure the spatial distribution of illumination at any chosen point within the space in order to examine this effect.

Consider the point P as a point in space with its location defined by the three mutually perpendicular axes, x, y, and z, as shown in Figure 5.8. Figure 5.9 shows a section through P in the plane of the z axis and the point source S1, which is the sole source of illumination at P. A solid plane passing through P is rotated for maximum illuminance on surface A, and for this condition, the distance shown at P to the perimeter of the illumination solid is proportional to $E_{A(max)}$. Rotation of the plane from this direction causes E_A to reduce in proportion to the cosine of the rotation angle, so that when the angle exceeds 90°, $E_A = 0$.

In this way, the circular form in Figure 5.9 can be envisaged as an illumination solid that forms a three-dimensional representation of the distribution of E_A, and for this special case of the illumination distribution due to a single point source, the illumination solid is a three-dimensional cosine distribution, represented by a sphere whose surface passes through the reference point, and for which a diameter from the reference point coincides with the direction of the source. It can be seen that the illumination distribution about P is totally asymmetric, so that if a small three-dimensional object is placed at P, one side will be illuminated and the other side will be in total darkness. This illumination difference on opposite sides of an object is of interest. If, instead of recording the distribution of E_A, we record the distribution of $(E_A - E_B)$, that is to say, the difference on opposite sides of the plane, the solid would be unchanged because when surface A is facing away from S1, $(E_A - E_B)$ would have a negative value.

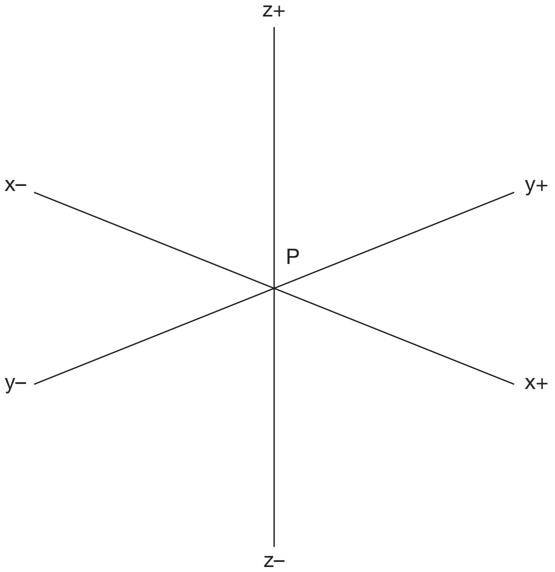

FIGURE 5.8 The point P is located at the intersection of the x, y and z orthogonal axes. The x and y axes are in the horizontal plane, and the z axis is vertical. Unless otherwise specified, it is convenient to assume a direction of view from the y-direction ('eye' direction), so that x is 'a-cross'. While any other view direction may be possible, this simple convention tends to avoid errors.

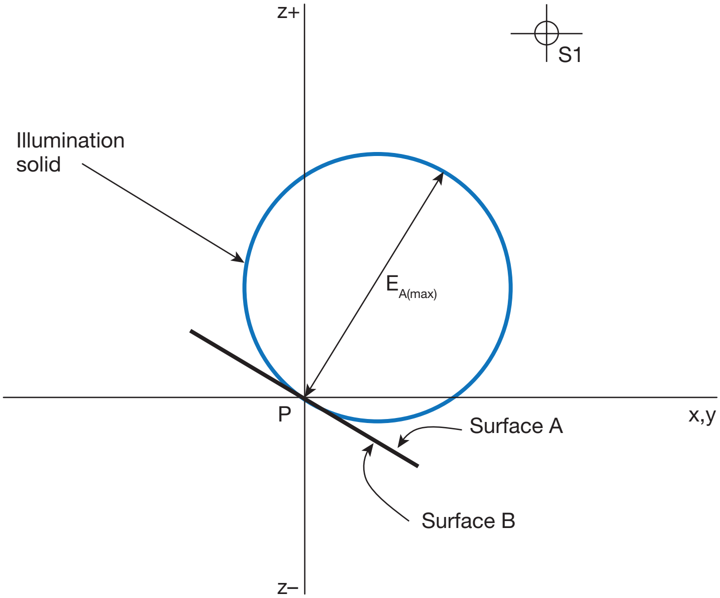

FIGURE 5.9 The three-dimensional illumination distribution about point P due to the small source S1 is defined by a spherical illumination solid, where the length of $E_{A(max)}$ is proportional to the illuminance on surface A when normal to the direction of S1.

Figure 5.10 shows the effect of adding a second point source S2. In this case, the blue contours show parts of the illumination solids for the individual sources, but where the solids coincide, the value of $(E_A - E_B)$ is shown by the red contour. The values of $E_{A\ max}$ and for S1 and S2 are shown as vectors, and the value of the resultant vector, $(E_A - E_B)_{max}$, is given by completing the vector parallelogram. It can be seen that the red contour is similar to the illumination solid for the single point source, meaning that the distribution of illuminance difference on opposite sides of the plane is identical to that produced by a point source. If this happens when we add a second source, it will happen when we add a third, or fourth ... or an infinite number of sources. We have established the point that at any illuminated point in space, the distribution of illuminance difference in opposite directions $(E_A - E_B)$ may be represented as an illumination vector. This concept is attributed to Professor A.A. Gershun, whose book, *The Light Field*, was published (in Russian) in 1936.

In Figure 5.11, we move from hypothetical situations to a real situation. The blue contour is typical of an illumination solid that might occur in an indoor location illuminated predominantly from overhead, but with a sideways bias as might occur near a dark coloured wall. The contour is smooth because it is the sum of spherical solids due to every luminous element surrounding the measurement point. Illumination solid contours cannot display sharp peaks or troughs. The red contour is the distribution of $(E_A - E_B)$, and the plane passing through P has been rotated as previously, but this time the aim has been to find the direction that gives maximum illuminance difference on opposite sides of the

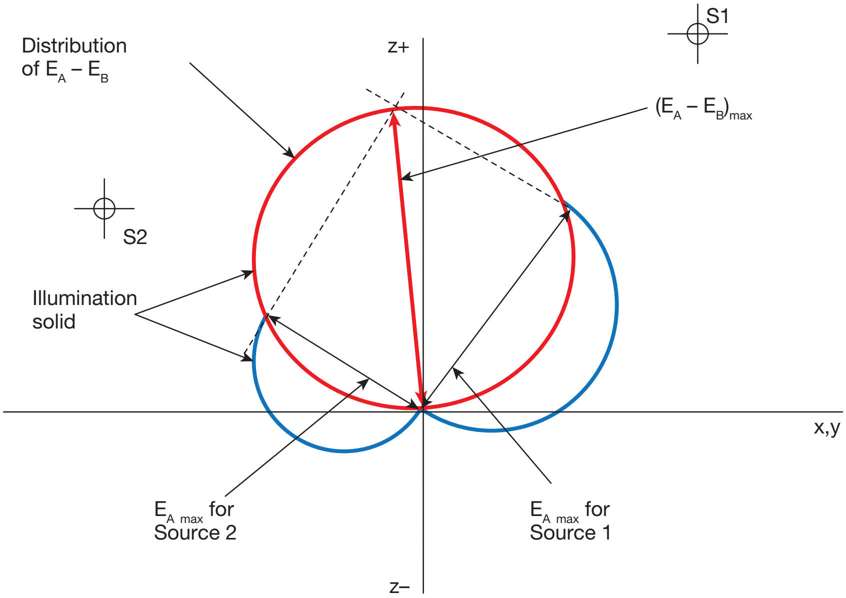

FIGURE 5.10 The illumination solid is now the sum of component solids due to sources S1 and S2, but the distribution of $E_A - E_B$ is a spherical solid, identical in form, but not magnitude or direction, to the illumination solid due to S1 alone.

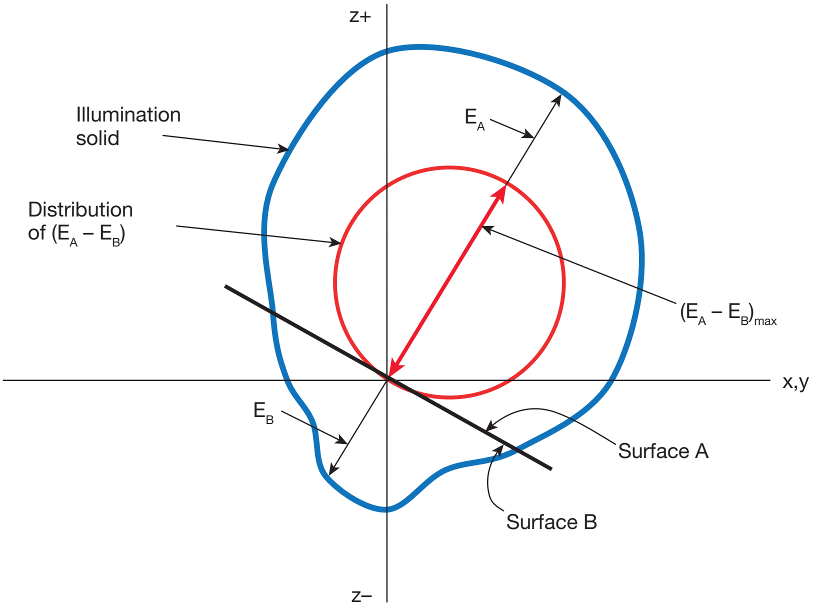

FIGURE 5.11 The illumination solid at a point in a space where light arrives from every direction, but predominately from overhead although with a sideways bias. Despite the irregularity of the illumination solid, the distribution $E_A - E_B$ is defined by a spherical solid identical in form to the illumination solid produced previously by S1.

plane, which may not coincide with the maximum value of the illumination solid contour. Rotation of the plane from this direction would cause ($E_A - E_B$) to reduce in proportion to the cosine of the rotation angle, so that when the rotation angle equals 90°, $E_A = E_B$. The distribution of ($E_A - E_B$) is a three-dimensional cosine distribution identical in form to the illumination solid due to a single point source. As shown in Figure 5.8, the x, y axis lies in the horizontal plane, and the z axis is vertical.

We are now in a position to analyse the illumination distribution about a point in space into its two components. In Figure 5.12 the maximum value of ($E_A - E_B$) and the direction in which this value occurs define the illumination vector **E.** For any plane passing through P, the illuminance difference on opposite surfaces equals the vector component on the axis normal to the plane. For the horizontal plane through P, $\mathbf{E}_{(z)} = E_{(z+)} - E_{(z-)}$, and similarly, for a vertical plane through P normal to the x axis, the magnitude of the illumination vector component is $\mathbf{E}_{(x)}$. Note that the symbol for a vector is shown in bold type, and while this distinction is clearly indicated in print, in manuscript it is made by a small arrow over the E. Note that a vector is defined in terms of both magnitude and direction. The distribution of the vector component is defined by the three-dimensional vector solid, which, as we have noted, is always a spherical cosine distribution with its surface passing through P and its diameter equal to the vector magnitude.

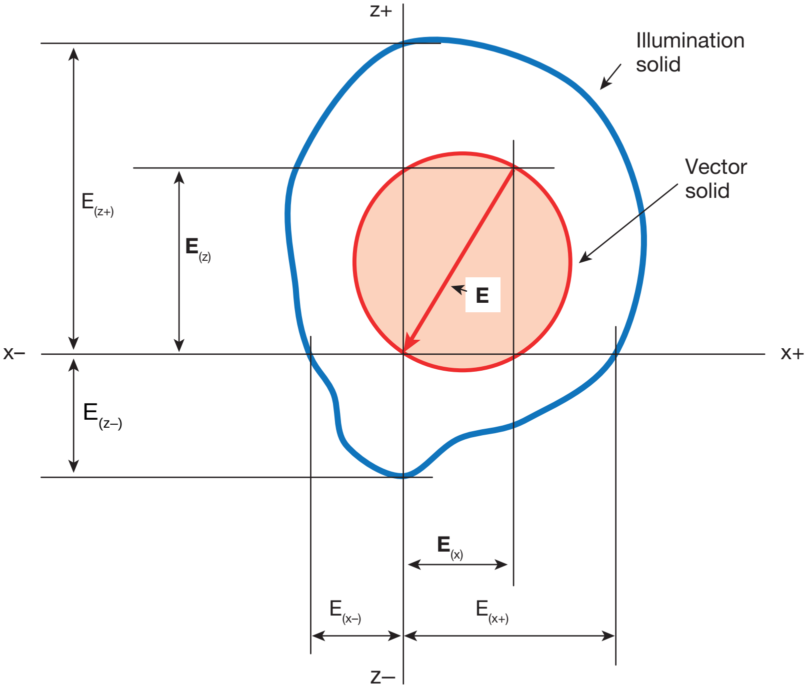

FIGURE 5.12 The magnitude and direction of $(E_A - E_B)_{max}$ defines the illumination vector, which is depicted as an arrow acting towards the point. The vector in turn is defined by its components on the x, y, and z axes. The vector solid accounts entirely for the asymmetry of the illumination solid.

In Figure 5.13, the vector solid has been subtracted from the illumination solid and what remains is a three-dimensional solid that is divided by the axis normal to the vector direction. This solid has point symmetry about P, that is to say, for any axis through P, the distance to the contour of this solid in one direction equals the distance in the opposite direction. This is the symmetric solid, and while it may depart from uniformity, the illuminance due to the symmetric solid ~E in any direction from P is equal to ~E in the opposite direction. If a plane passing through P is rotated, for every orientation, the illuminance values on opposite sides of the plane due to the symmetric solid will be equal. In other words, it is the solid for which $E_A - E_B = 0$ for every orientation.

In this way, we arrive at the following conclusions:

1 That at any illuminated point in space, the three-dimensional distribution of illuminance may be defined by an illumination solid.

2 The illumination solid is the sum of two component solids: the vector solid and the symmetric solid.

3 The vector solid is a spherical cosine distribution, and is defined by the magnitude and direction of the illumination vector **E**. The illuminance distribution at the reference point P represented by the vector solid is identical to the distribution that would be produced by a single compact source located in the vector direction.

4 The symmetric solid has the property that, for any plane passing through P, it produces equal illuminance ~E on opposite sides.

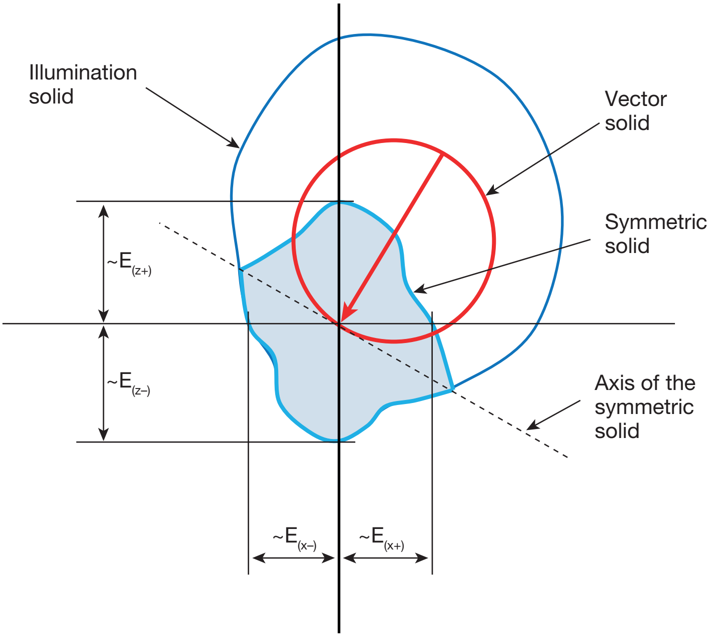

FIGURE 5.13 If the vector solid is subtracted from the illumination solid, what is left is a solid that is symmetrical in every direction about the point. This is the symmetric solid.

5 The visible characteristics of the illuminance distribution over the unobstructed surface of a three-dimensional object that is small in relation to the surrounding light field may be analysed as the sum of distributions due to the vector and symmetric components, one being entirely asymmetrical about the measurement point, and the other entirely symmetrical.

6 Two special cases may be noted:
- For a single point source, the illumination solid is coincident with the vector solid, and the symmetric component $\sim E = 0$.
- For an integrating sphere, the illumination solid is coincident with the symmetric solid, comprising ideally a spherical distribution centred at P, and the illumination vector $\mathbf{E} = 0$.

To all of the above, I wish to add a personal observation. The concept that the spatial distribution of illumination at any illuminated point in space comprises two components – one of which is entirely asymmetric about the point and could be produced by a compact source in the direction of the vector, while the other is entirely symmetric about the point – is not intuitive. It emerges from a mathematical analysis, and is, in my opinion, the most remarkable finding to emerge from the study of illumination engineering. It provides a unique design insight, and if you look for it, you can see it.

Illumination solids and the 'flow' of light

Look back to Figure 5.2, and note particularly the changing appearance of the matt white sphere in the three lighting conditions. This object forms a different shading pattern with each variation of the light field and, every time, the appearance of the shading pattern can be described in terms of the apparent strength and direction of the 'flow' of light. Equally, it may be described in terms of different relationships of the asymmetric and symmetric components of the illumination solid. We have here the basis of a means for assessing lighting according to its potential to influence the appearance of three-dimensional objects through the creation of shading patterns, which in turn, may be described in terms of the 'flow' of light.

If an object is small enough in relation to its surrounding environment for us to be able to examine its illumination by considering the illumination distribution at a point, then we can think of every element visible from the point to be contributing its own mini-vector at the point. We have two alternative ways of summing these mini-vectors. If we sum them individually, we have the illumination solid. If we sum their opposite differences, the sum of these individual vectors is always a single vector that defines the magnitude and direction of the (asymmetric) vector solid. The difference between the illumination solid and the vector solid is the symmetric solid. It should be apparent that if the vector solid is large in relation to the symmetric solid, then the 'flow' of light will appear to be strong. It might seem, therefore, that the ratio of asymmetric to symmetric solids would provide a useful index of this effect, but it would have a range from zero to infinity, which is inconvenient. In mathematics, a vector quantity is one that has both magnitude and direction, while a quantity that has magnitude only is termed a scalar. It was with this in mind that J.A. Lynes proposed the concept of scalar illuminance, which is defined in terms of the average illuminance over the whole surface of a small sphere centred at a reference point (Lynes *et al.*, 1966). It follows that for any illumination solid, the scalar illuminance will be the sum of contributions from the vector and symmetric solids. The contribution from the symmetric solid will be equal to the symmetric illuminance ~E, and from Figure 5.14 is can be seen that the asymmetric solid will contribute one-quarter of the vector magnitude, so that scalar illuminance:

$$E_{sr} = \frac{\mathbf{E}}{4} + \sim E \tag{5.1}$$

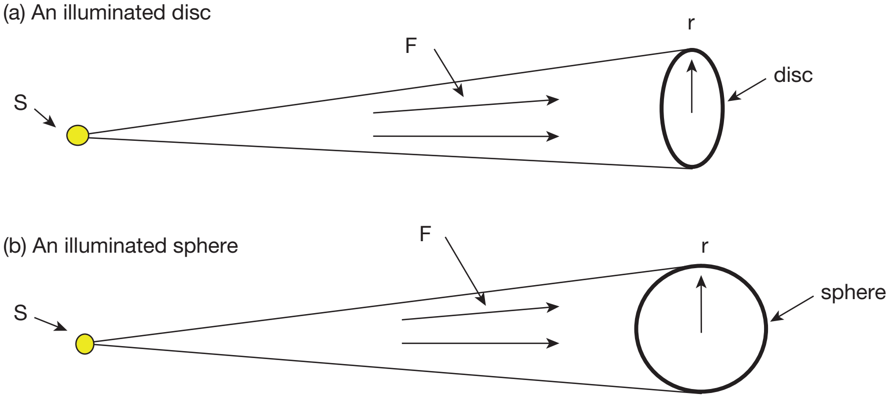

FIGURE 5.14 In (a), a small source S projects luminous flux of F lm onto a disc of radius r, producing a surface illuminance E = F/(π.r²). In (b), the disc is replaced by a sphere of radius r, giving a surface illuminance E = F/(4π.r²).

This enables us to specify the apparent strength of the 'flow' of light in terms of the vector/scalar ratio:

$$VSR = \mathbf{E} / E_{sr} \tag{5.2}$$

VSR has a scale from zero (the integrating sphere condition) to four (the point source in a black environment). Research studies in a face-to-face situation indicated preference for VSR within the range 1.2 to 1.8 (Cuttle *et al.*, 1967) and this finding has more recently been corroborated by Protzman and Houser (2005). Table 5.1 gives an approximate indication of how assessments of the perceived strength of 'flow' are likely to vary with the VSR.

Regardless of the number of light sources present, the asymmetric component resolves into a cosine distribution defined by the illumination vector, and providing that the VSR is sufficient for the 'flow' direction to be apparent, its direction coincides with the vector direction. There are two alternative ways of defining the vector direction. One is to specify vector altitude (α) and azimuth (φ) angles, where Figure 5.15(a) shows:

$$\alpha = sin^{-1}(\mathbf{E}_{(z)} / \mathbf{E}) \tag{5.3}$$

TABLE 5.1 Vector/scalar ratio and the perceived 'flow' of light

Vector/scalar ratio	*Assessment of appearance*	*Application*
4.0 (max)		
3.5	Dramatic	
3.0	Very strong	Strong contrasts, detail in shadows not discernible
2.5	Strong	Suitable for display; too harsh for human features
2.0	Moderately strong	Pleasant appearance for distant faces (formal)
1.5	Moderately weak	Pleasant appearance for near faces (informal)
1.0	Weak	Soft lighting for subdued effects
0.5	Very weak	Flat shadow-free lighting
0 (min)		

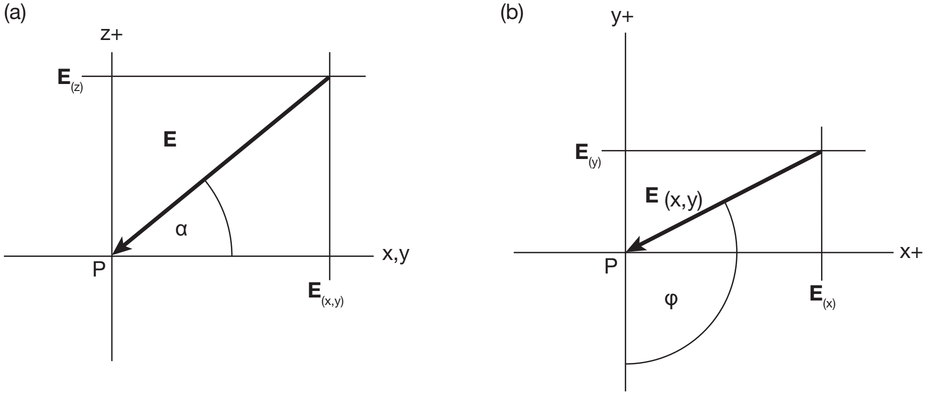

FIGURE 5.15 (a): Vertical section through P showing illumination vector altitude angle α, and (b): Horizontal section through P showing azimuth angle φ of the horizontal vector component.

There is more than one way of specifying the azimuth angle, and Figure 5.15(b) shows φ measured anticlockwise from the y- axis, as this is often taken to represent the direction of view. Care needs to be taken to cope with the full 360 degrees of rotation.

Another way is to specify the vector direction in terms of a unit vector, which assumes the vector to have unity value and expresses the direction in the form ($\mathbf{e}_{(x)}$, $\mathbf{e}_{(y)}$, $\mathbf{e}_{(z)}$), where the unit vector component on the x axis:

$$\boldsymbol{e}_{(x)} = \boldsymbol{E}_{(x)} \,/\, \boldsymbol{E} \tag{5.4}$$

and similarly for $\mathbf{e}_{(y)}$ and $\mathbf{e}_{(z)}$. It can be seen that each of these unit vector values does in fact specify the cosine of the angle that the vector forms with the axis. While care needs to be taken over the signs of the unit vector components, this concise form of notation is recommended as largely avoiding the confusions that are likely to occur when dealing with angles greater than 2π.

The previously cited research into preferences for face-to-face viewing (Cuttle *et al.*, 1967) found distinct preference for vector altitudes in the range 15 to 45 degrees, or $0.25 < \mathbf{e}_{(z)} < 0.7$. Even more distinct was the identification of a downward 'flow' of light as the least preferred condition, for which $\alpha = 90$ degrees and $\mathbf{e} = (0,0,1)$. For face-to-face viewing situations where overhead lighting is unavoidable, VSR should be kept to a low value.

In this way, the characteristics of a three-dimensional distribution of illumination, as it may affect the perceived strength and direction of the 'flow' of light, can be specified in terms of simple photometric quantities. Procedures for predicting and measuring these quantities are described in the following chapter.

The 'sharpness' of illumination

While 'flow' relates to the appearance of the shading patterns and the density of the shadow patterns, 'sharpness' relates to the appearance of the highlight patterns and the crispness of the shadow patterns. Look back to Figure 5.2, and appreciate how differently these two lighting concepts appear.

A thought experiment

Once again, you must clear your mind of what you expect to experience and let your imagination take control. In Figure 5.16, a surface is illuminated by a diffusing disc light source. The illuminance at P is given by the disc source formula (Simons and Bean, 2001):

$$E_P = \frac{\pi L_S}{2}(1 - cos\alpha) \tag{5.5}$$

The subtence angle of the source, α, may have any value from a degree or two, for which the source would be close to the hypothetical point source, up to 180 degrees, at which point the source becomes a uniform diffusing hemisphere. At the point P, we place the comparison panel shown in Figure 5.17, which compares two materials, a sample of black glass and a matt white surface. This panel was originally proposed by J.A. Worthy (1990) to explain his own research into this aspect of lighting.

Imagine that as we vary α, the source luminance adjusts to maintain the illuminance E_P at a constant value of 100 lux. The appearance of the matt white surface will not change while we make this variation because its luminance remains constant, but the appearance of the black glass sample will undergo radical changes. If we start from the luminous hemisphere condition ($\alpha = 180$ degrees), the glass appears to have a grey cast over it. As α is reduced, this cast shrinks to become an image of the disc source, and around the image we see the blackness of the glass. As the image continues to shrink, it increases in brightness until it becomes an intensely bright, small dot that appears sharply defined against the blackness of the glass. The lighting now has 'sharpness', and this is revealed by the appearance of the glass, not the white disc. This effect is similar to the highlight patterns on the white and black spheres shown in Figure 5.2(a) to (c).

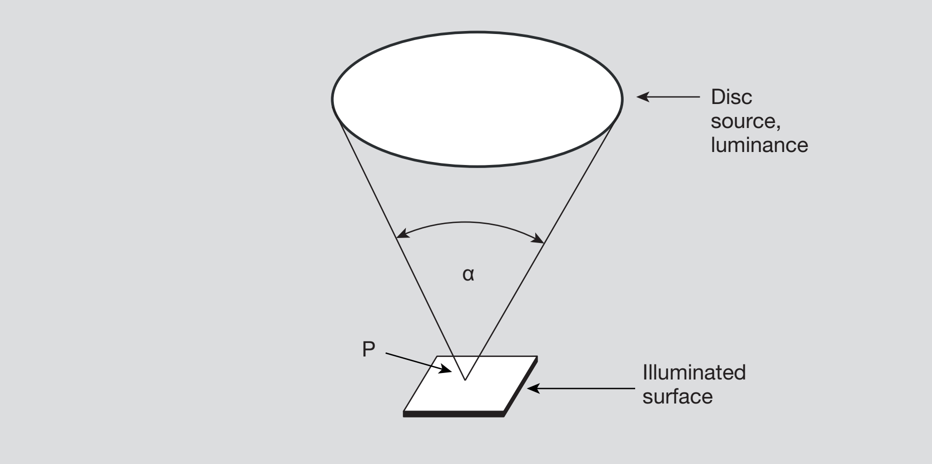

FIGURE 5.16 The point P is on a surface, and is illuminated by a disc-shaped source that is normal to the surface and of angular subtence α.

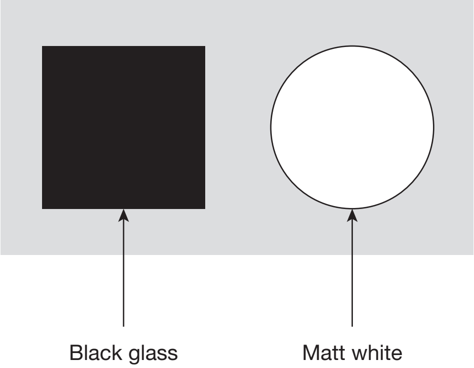

FIGURE 5.17 This comparison surface has two mounted samples that respond differently to the disc source. After Worthy (1990).

If we rearrange the disc source formula to $L_S = \frac{2E_P}{\pi(1-\cos\alpha)}$, Figure 5.18 shows how the value of L_S has to be varied to maintain E_P = 100 lx. It can be seen that a relatively low luminance value satisfies over a substantial angular range, but as the source becomes smaller than about 30 degrees, its luminance has to be increased quite sharply. However, it is when we get down to the really small sources that the source luminance has to escalate in order to provide the required illuminance, as shown in Figure 5.19.

It can be seen that when α = 180 degrees, L_S = 100/π, or approximately 31 cd/m^2. Reducing α to 90 degrees requires L_S to be doubled, but this is still a large source. When α comes down to 30 degrees, L_S has to be increased to 475 cd/m^2, and at 10 degrees it has to be over 4000 cd/m^2. However, it is when we get to a source subtending less than 10 degrees that the luminance value really climbs. A source subtending just 1.0 degree has to have a luminance of nearly half a million cd/m^2 to deliver just 100 lux.

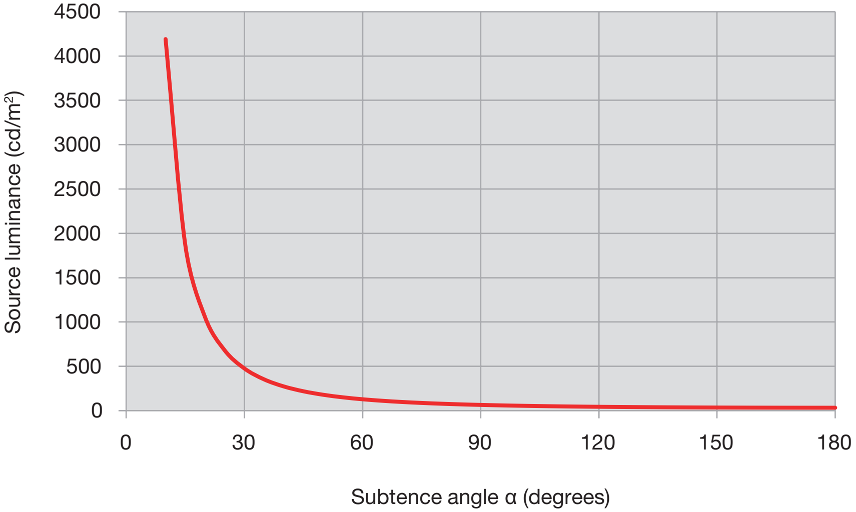

FIGURE 5.18 As the subtence of a large disc source is reduced, the source luminance required to maintain an illuminance value of 100 lux increases rapidly as subtence falls below 30 degrees.

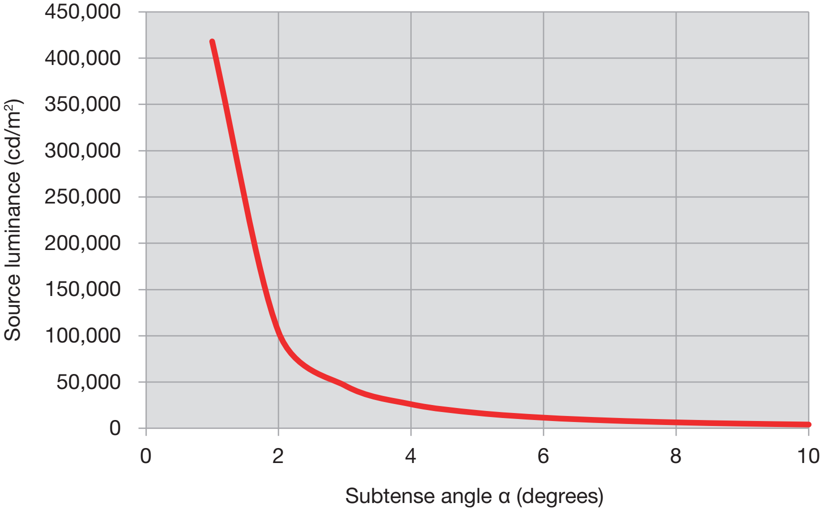

FIGURE 5.19 For small sources, the increase in luminance required to maintain 100 lux increases dramatically for subtence angles less than 3 degrees.

Imagine now that you want to deliver a given illuminance E_{tgt} onto a three-dimensional target, and you have selected a location for the luminaire at distance D. The required source luminous intensity $I_S = E_{tgt} \times D^2$ cd (for a two-dimensional target you will need to take account of the angle of incidence), so you scroll through the luminaire manufacturers' websites looking for a spotlight with suitable performance. While most manufacturers will give you intensity data, they are unlikely to give source luminance values, but clearly this will affect substantially the perceived 'sharpness', so you will need to check this for yourself. From the source dimensions, work out the luminous area A_S projected towards the object, and then the source luminance $L_S = I_S/A_S$ cd/m². This is your first step towards assessing the potential for 'sharpness'.

Highlight contrast potential (HCP)

Generally, smooth dielectric (non-electroconducting) materials have specular components of their total reflectance of around 4 per cent (although for electroconducting materials, such as polished metals, it can be much higher). Typically then, the luminance of the reflected highlight seen on a glossy surface $L_{hl} = 0.04\ L_S$, where L_S is the source luminance. The visibility of the highlight depends primarily on the luminance contrast of the highlight against the background on which it is seen.

The highlight contrast potential (HCP) is a measure of the extent to which a light source may provide a visible highlight. For this we ignore light that may be reflected from the surrounding environment (the highest possible highlight contrast will occur in a black environment where S is the only source of light) and consider a dielectric target surface *tgt* that has a reflectance ρ_{tgt} (which includes the 0.04 specular component) illuminated by source S, then the highlight luminance:

$$L_{hl} = 0.04 L_S$$

And the luminance of the target surface:

$$L_{tgt} = \frac{E_{tgt}\rho_{tgt}}{\pi}$$

Applying the disc source formula as previously,

$$E_{tgt} = \pi \frac{L_S}{2}(1 - cos\alpha)$$

So,

$$L_{tgt} = \frac{\pi L_S}{2}\frac{(1 - cos\alpha)\rho_{tgt}}{\pi}$$

$$= 0.5\ L_S(1 - cos\alpha)\rho_{tgt}$$

Then Highlight Contrast Potential:

$$HCP = \frac{L_{hl} - L_{tgt}}{L_{tgt}}$$

$$= \frac{0.04 - 0.5\rho_{tgt}(1 - cos\alpha)}{0.5\rho_{tgt}(1 - cos\alpha)}$$

$$= \frac{0.08}{\rho_{tgt}(1 - cos\alpha)} - 1 \tag{5.6}$$

Note that although L_S does not appear in this formula, the source subtence angle is in there. If there are no other sources of light, then the only other factor determining HCP is target reflectance. In reality, other sources of light will be present and they will have the effect of reducing the highlight contrast, so that for a given light source, this is an expression for its maximum potential to provide highlight contrast. Figure 5.20 shows how the conspicuousness of highlights is dependent on low diffuse reflectance, such as the black glass sample in the comparison panel, as well as small angular size of the light source.

General lighting practice seeks to avoid specular reflections, identifying them as 'veiling reflections', but designers should distinguish between highlights and veiling reflections. When we considered the appearance of the comparison panel (Figure 5.17) in the thought exercise, the effect of the large source was to create a grey cast over the

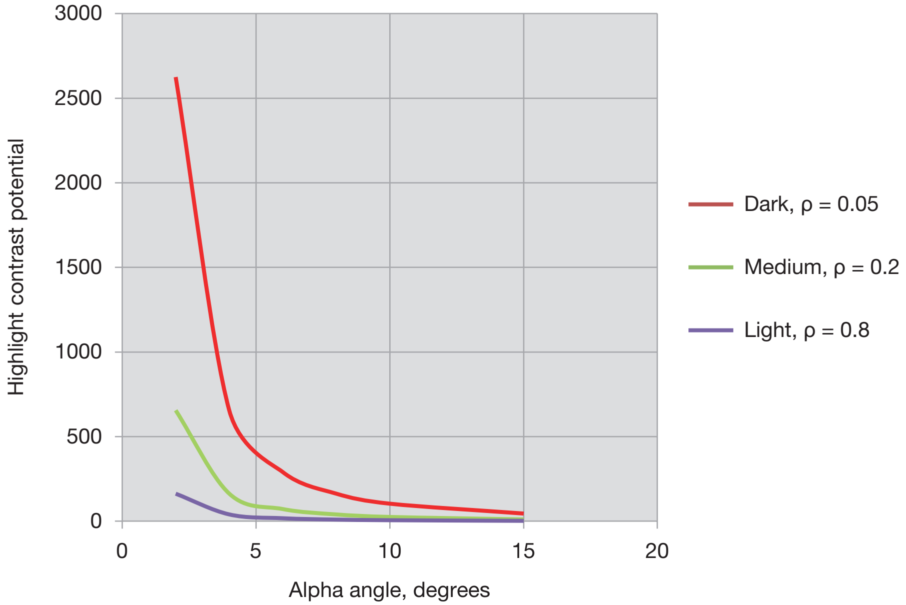

FIGURE 5.20 Highlight contrast potential HLC for three values of target reflectance, representing low, medium and high surface lightness, and a range of source angular subtence angles.

glossy black surface, reducing its blackness but giving no hint of its glossiness. This was a veiling reflection. However, when the source subtence was reduced, the specular reflection became a highlight pattern, seen in contrast against the undiminished blackness of the glass. If it had the effect of reducing the visibility of surface detail, this could easily be avoided by head movement, and meanwhile, the smooth, shiny surface of the glass would be given visual emphasis. The ability to create highlight patterns when and where required is an important skill in the lighting designer's toolkit. Again, mathematical analysis of a readily observed characteristic of lighting gives insight into its occurrence that is not intuitive.

That we have an expression for HCP does not mean that target values should be set, or that we have another factor to be calculated and measured. What matters is that we are able to identify the physical parameters on which HCP depends, and this enables designers to exercise control over the aspects of lighting that are influential. In the section entitled 'The three object lighting patterns' (page 66) it was noted how the appearance of some objects can be brought alive by highlight patterns, while others benefit from their complete absence. The usefulness of HCP lies in enabling design decisions to be guided by understanding of the conditions that govern the 'sharpness' of lighting.

The appearance of shadow patterns

Shadow patterns might seem to be the simplest of the three types of lighting patterns to come to terms with, but this is not so. While the perceived strength and direction of a shadow pattern relates to the VSR and the vector direction, its 'sharpness' relates to the HCP. In this way, the appearance of the shadow patterns within a space vary with both the overall impression of the 'flow' of light and the perceived 'sharpness' of the illumination.

Look once more at Figure 5.2, and note the role of 'sharp' shadow patterns, both those cast onto objects and those cast onto the background, in creating the appearance of depth and a sense of 'crispness' within the overall scene. As has been discussed, achieving these effects may support design objectives, as in Figure 5.4, or the situation may call for their avoidance, as in Figure 5.7. It is all a matter of being able to visualise the space and its objects in light, and being able to control lighting patterns to reveal, or to subdue or to emphasise surface attributes.

Figure 5.21 shows the formation of the penumbra, the extent of which is inversely related to the perceived 'sharpness' of a shadow pattern. Meanwhile, the apparent density of the umbra is determined by the VSR, and in this way we can see how the concepts of the three object lighting patterns – the shading, highlight and shadow patterns – are concepts that can readily be visualised and discussed with clients and other design professionals. On the other hand, the concepts of 'flow' and 'sharpness' of illumination provide means for describing illumination in terms of its potential to create object lighting patterns, and as such, they can enable members of a design team to build a shared understanding of three-dimensional light fields that fill spaces and influence appearances of everything within it. That both of these concepts – 'flow' and 'sharpness' – can be specified in terms of photometric concepts – vector/scalar ratio, vector direction, and highlight contrast potential – enables them to be described with confidence that they will be provided. The means for doing this are described in the next chapter.

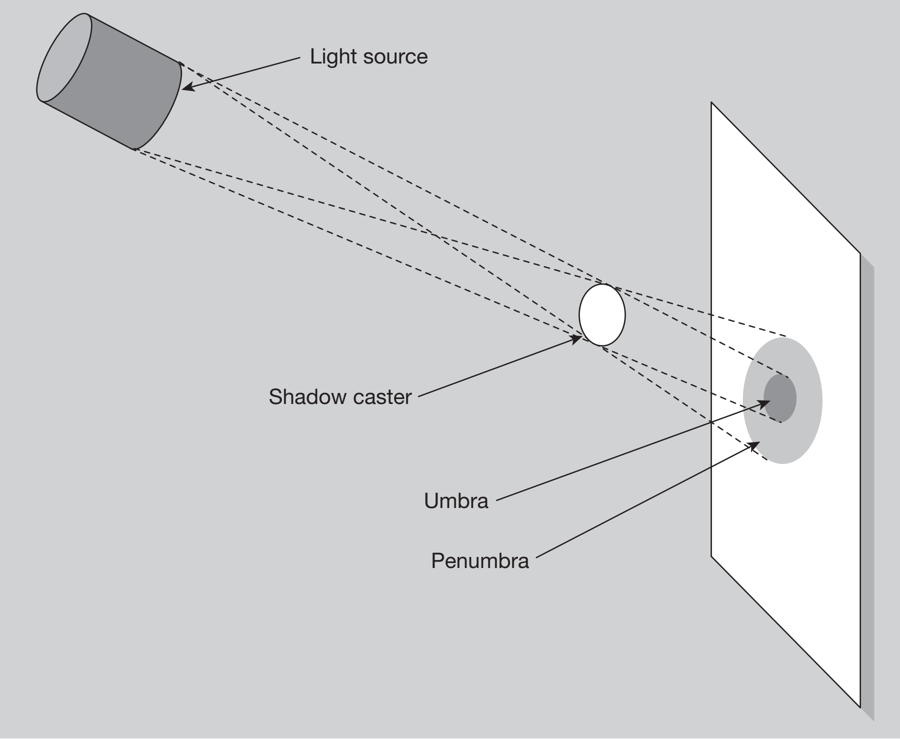

FIGURE 5.21 Light sources of smaller subtence angle produce less penumbra, increasing the 'sharpness' of the lighting. The perceived density of the umbra is determined by the strength of the 'flow' of light.

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6

DELIVERING THE LUMENS

Chapter summary

Throughout this book, the aim has been that a lighting designer should develop the skill to visualise the distribution of light within the volume of a space in terms of how it affects people's perceptions of both the space and the objects within it. These envisioned distributions of light comprise reflected light, while the distributions that the designer controls are the direct light to be provided by the lighting installation. Furthermore, they are, for the most part, three-dimensional variations of the light field, and the concept of cubic illumination is introduced to provide a basis for understanding them and enabling predictive calculations. Procedures are explained for specifying lamps and luminaires of correct performance, as well as controls to enable installations to respond to daylight availability. Measurement procedures are described for ensuring that design objectives have been achieved, and two Cubic Illumination spreadsheets are introduced that perform the calculations automatically.

Lighting calculations

Lighting calculations do not solve problems. Their purpose is to enable a designer to specify a layout of lamps, luminaires and control circuits with a reasonable level of confidence that it will create an envisioned appearance. No matter how well thought through the envisioned appearance might be, it will not be achieved by guesswork or 'hoping for the best'. Lamp wattages, luminaire spacings and beam spreads need to be correct for the distribution and balance of the lighting to look right.

Even so, some common sense needs to be applied. Photometric laboratories do, very properly, work to high levels of precision to specify the performances of lighting products, but while lighting designers need to have confidence in the reliability of the data that they are working with, precision in what they provide needs to be no better than differences that users (perhaps critical users) are likely to notice.

The aim has to be that a client who has had a lighting design proposal described in terms of perception-based objectives will be satisfied that their expectations have been met. Specifying and predicting performance in terms of lighting metrics, followed by checking the actual performance levels achieved, are necessary parts of the design process, but need not unduly concern clients.

Lighting design should not be thought of as a linear process, but nonetheless, this chapter follows a sequence that relates, quite sensibly, to a rational design procedure.

Mean room surface exitance, MRSE

Starting from how brightly lit, or dimly lit, the space is to appear, the designer decides upon a level of ambient illumination and specifies this in terms of mean room surface exitance, as explained in Chapter 2 and referring to Table 2.1. The general expression is:

$$MRSE = FRF \,/\, A\alpha \tag{6.1}$$

where FRF is first reflected flux:

$$FRF = \sum E_{s(d)} \cdot A_s \cdot \rho_s \tag{6.2}$$

and $A\alpha$ is the room absorption:

$$A\alpha = \sum A_s(1-\rho_s) \tag{6.3}$$

where:

$E_{s(d)}$ = direct illuminance of surface *s* (lux)
A_s = area of surface *s* (m^2)
ρ_s = reflectance of surface *s*

Estimating the reflectance of a surface is not as simple as it might seem. Patterned surfaces are particularly difficult, but reasonably reliable measurements can be made by attaching an internally blackened cardboard tube to a light meter, as shown in Figure 6.1, and taking a reading of the surface in question, taking care to avoid specular reflections. Then, without moving the meter, slide a sheet of white paper over the surface and take a comparative reading. Good quality writing paper typically has a reflectance around 0.9. Alternatively, paint manufacturers often quote reflectance values for their products, and a paint colour swatch can be used to make matches to surface colours.

It is sometimes useful to be able to determine the equivalent reflectance of a cavity plane, ρ_{eq}, such as that of a luminaire plane, in which case the upper walls and the ceiling form the cavity. Start by calculating the ratio of the area of the cavity plane A_{cp} to the area of the cavity surfaces A_{cs}, and the average reflectance of surfaces within the cavity, ρ_{av}, then:

$$\rho_{eq} = \frac{\rho_{av}(A_{cp} \,/\, A_{cs})}{1-\rho_{av}[1-(A_{cp} \,/\, A_{cs})]} \tag{6.4}$$

FIGURE 6.1 Measuring surface reflectance, using an internally blackened cardboard tube fitted over an illuminance meter. Comparative readings are taken of the surface, avoiding specular reflections, and of a sheet of white paper.

When using formula 6.3 to calculate the room absorption value, $A\alpha$, it is often convenient to use A_{cp} and ρ_{eq} values. After that, the total first reflected flux required to provide the MRSE value is calculated:

$$FRF = MRSE \cdot A\alpha \tag{6.5}$$

This FRF value is the number of 'first bounce' lumens that has to be provided to achieve the design value of MRSE, and ways of accounting for this value are explained in 'Illumination hierarchy design' (page 32). It needs to be noted that room surface reflectance values are much more strongly influential in MRSE calculations than in conventional HWP calculations, and it is important that designers work with realistic values. The bad old practice of assuming room surface reflectance values is a recipe for disaster.

Illumination hierarchy and target illuminance values

After selecting the design value for the ambient illumination, the lighting designer decides upon the illumination hierarchy, which determines the distribution of illumination within the space. This is achieved by providing direct illumination selectively onto specific surfaces and objects, as demonstrated in Boxes 3.1 and 3.2, using the Illumination Hierarchy spreadsheet. The schedule of TAIR values is the first crucial statement of design objectives. The principal tool for devising this distribution is the classic *inverse square cosine law* (sometimes referred to as the 'point-to-point' formula), which is stated as:

$$E_P = \frac{I_S \cdot \cos\theta}{D^2} \tag{6.6}$$

Where

E_P = illuminance at point of incidence P (lux)
I_S = luminous intensity due to light source S (candelas)
θ = angle of incidence
D = distance from source S to point P (metres)

This statement of the law is often accompanied by a diagram of the sort shown in Figure 6.2 in which the whole issue of providing direct illumination is reduced to two dimensions and, by default, it often happens that the plane of incidence is assumed to be the horizontal working plane.

Once we become concerned with providing illumination onto planes that people actually look at, we are likely to find ourselves dealing with situations that are far more like Figure 6.3. Here point P is on a vertical surface which may be of any orientation, and illuminated by a directional light source S. The location of S relative to P is determined by dimensions X, Y and Z (which may be positive or negative according to direction), and then, depending on circumstance, it can be convenient to think of Y as being in the 'eye' direction, so that X is 'a-cross' and measures positive to the right and negative to the left, while on the vertical axis, Z measures positive up and negative down. It can be handy to keep this picture in mind as it can avoid a lot of confusion when it comes to analysing measured data.

The performance of the light source S is indicated by its distribution of luminous intensity, I_S, specified in candelas (cd), and often this can be simplified into two essential items of performance data. These are the intensity value on the beam axis, which for historical reasons is still often referred to as the centre beam candle power (CBCP), and the beam angle, B, for which the beam edge is defined by the angle at which intensity drops to 50 per cent of the CBCP value. For example, if CBCP = 3000cd and B = 12°, then at 6° to each side of the beam axis, intensity I_S = 1500cd. Any light emitted outside the beam should be regarded as 'spill', and blocked by louvres or baffles.

First we will consider how to use these data to calculate the illuminance E_P at point P. Then we take note that, providing the beam is conical, it forms an elliptical pattern on the surface, with minor and major axes q′ and q″. These too we need to be able to predict, particularly as we often need to use several light sources to build up a pattern of overlapping ellipses to provide coverage over a target surface. Also, it needs to be kept in mind that, following the procedures described in the foregoing chapters, the purpose may

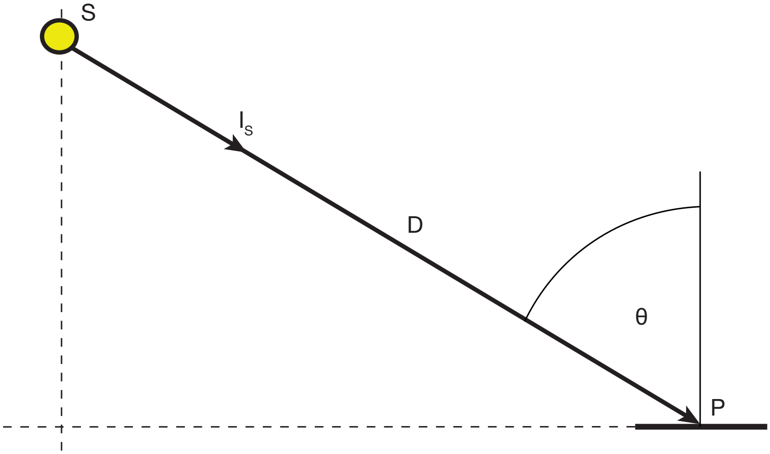

FIGURE 6.2 Application of the point-to-point formula, $E_P = I_S \cos\theta / D^2$, for determining the illuminance at point P on a horizontal plane. I_S is the beam centre luminous intensity.

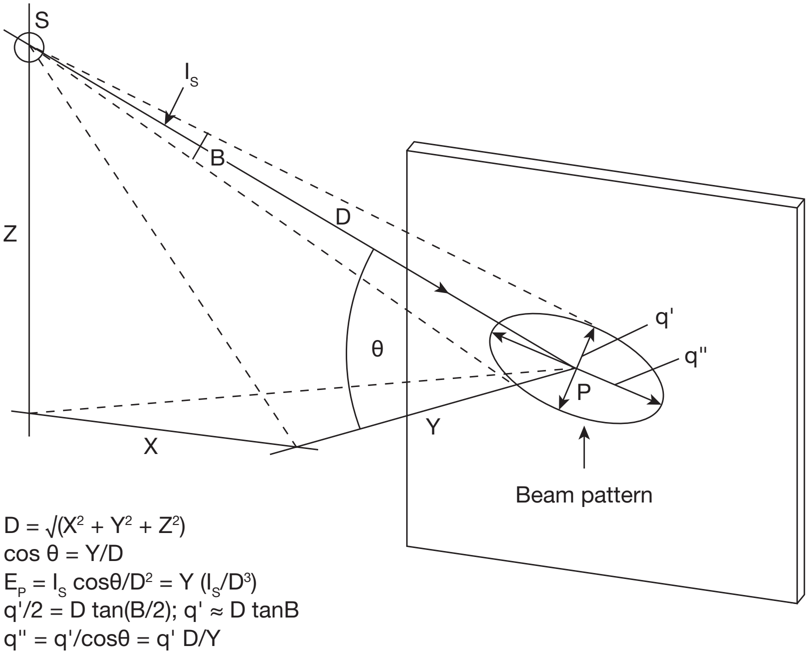

FIGURE 6.3 Determining the illuminance at point P on a vertical plane, and the beam pattern formed on the plane. B is the beam angle, which defines the cone over which luminous intensity equals more than 50% of I_S, the CBCP value.

be to provide the direct illumination required to provide the target/ambient illuminance ratios (TAIRs) determined for the illumination hierarchy. Keep in mind that this means that we need to start off knowing the illuminance that is required, and the aim is to determine the luminous intensity to be provided. As we look though suppliers' data for suitable luminaires, we check the suitability of potential luminaires by noting their CBCP and B values.

Application of the inverse square law to the situation shown in Figure 6.3 calls for some careful examination of the situation. Pythagoras' theorem tells us that the distance D of P from S is given by $D = \sqrt{(X^2 + Y^2 + Z^2)}$, but what seems a little more tricky in this three-dimensional situation is finding the cosine of the angle of incidence, θ. This is the angle that the beam axis forms with the y axis, which is the normal to the surface at P, so that $\cos\theta = Y/D$. Look back to Formula 6.6, and it can be seen that we can rewrite the formula for calculating the illuminance at P as:

$$E_P = Y\frac{I}{D^3} \tag{6.7}$$

Take good note of this 'D to the 3' expression. By eliminating cosθ we have greatly simplified the 'point-to-point' calculations, and we will make use of this formula. It may be rearranged to give the required source intensity to achieve E_P:

$$I_S = E_P \cdot D^3 / Y \tag{6.8}$$

Now we turn our attention to the elliptical beam pattern formed on the surface. This pattern becomes crucial when we are selectively illuminating a chosen surface from some distance. According to the shape of the surface, it may be necessary to build up coverage of overlapping ellipses using several light sources.

Referring again to Figure 6.3, it can be seen that:

$$q'/2 = D.\ tan(B/2)$$

and unless B is large, in which case the beam flux method described in Section 6.7 is likely to be more suitable, this expression may be approximated to:

$$q' = D.\ tanB \tag{6.9}$$

Note also that $\cos\theta = Y/D$, so that:

$$q'' = q'/\cos\theta = q'.D/Y \tag{6.10}$$

These handy expressions, which enable illumination to be provided onto vertical surfaces evenly and with minimal spill, are summarised on Figure 6.3. Inclined surfaces can also be dealt with by keeping in mind that Y is the dimension on the surface normal at P. For the mathematically agile, an even more versatile approach employing vector algebra is available (Cuttle, 2008).

As the perimeter of the beam pattern ellipse is defined by the contour where luminous intensity drops to half the beam axis value, even coverage of a surface is achieved by butting ellipses up edge to edge. It is reasonable to assume that the average illuminance within an individual ellipse is 75 per cent of the calculated E_P value.

The D/r correction

There is a lingering concern. The *inverse square cosine law* is referred to as the 'point-to-point' formula for a good reason. It is based on the concept of a point source illuminating a point on a surface, and of course, point sources are hypothetical as they have no area. It may be shown that error will be not more than 1 per cent if the distance *D* is at least five times the maximum dimension of the luminaire *d*, and on this basis it is generally recommended that use of 'point-to-point' formulae is restricted to situations where $D > 5d$. In practice, many situations may occur where D will be less than 5d, particularly where there is a need to get in close with the lighting or large, diffusing light sources are being used. For these situations various 'area source' formulae have been published, but they tend to be cumbersome. A more simple solution is to stay with the prediction formulae based on the inverse square cosine law and to apply the *D/r correction*.

Figure 6.4 shows a point P illuminated alternatively by two light sources, both at distance D and normal to the surface at P. S1 is a hypothetical point source, and S2 is a diffusing disc source of radius r and normal to the direction of P. For S1, the illuminance at P is:

$$E_{S1} = I_{S1} / D^2$$

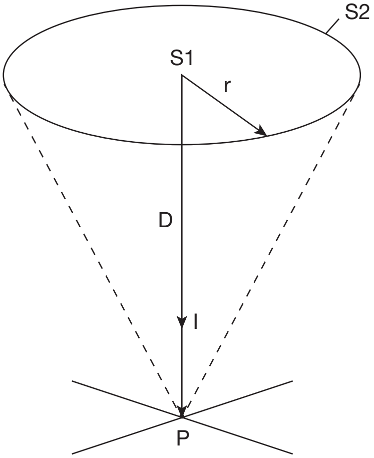

FIGURE 6.4 The point P is illuminated by two alternative sources, S1 being a point source and S2 a luminous disc of radius r. Both sources are at distance D.

For S2, we apply the disc source formula (Simons and Bean, 2001):

$$E_{S2} = M_{S2} \frac{r^2}{D^2 + r^2}$$

where M_{S2} is the exitance of source S2.

For a diffusing source, the luminous intensity normal to the surface equals the luminous flux output divided by π, so that:

$$I_{S2} = \frac{M_{S2} \pi r^2}{\pi} = M_{S2} r^2$$

So:

$$E_{S2} = \frac{I_{S2}}{r^2} \times \frac{r^2}{D^2 + r^2} = \frac{I_{S2}}{D^2 + r^2}$$

If we assume that $I_{S1} = I_{S2}$, and we apply the more simple E_{S1} expression to calculate the illuminance due to an area source, the illuminance value will be overestimated. This could be overcome by applying a (D/r) correction:

$$C_{(D/r)} = \frac{E_{S2}}{E_{S1}} = \frac{I}{D^2 + r^2} \times \frac{D^2}{I}$$

$$= \frac{D^2}{D^2 + r^2} \qquad (6.11)$$

Note that D is the distance S to P, and r is the radius, or half the maximum dimension, of the light source normal to the direction of P.

The value of $C_{(D/r)}$ can be read from Figure 6.5 and applied directly to calculations using Formulae 6.6 or 6.7. It may be noted that the value of D/r needs to reduce to a low value before the correction makes much difference, in fact, the source radius has to approach the distance before the error becomes really significant. Added to that, it may be noted that Formula 6.11 assumes that the light source is a luminous disc of diameter 2r that is normal to the direction of P, and this defines the 'worst case' situation. If a linear source is used instead of a disc source, the $C_{(D/r)}$ correction will overestimate the illuminance reduction by about one-third. The reality is that when we assume a point source we are tending to overestimate illuminance, and when we assume a disc source, we are tending to underestimate. Unless the source is large in relation to the distance, sensible judgment will suffice.

In this way, Formula 6.11 enables simple 'point-to-point' expressions to be applied for a wide range of practical lighting situations, and the $C_{(D/r)}$ correction may be applied with reasonable confidence wherever the aim is to illuminate a two-dimensional surface with a source that is other than small in relation to its distance from the surface. Practical examples might include selected room surfaces, or pictures displayed on them, or freestanding panels, as well as any surfaces for which target/ambient illuminance ratios, TAIRs, have been specified as part of the illumination hierarchy planning.

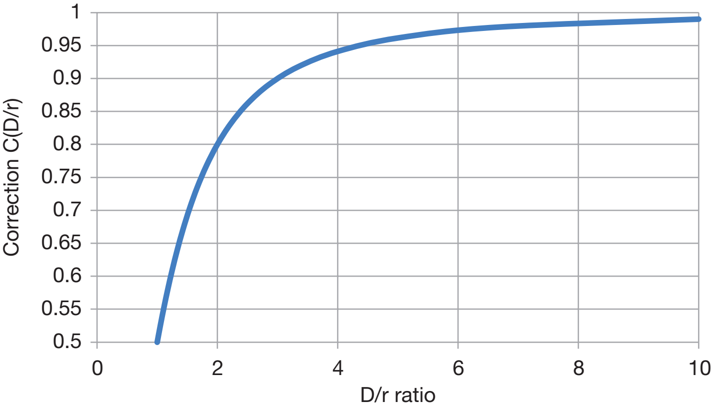

FIGURE 6.5 The correction factor $C_{(D/r)}$ to be applied to point source illumination formulae to allow for the ratio of distance D to source radius r.

It may be noted that the classic 'point-to-point' formula (Formula 6.6) could be restated in a generally applicable form:

$$E_P = \frac{I_S \cdot cos\theta}{D^2 + r^2} \tag{6.12}$$

We will now move on to consider three-dimensional applications of these formulae, where examples are given that deal with both two-dimensional surfaces and three-dimensional objects.

Cubic illumination

The principle of cubic illumination (Cuttle, 1997) is illustrated in Figure 6.6. As has been explained in Chapter 5, the illumination distribution about a point in three-dimensional space, however irregular, may be represented as the sum of two simple distributions. One of these is defined by a vector solid that accounts for the entire asymmetry of the illumination distribution about a point, while the other is a symmetric solid that is, as its name suggests, entirely symmetric about the point. To analyse an illumination distribution into these components, we calculate (or measure) the illuminance values on the six faces of a small cube centred at the point, orientated so that its facets are normal to the x, y and z axes, as shown in Figure 6.6. The x and y axes lie in the horizontal plane and the z axis is vertical, and the six facet illuminance values are designated $E_{(x+)}$, $E_{(x-)}$, $E_{(y+)}$, $E_{(y-)}$, $E_{(z+)}$ and $E_{(z-)}$. If these conventions are adhered to, the procedure for dealing with six illuminances at a point becomes surprisingly painless.

Distances of source S from P on the axes are indicated by X, Y, and Z dimensions which may be positive or negative according to direction, as shown in Figure 6.7. The location of the cube is X = Y = Z = 0, which would be recorded as (0,0,0), and if we refer back to Figure 6.3, it can be seen that if we were to replace the two-dimensional surface shown there with the three-dimensional cube, the location of the light source S would be indicated by (X–, Y–, Z+) dimensions.

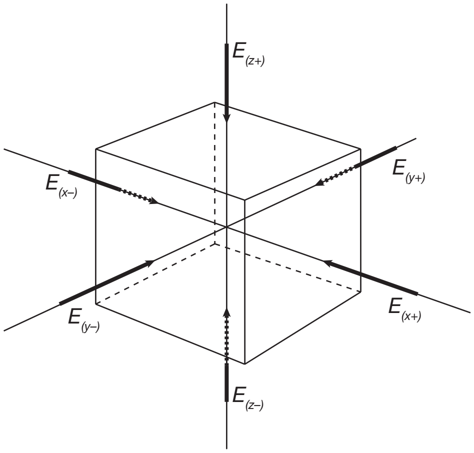

FIGURE 6.6 The Cubic Illumination concept. The spatial distribution of illumination at a point is characterised by six illuminance values on the facets of a cube centred at the point, with the facets aligned normal to the x, y, and z axes. From these six values, the illumination vector magnitude and direction can be defined, and the scalar illuminance can be estimated.

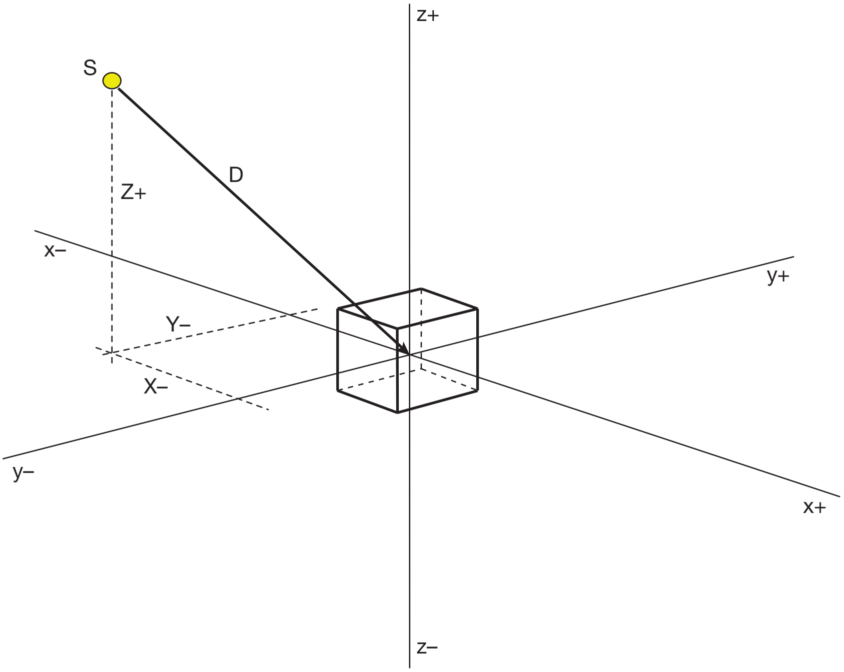

FIGURE 6.7 The location of source S relative to a three-dimensional object is defined in terms of X, Y, and Z dimensions, which may be positive or negative according to direction.

Looking back to Formula 6.7, we can define the cubic illuminance values as:

$$E_{(x)} = X\frac{I}{D^3} \tag{6.13}$$

$$E_{(y)} = Y\frac{I}{D^3} \tag{6.14}$$

$$E_{(z)} = Z\frac{I}{D^3} \tag{6.15}$$

According to the signs of the X, Y, and Z dimensions, the illuminance values may be positive or negative, so that if $E_{(x)}$ has a positive value, that illuminance is incident on the (x+) facet of the cube, and if negative, it is incident on the (x–) facet. It follows that positive and negative $E_{(x)}$ values have to be summed separately, and negative values do not cancel positive ones.

Consider a 50 watt halogen reflector lamp, such as the MR16 EXT, which we will identify as S1, and this source is aimed so that its peak beam candlepower (I_S = 9150 candelas) is directed towards P. The location of S1 relative to P is defined by the dimensions X = –1.9m, Y = –2.7m, and Z = 3.2m. Then:

$$D = \sqrt{((-1.9)^2 + (-2.7)^2 + (3.2)^2)} = 4.6\text{m}$$

and

$$I_S/D^3 = 9150/(4.6)^3 = 94.1$$

Then from formulae (6.13–6.15):

$$E_{(x)} = X\ (I/D^3) = -1.9 \times 94.1 = -179 \text{ lux}$$
$$E_{(y)} = Y\ (I/D^3) = -2.7 \times 94.1 = -254 \text{ lux}$$
$$E_{(z)} = Z\ (I/D^3) = 3.2 \times 94.1 = 301 \text{ lux}$$

Yes, it really is as simple as that: no angles, no cosines and three illuminance values for the price of one. However, it is necessary to keep an eye on those signs. Note that $E_{(x)}$ = –179 lux is simply another way of writing $E_{(x-)}$ = 179 lux. As we add the contributions from different sources on each facet of the cube, we add separately the sums of $E_{(x+)}$ values and $E_{(x-)}$ values, as they are the illuminances on opposite sides of the cube.

This example shows the underlying process for determining the six direct cubic illuminance values, but for practical calculations we again utilise the facilities of a spreadsheet. Box 6.1 shows the output of the Cubic Illumination spreadsheet, and as previously, the only data to be entered by the user are those in red, as all other data are calculated automatically. In the box, source S1 from the foregoing example is shown, and three more sources have been added. Rather than have a separate spreadsheet for two-dimensional surfaces, it is more simple to use this spreadsheet and to keep in mind that, following the view direction convention shown in Figure 6.3, the $E_{(y-)}$ value gives the surface illuminance.

BOX 6.1

CUBIC ILLUMINATION SPREADSHEET

140121

Project: Box 6.1

MRSE 150 lm/m^2

Source	Is (cd)	X+	X-	Y+	Y–	Z+	Z–
		Distances S-P					
S1	9150	0	1.9	0	2.7	3.2	
S2	6200	0	4.1	1.9		2.8	
S3	5800	3.2			1.7		0.8
S4	7220	0	2.6		0.9	3.4	
S5		1					
S6		1					

Source	D	I/D^3	E(x+)	E(x–)	E(y+)	E(y–)	E(z+)	E(z–)
S1	4.5	94.1	0	178.8	0	254.1	301.2	0
S2	5.3	41.2	0	169.2	78.4	0	115.5	0
S3	3.7	113.5	363.2	0	0	192.9	0	90.8
S4	4.3	86.2	0	224.3	0	77.6	293.3	0
S5	1	0	0	0	0	0	0	0
S6	1	0	0	0	0	0	0	0
	Total E^3 values		513.2	722.4	228.4	674.7	860.1	240.8

Vector components		**Symmetric components**			
Evr(x)	–209.2	Esym(x)	513.2	Evr	791.6
Evr(y)	–446.3	Esym(y)	228.4	Esym	327.4
Evr(z)	619.3	Esym(z)	240.8	Esr	525.3
				Esr(d)	375.3

Vector/scalar ratio		**Unit vector components**		**Vector direction**
Evr/Esr	1.51	e(x)	-0.264	α 51°
		e(y)	-0.564	
		e(z)	0.782	

Notes

Enter data only in cells shown in red.

Is = luminous intensity of S in direction of P.

MRSE is the design level of ambient illumination within the space.

Check Distances S-P: either a '+' or a '–' dimension; never both.

For a typical outdoor application it would be necessary to consider only the direct illuminance values on the six faces of the cube, but otherwise, the effect of ambient illumination needs to be included. As shown in Box 6.1, the user specifies the MRSE value to be provided within the space by the entire lighting installation. Each of the six cubic illuminance values will be the sum of direct and indirect values, and the MRSE value is added to each direct cubic illuminance value to represent the effect of indirect light. This assumes that the contribution of indirect light is uniform for all six facets, and while this avoids the tedious process of making a precise evaluation of the indirect illuminance onto each facet of the cube, some caution needs to be observed. For a situation where the distribution of reflected flux is likely to be distinctly asymmetric, such as where an object is located close to a dark wall surface, this simplification could lead to a misleading outcome, and users need to be alert for this. Even so, the assumption is not unreasonable. In an indoor space where the proportion of indirect illumination is low, it will have little visible effect and so it would be a waste of time to evaluate its spatial distribution. Where the proportion of indirect light is high, it is likely to be highly diffused by multiple reflections from light-coloured room surfaces so that its contribution to the visible effect will be to soften the directional effect of the direct light rather than to impart a distinct directional effect. The user should be alert for situations where indirect light could be both dominant and directional, and for a more rigorous treatment of indirect illuminance, see Simons and Bean (2001).

The reason for predicting, or measuring, the cubic illuminance values is to enable vector analysis of the illumination solid, and the Cubic Illumination spreadsheet performs the analysis to produce Box 6.1 by applying the formulae given in the previous section. The great benefit of using spreadsheets is not simply that they automate the calculations, but that they enable the user to explore alternative options, and the reader is strongly encouraged to access the spreadsheet and to experience how this is done. It is simple to change a light source, or to move it from one location to another, and instantly the effects on the vector/scalar ratio (VSR) and the vector direction are given, so that the user can envisage how an arrangement of luminaires will influence the 'flow' of light, and how this might affect the perception of a selected three-dimensional object.

Providing an illumination hierarchy

An illumination hierarchy expresses a lighting designer's concept for the overall appearance of a lit space. It specifies the ambient illumination level as a mean room surface exitance (MRSE) value, and it expresses how the distribution of direct flux from the luminaires will affect the relative appearances of specified targets in terms of a distribution of target/ambient illuminance ratios (TAIR) values.

The effect of ambient illumination upon the impression of the brightness or dimness of illumination within a space is at least as much determined by the MRSE level in adjacent spaces as by the actual level within the space, and both Tables 2.1 and 2.2 need to be considered for making a design decision. As described in Chapters 2 and 3, Table 2.2. is used also for making decisions about TAIR values, and it can be seen that for target illumination to be even noticeable, a TAIR value of at least 1.5 is necessary, with higher levels needed to achieve distinct or strong effects. Emphatic differences can be difficult to achieve, as unless very high target illuminance values are to be used, they call for distinctly low levels of MRSE.

A schedule of direct illuminance levels to be provided onto each selected target can be generated from the MRSE and TAIR values:

$$E_{tgt(d)} = MRSE\ (TAIR_{tgt} - 1) \tag{6.16}$$

The sum of individual target FRF values gives the total first reflected flux due to direct illumination of all target surfaces:

$$FRF_{ts} = \sum E_{tgt(d)} \cdot A_{tgt} \cdot \rho_{tgt} \tag{6.17}$$

For two-dimensional targets, $E_{tgt(d)}$ is the average direct illuminance, and for three-dimensional targets, the best guide is the direct component of the scalar illuminance, where $E_{sr(d)} = E_{sr} - MRSE$. This value can be read from the Cubic Illumination spreadsheet (Box 6.1).

The level of first reflected flux (FRF) that is required to provide the design value of ambient illumination, specified in terms of MRSE, comprises the sum of components due to direct light reflected from target surfaces (FRF_{ts}) and from room surfaces (FRF_{rs}):

$$FRF = FRF_{ts} + FRF_{rs} \tag{6.18}$$

Refer back to Boxes 3.1 and 3.2 and note the distinction that was made between first reflected flux due to illumination directed onto target surfaces with the aim of establishing an illumination hierarchy, and first reflected flux that was then required to bring the ambient illumination up to the MRSE design value. While targets need significant levels of selective illumination directed onto them in order to achieve appreciable differences of appearances, for providing illumination onto other surfaces to bring up the MRSE level, the aim should be to keep the $E_{tgt(d)}$/MRSE well below 3.0, and preferably below 1.5 (although this can be difficult), so that the flux directed onto these surfaces will not noticeably detract from the illumination hierarchy.

From Formula 6.16, it follows that $FRF_{rs} = FRF - FRF_{ts}$, and to provide this both efficiently and with low $E_{tgt(d)}$/MRSE will need one or more large, high-reflectance room surfaces to receive direct flux. The ceiling is often the obvious choice, but other options should be sought. A series of illuminated white ceilings can have a bland overall effect.

Before looking further at calculational procedures, it should be acknowledged that a very effective way to explore design options for providing FRF_{rs} is to use a proprietary lighting design software package such as AGI32 or DIALUX. The trick is to set all surface reflectance values to zero, so the program gives you direct surface illuminance values. These packages usually give serious attention to working plane (or floor) uniformity and provide precise-looking illuminance contours, while giving only average illuminance values for walls and ceiling, so it pays to give attention to how the appearance of these surfaces may be affected by luminaire spacing. However, used in this way, these packages can provide a useful design facility.

Lighting techniques such as cove lighting onto ceilings, wallwashing and recessed lighting onto floor planes are widely used for providing room surface illumination, but do not overlook opportunities for suspended (and visible) pendant luminaires, or incorporating lighting into furniture or handrails. Whatever lighting technique is employed, selection of suitable luminaires involves careful examination of the angular relationships between the source locations and the receiving surfaces. Where multiple sources are to be used, choose sources with beam angles that are smaller than the subtence angle of the receiving surface, but large enough to provide full coverage from overlapping beams. The number of luminaires required is:

$$n = FRF_{rs} / (F_B \cdot \rho_S) \tag{6.19}$$

where F_B is the 'beam flux', or the quantity of lumens within the beam(s).

Manufacturer's data for lumen outputs of directional luminaires have to be examined with care. The only lumens that count are those within the beam, as those outside the beam are 'spill' and need to be blocked or shielded. For luminaires with conical beams (i.e., not shaped beams as in wallwashers) it is generally recognised that beam width is measured to the direction in which the luminous intensity falls to 50 per cent of the maximum value (Figure 6.3), and usually the quoted angle is whole angle from edge to edge of the beam, although sometimes it is the half-beam angle, measured from the beam axis to the edge. For this text, the whole beam angle is given the symbol B, and the half-beam angle is b.

Because it is not always clear whether 'lumen output' data refer to the entire output of the luminaire or just the beam lumens, the most reliable way of determining the value is to work from data for the luminous intensity distribution, given in candelas. The beam flux, in lumens, is given by:

$$F_B = 1.5 I_{max} \cdot \pi(1 - \cos b) LD \tag{6.20}$$

here:

I_{max} = maximum beam luminous intensity, or CBCP, in candelas
b = half beam angle
LD = lumen depreciation factor

Consider the MR16 EXN halogen lamp, which has a beam angle of 36° and a CBCP of 1800cd. Allowing for a lumen depreciation of 0.8, $F_B = 1.5 \times 1800 \times \pi(1 - \cos(18^\circ)) \times 0.8 = 332$ lm. It should not escape notice that the luminous efficacy for beam lumens for this lamp is just 6.6 lm/W, and that is not allowing for transformer losses. It is clear that even with the precision focussing that these lamps achieve, a significant proportion of the filament lumens do not find their way into the beam. This 'spill' light is not only a concern from the point of efficiency, but also for achieving a controlled distribution of light. Reflector lamps should always be housed in luminaires that are shrouded or have baffles or louvres to intercept light spill. This becomes particularly important where spill onto surfaces adjacent to the luminaires could produce very bright unwanted lighting patterns.

It is in this way that a layout of luminaires is developed that will deliver the required quantity of lumens onto each selected room surface. The designer's aim is to devise a flux distribution that will provide the first reflected flux for the required ambient illumination, together with the range of TAIR values that will achieve the envisaged illumination hierarchy.

Daylight illumination

Lighting designers may, from time to time, become involved in fenestration design for special applications, such as the windows for an observation tower or a picture gallery skylight, but regrettably, it is much more usual practice (in this author's experience) that by the time a project is introduced to a lighting designer, others have determined the layout of windows, clerestories and skylights, as well as the type of glazing, sunshading and blinds to be installed. In case some readers should find themselves confronted with demands for advice that differ from my experience, it may be noted that there is no shortage of books on daylighting practice written for architects. However, this section is based on the assumption that the lighting designer's task is restricted to devising electric lighting installations that may from time to time need to respond to significant presence of daylight.

The principal means for assessing the performance of a daylighting installation has for many years been the *daylight factor*, and despite a fair amount of recent activity aimed at improving the modelling of outdoor daylight availability, the daylight factor continues to be concerned with provision of illumination onto indoor horizontal working planes (HWPs). In this section, a quite different approach is proposed. Every indoor space needs to have an electric lighting installation. Where there is significant daylight admission, the appearance of that space and its contents will be affected at different times and in different ways, and a lighting designer needs to give thought to how the electric lighting installation is to respond to the presence of daylight. This is to take account of both achieving what may be perceived to be an appropriate balance of illumination at all times, while at the same time gaining energy savings from reduced use of electric lighting.

Opportunities for either of these objectives vary hugely, and some elaborate evaluation systems have been proposed. Taking a simple approach, fenestration systems can be broadly categorised as side windows, clerestories, or skylights – or some combinations of those types. Their impacts upon lighting design may be assessed in terms of the contributions they make towards provision of ambient illumination, target illumination, view-out and energy efficiency (Figure 6.8).

Skylights can provide very effectively for ambient illumination, as well as providing for HWP illumination. As has been discussed, ambient illumination, indicated by the MRSE level, is concerned with how inter-reflected light influences the appearance of surrounding room surfaces, whereas the daylight factor is concerned with enabling effective performance of visual tasks located on desktops or work benches. Skylights that are designed so that sloped glazing is orientated in the polar direction (north-facing in northern hemisphere; south-facing in southern hemisphere) can provide fairly consistent, diffused, ambient illumination over much of the year, and this should be taken into

	Side windows	Clerestories	Skylights
Ambient illumination	★	★★	★★★
Target illumination	★★	★	
View-out	★★★	★	
Energy efficiency	★	★★	★★★

★★★	Good prospects
★★	Moderate prospects
★	Limited prospects

FIGURE 6.8 Assessment of likely prospects for various roles for fenestration in buildings.

account in developing an electric lighting installation to provide room surface illumination out of normal daylight hours. The daytime and night time illumination distributions may be quite different, requiring careful thought about the transitions between these two conditions. Progressive photoelectrical control is likely to be the option of choice, and for large area, single-storey buildings, the prospects for doing this effectively and attractively by daylight are good (Figure 6.8). By comparison, successful provision of ambient illumination by clerestory windows is restricted to spaces having fairly high height/width proportions, and more limited still, are side windows. This is not to imply that they are necessarily ineffective, but rather that their use for providing useful ambient illumination is more restricted, particularly where they occur only in one wall. It is common experience that windows in one wall can provide all the illumination required for much of the time in spaces of domestic scale, but that becomes uncertain in spaces where the room width is more than double the height of the window head.

Effective target illumination favours electric lighting as the reliable means for setting up an illumination hierarchy, but nonetheless, nothing can compare with the impact created when side windows enable an object, such as a sculpture, to be positioned to ‘catch the light’ as discussed in Chapter 5. It is, perhaps, the obviously transitory nature of the experience that adds to its appeal. To design fenestration specifically for the purpose of providing target illumination raises the issue of how to integrate that illumination with electric lighting to take over when daylight is inadequate. Where the circumstances are seen to demand it, careful attention to achieving effective target illumination by daylight can be very rewarding, but otherwise it needs to be recognised that the ever-changing nature of daylight makes it a difficult source to use where the appearance of a specific target forms an important component of the designer's overall concept.

The suitability of side windows for providing view-out might seem to be too obvious to warrant discussion, but in fact, misdirected thinking on this issue is so common that it really does need some careful attention. Most surveys of building occupant satisfaction have been conducted on office workers, and again and again, they report daylight as being a highly rated option, and this has been translated into standards demanding that specified minimum daylight factor values are provided over some specified percentage of the HWP. The well-known fact that, in open plan offices, desks that are located close to windows are regarded as prime locations, despite their much lower ratings on thermal comfort indices, is widely accepted as confirmation of this preference. However, rethinking the basis of this preference in terms of provision of view is likely to lead to distinctly different design options. Side windows designed for view-out combined with reasonably high levels of thermal comfort would be quite different from windows designed to maximise daylight admission. In particular, they would be likely to incorporate sunshading devices, fixed or adjustable, specifically designed for the orientation of the window, and which would intercept sunlight with minimal obstruction of view-out.

So far, little attention has been given to energy efficiency, although this topic is discussed in the final chapter. It should not be a matter of surprise that prospects for energy efficiency are shown in Figure 6.8 to be in step with daylight provision of ambient illumination. This is because daylighting systems that have good prospects for ambient illumination are likely to also have good prospects for photoelectric control that will balance electric light use against daylight availability. The essential difference from common practice is how photosensors are located and commissioned. Sensors need to respond to levels of inter-reflected light within the space, and so they need to be shielded from direct light from both the daylighting and the electric lighting systems. For example, in a space with side windows, a good location for a sensor is mounted vertically on the wall above the window head, and shielded from direct light from the electric lighting installation so that it is exposed to reflected light within the room, but not to direct light. This is quite different from conventional practice, which is directed by the notion that the purpose for admitting daylight into buildings is to provide working plane illumination. The role that daylight can fulfil best of all is providing ambient illumination.

It may be noted that where the foregoing procedures have led to an electric lighting installation that provides, out of daylight hours, an effective illumination hierarchy through a combination of target and room surface illumination, the prospect exists for effective lighting control by dimming just the room surface illumination. In this way, an effective daytime balance of ambient illumination with a maintained illumination hierarchy may be achieved with worthwhile energy savings.

Checking delivery: measuring the lumens

The on-site measurable illumination quantities that are integral to this perception-based approach to lighting design are:

- mean room surface exitance, MRSE
- target/ambient illuminance ratio, TAIR
- vector/scalar ratio, VSR, and vector direction.

While highlight contrast potential (HCP) has also been introduced as a relevant metric, its usefulness is for making comparisons at the design stage, rather than as a metric to be checked on site. Also, at the time of writing, there are no generally available meters for checking metrics relating to the spectral distributions of illumination, but this may be about to change. CCD-based spectrometers have recently become reasonably affordable, and this could lead to the availability of portable instruments capable of making on-site measurements of many of the visible and non-visible factors discussed in Chapter 4.

It is an essential part of acting as a professional lighting designer that the performance of every installation is checked against the predicted performance, regardless of whether the client has shown interest in the data. There never will be a perfect match, but knowing the nature and extent of the departures is how a designer gains feeling for exercising control over perceived aspects of illumination.

Measuring MRSE

While MRSE is reasonably straightforward to calculate, it is not obvious how to obtain a reliable measure of its quantity. Conventional light meters have been developed to give measurements of lumen density incident on a surface, without regard for the direction from which the light is incident. MRSE is not related to any particular surface of incidence, and it discriminates according to the origin of arriving light. It takes account only of indirect light, and disregards light arriving directly from light sources, and this creates a difficulty for measurement.

The purpose of MRSE is to provide us with a useful measure of ambient illumination, and that means that we need to make a measurement that relates to light arriving at the eye, rather than light incident on things that people might choose to look at. Figure 6.9 shows a simple approach. Choose a position and direction of view that, while it takes in much of the space, avoids light from windows, table lights and so forth, and then hold a luxmeter up to the eye and shield it from any luminaires before taking a measurement. Depending on the size of the space, repeat this for other positions to obtain an average value. Making measurements in this way can provide a reasonable indication of the extent to which a predicted MRSE value has been realised, and this is valuable information for the designer.

Proposals have been made for more rigorous procedures for MRSE measurement (Cuttle, 2013). This approach involves using high dynamic range imaging to produce a

FIGURE 6.9 A simple way of making an approximate measurement of MRSE using a conventional light meter. Expose the meter to a wide view of the space avoiding, as far as possible, windows and other light sources, and shield direct light from any overhead luminaires.

wide-field image of a space defined in terms of luminance. Light sources could then be identified and excluded, so that the remaining field of view would represent the total inter-reflected illumination. It is to be hoped that such a system will one day become available, particularly as it could enable not only measurement of MRSE, but also of discomfort glare.

Measuring TAIR

The next step in evaluation will be to check TAIR values. Once again, the designer will have explained the illumination hierarchy in terms of perceived difference, and will have planned the luminaire layout to achieve specified TAIR values. Checking by measurement develops confidence in relating appearance to metrics, as well as application of metrics for determining required luminaire performance.

For a two-dimensional target, TAIR = E_{tgt}/MRSE, which is quite straightforward, but measuring E_{tgt} for three-dimensional targets can pose difficulties. If practical, it is usually best to move the target to one side and to measure the cubic illumination at the spot, using the procedure described in the following paragraphs, from which the direct component of scalar illuminance is determined by use of the Vector Measurement spreadsheet, which is described in the following paragraphs. Otherwise, measurements corresponding to the cubic illumination axes may be taken over the object's surface, but it should be noted that if a particular direction of view is significant in the overall appearance of that object within the space, then a single measurement normal to that direction might provide for a better indicator of how well the TAIR value relates to the illumination hierarchy.

Measuring VSR

It might seem that the most straightforward way to measure the six cubic illuminance values would be to mount a small cube at the measurement point and take successive readings on the cube's facets, but in fact, this procedure is cumbersome and tedious, particularly when it comes to taking the measurement on the downward facing facet. Various cubic illumination meters incorporating six photocells have been developed, such as the one shown in Figure 6.10, but it is worth taking note of a simple procedure that makes use of just one photocell mounted on a photographic tripod (Cuttle, 2014).

Envisage the cube tilted, as indicated in Figure 6.11, so that a long corner-to-corner diagonal of the cube is vertical, and three facets of the cube face upwards and three downwards. The familiar *x, y, z* spatial axes are unchanged, but now the axes of the cube are designated *u,v,w*. Figure 6.12 shows a vertical section through the tilted cube on the *y* axis, where BC is one external edge of the cube, AB is a facet diagonal and AC is the vertical long diagonal. The ratios of the triangle sides BC, AB and AC are 1, √2, and √3, and the angle a = a′ = $\sin^{-1} 1/\sqrt{3}$ = 35.3°. This is the angle by which the *u, v* and *w* axes are tilted relative to the horizontal plane, and as shown in Figure 6.11, the *u* axis is assumed to lie in the same vertical plane as the *y* axis.

To make the cubic illumination measurements, a right-angle bracket is constructed to support the photocell vertically on the head of a photographic tripod, as shown in Figure 6.13. It helps to have a tripod with a spirit level to ensure verticality and with the horizontal and vertical movements scaled in degrees. The measurement procedure is then straightforward. Set the photocell tilt to +35° as shown in Figure 6.14, and rotating the horizontal movement of the tripod, read $E_{(u+)}$ at 0°, $E_{(v+)}$ at 120° and $E_{(w+)}$ at 240°. Reset the photocell tilt to –35°, and read $E_{(u-)}$ at 180°, $E_{(v-)}$ at 300° and $E_{(w-)}$ at 60°.

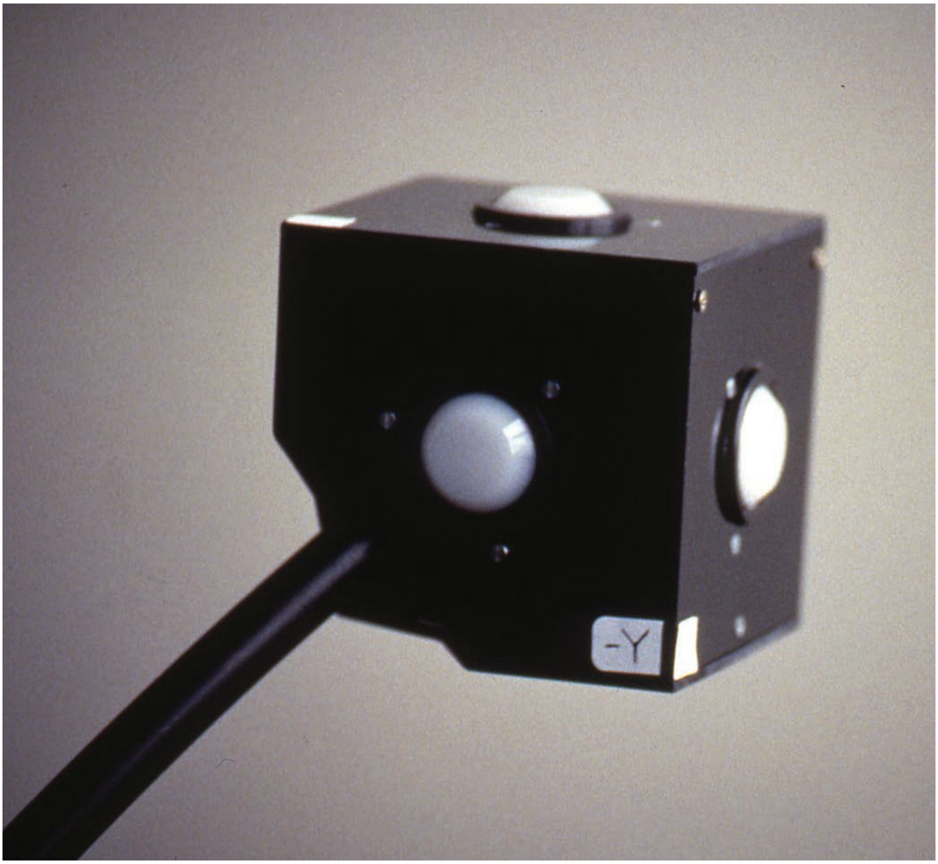

FIGURE 6.10 A six-photocell cubic illumination meter. This instrument is self-levelling and is connected to a laptop computer that automatically analyses the data. Photographed at the Lighting Research Center, Rensselaer Polytechnic Institute, Troy, New York.

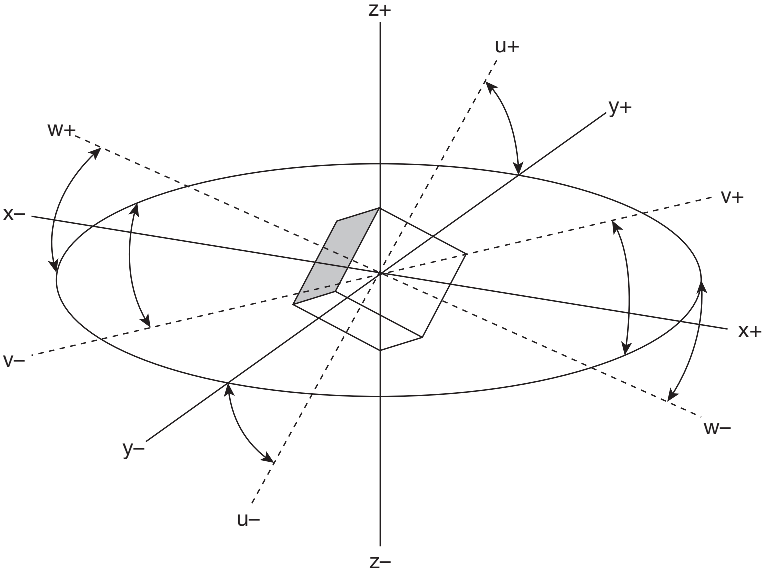

FIGURE 6.11 The measurement cube is tilted so that a long axis is coincident with the z axis, and three facets face upwards and three downwards. The facets are normal to the u, v, and w orthogonal axes.

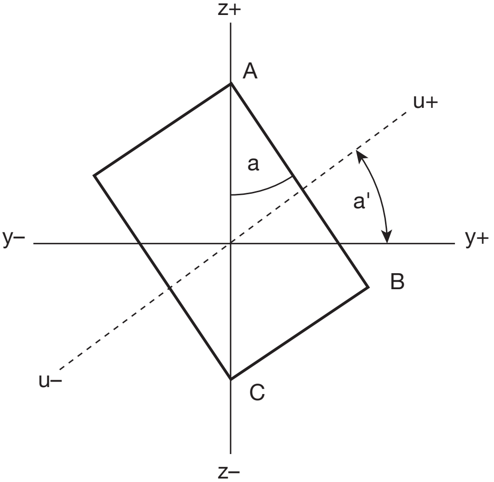

FIGURE 6.12 A vertical section through the tilted cube on the u axis, which lies in the same vertical plane as the y axis, against which it is tilted through the angle a.

FIGURE 6.13 A photocell head mounted on a right-angle bracket, onto a photographic tripod.

FIGURE 6.14 The photocell tilted to +35° relative to the horizontal plane, and ready for measuring the three-dimensional illumination distribution.

Box 6.2 shows the output of the Vector Measurement Spreadsheet. The only data to be entered by the user are the six measured values, and from these a range of derived data relating to the spatial illumination distribution is given based on formulae given in Chapter 5. While the illumination vector magnitude is derived directly from the measured data, the output data for vector direction are converted from *u, v, w* axes to the more familiar *x, y, z* axes, using the following formulae:

$$\boldsymbol{e}_{(x)} = 0.707(\boldsymbol{e}_{(v)} - \boldsymbol{e}_{(w)}) \tag{6.21}$$

$$\boldsymbol{e}_{(y)} = 0.816\boldsymbol{e}_{(u)} - 0.408(\boldsymbol{e}_{(v)} + \boldsymbol{e}_{(w)}) \tag{6.22}$$

$$\boldsymbol{e}_{(z)} = 0.577(\boldsymbol{e}_{(u)} + \boldsymbol{e}_{(v)} + \boldsymbol{e}_{(w)}) \tag{6.23}$$

While there are other lighting quantities that are relevant to the design process, such as correlated colour temperature and the highlight contrast, application of these concepts need not involve calculations and so confirmation by measurement is not usual practice. Nonetheless, when designers are verifying that all is according to expectations, it is necessary that every aspect of interaction between the lighting installation and the space and its contents must come under scrutiny.

BOX 6.2

CUBIC ILLUMINATION MEASUREMENT (u,v,w)

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Project	Box 6.2		
Illuminance data input			
E(u+)	109	E(u-)	311
E(v+)	365	E(v-)	305
E(w+)	342	E(w-)	70
Illuminance components			
E(u)	-202	~E(u)	109
E(v)	60	~E(v)	305
E(w)	272	~E(w)	70
Vector and scalar data			
E	344	~E	161
Esr	247	E/Esr	1.39
Horizontal and cylindrical data			
Ewp	236		
Ecl	268	Ecl/Ewp	1.13
Vector direction (unit vector)			
e(u)	–0.587	**e**(x)	–0.436
e(v)	0.174	**e**(y)	–0.873
e(w)	0.791	**e**(z)	0.218
e(u,v,w)	1	**e**(x,y,z)	0.999
Vector direction (altitude and azimuth angles)			
e(x,y)	0.975	alpha	12.7
e′(y)	–0.895	phi	–154.7

Notes

Input data shown in red only. All the rest are generated automatically.

alpha (vector altitude) may be +ive or -ive re horizontal

If phi (vector azimuth) = +ive then anticlockwise re y- axis; else clockwise

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7

DESIGNING FOR PERCEPTION-BASED LIGHTING CONCEPTS

Chapter summary

The development of a lighting design proposal involves bringing together the variety of perception-based lighting concepts into a balance that relates to the design objectives specific to the location. It requires the ability to envision a space and its contents in light, and seen in this way, the volume of the design space ceases to be a void, and instead is perceived as a three-dimensional light field creating interactions with room surfaces and the objects within the space. It is from this envisioned concept that the designer develops understanding of the required characteristics of the light field, leading to the layout of luminaires and light sources, together with strategies for their control. A flowchart linking the lighting concepts to metrics and procedures is introduced. Where the procedures involve calculations, their purpose is seen to be to increase the designer's level of confidence that the design objectives, stated in terms of perception-based concepts, will be achieved. The design outcome is a comprehensive lighting equipment specification.

Achieving perception-based lighting concepts

We now turn our attention to the task of applying the range of perception-based lighting concepts that has been discussed in the foregoing chapters. Each and every project is a fresh challenge that calls for understanding of the various roles that the space and its contents are planned to serve, backed up by the designer's creative imagination directed towards influencing people's perceptions of the space, its setting, and its contents through lighting.

Seen in this context, the lighting concepts provide a framework for ordering thinking about lighting's potential for influencing people's visual experiences of their surroundings. These range from overall impressions of brightness or dimness of spaces encountered in a sequence of entering and passing through a building; the ways in which the spectrum of light may arouse or subdue both visual and non-visual responses; through to ordered distributions of illumination that differentiate activities within spaces and which relate to the visual significance of objects; and on to the lighting patterns that reveal the form, texture, glossiness, or translucency of individual objects. Within the volume of a space, illumination may, at one extreme, be softly diffused, revealing everything without emphasis; and at the other extreme, be selective and sharply directional, differentiating surfaces and objects with clarity. As part of the same visualisation, lighting may on one hand be perceived as being without apparent source, or on the other hand, sources of light may be clearly expressed components of the scene. This is the gamut of variety (or at least a good part of it!) that a creative designer may bring to bear upon a project, and the perception-based lighting concepts provide means for both ordering creative thinking and exercising control.

While design is not to be reduced to a step-by-step procedure, the flowchart shown in Figure 7.1 presents a rational ordering of the lighting concepts and gives an overall guide to this section.

Ambient illumination

Is the first impression to be of a brightly lit space, or a dimly lit space, or something in between? This issue has been discussed in the sections in Chapter 2 entitled 'The MRSE conecpt' and 'Applying the ambient illumination concept in design', and it requires careful thought. A person visiting the space will inevitably experience it within a sequence, arriving from outdoors or from another indoor space, before moving on. It may be their destination, or a space that they will experience in passing. Perhaps the design aim is to arouse attention, or alternatively, to provide a place for rest. The possibilities are limitless, as are the roles that lighting may play, but throughout, the connection between the overall sense of brightness and the first impression is strong. Tables 2.1 and 2.2 together provide a simple introduction to ambient illumination, but it is up to the designer to develop sensitivity to the relationships that may arise.

While MRSE (mean room surface exitance) may be an unfamiliar concept, it is surprisingly easy and rewarding to come to terms with. The notions of visualising light within the volume of a space rather than incident on surfaces, and of thinking in terms of light at the eye, so that we achieve our aims through providing reflected light, and direct light is simply a means to achieving that end, lead naturally to effective lighting applications. The Ambient Illumination spreadsheet is a useful tool for the first stage of linking a vision to a luminaire layout.

Illumination colour appearance

Apart from the brightness or dimness of ambient illumination, its colour appearance can significantly affect the appearance of a space. Illumination that is basically 'white' may nonetheless have a distinct tint, and the acceptability, or even the attractiveness, of that tint, can be strongly affected by context and people's expectations.

As has been explained, the generally accepted practice is to specify the tint of 'white' illumination by CCT (correlated colour temperature) where low values (CCT < 3200K) are associated with yellowish-white light and 'warm' colour appearance, and high values

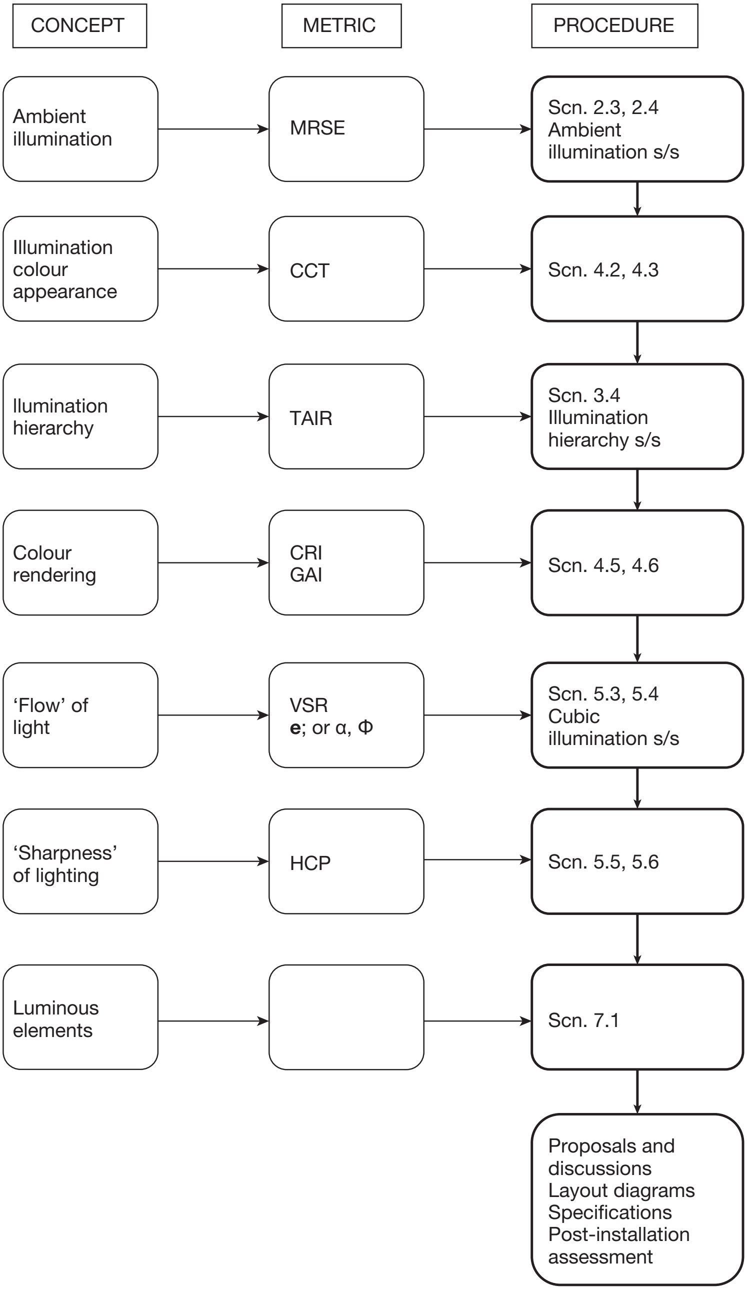

FIGURE 7.1 A lighting design flowchart. Follow through each row from concept, to metric, to procedure. The sequence of concepts is proposed as being logical, but may be adapted to suit circumstances. The aim is to develop proposals for discussion, which would lead to the design proposal. Post-installation assessment and measurement should also be included as part of the design process.

(CCT > 5000K) with bluish-white light and 'cool' colour appearance. At present, this is the choice that the lighting industry offers, but research findings have been noted (page 46) which indicate that light source chromaticities departing from the black-body locus may offer preferred colour appearance alternatives.

Illumination hierarchy

Situations occur where totally diffused illumination that reveals without emphasis can be highly effective, but more usually some ordering of illumination distribution is called for. There may be various reasons for this. The aim may be to distinguish between zones within a space; it may be to increase the visibility of selected detail; or it may be to draw attention to objects of visual significance. The ability to envision a structured distribution of illumination is a defining skill of a lighting designer, but it needs to be understood that while the envisioned effect is a distribution of reflected flux, it is achieved by providing a distribution of direct flux onto selected targets that will generate that distribution. This ability to separate in the mind the applied distribution of direct flux and the resulting distribution of reflected flux is crucial. It is an acquired skill that evolves from careful observation of how appearance is affected by the balance of direct flux applied to targets, and of diffusely-reflected ambient illumination.

The notion of an illumination hierarchy, by which the lighting designer's concept of emphasis forms the basis of a structured illumination distribution, is set out in terms of TAIR (target/ambient illumination ratio). The Illumination Hierarchy spreadsheet is a useful tool for seeing through this stage of the procedure.

Colour rendering

CRI (colour rendering index) is the readily available metric, and its limitations have been discussed at some length. CRI serves the needs of specifiers, but designers need more. The GAI (gamut area index) adds an indication of colourfulness to that of fidelity, but too often the values on this scale are unavailable. Really useful information, such as CMV (colour-mismatch vector) data, is unlikely to be available, so that designers need to develop through directed observation, as described in the section 'Source spectrum and human responses' in Chapter 4, the experience to be able to select light sources with colour rendering properties that really suit particular applications.

The 'flow' of light

The directional properties of a light field that generate shading patterns through interactions with three-dimensional objects provide a dynamic quality to the appearance of a space. This aspect of lighting is particularly associated with spaces lit by side windows, and where daylight creates strong 'flow' of light effects, careful consideration needs to be given to how the electric lighting is to respond to the varying shading patterns. Distinct shading patterns on individual objects are easily produced by spotlights, but the 'flow' of light concept refers to a lighting effect that creates a coherent sense of illumination distribution within a space.

The VSR (vector/scalar ratio) relates to the perceived strength of the 'flow', and the direction of 'flow' may be indicated by the unit vector **e**, or by the vector altitude and azimuth angles.

The 'sharpness' of lighting

The potential for lighting to generate highlight patterns on glossy-surfaced three-dimensional objects is indicated by the HCP (highlight contrast potential), which also relates to the perceived 'sharpness' of shadow patterns and the overall appearance of the 'crispness' of lighting.

Luminous elements

This is the only one of the concepts listed in Figure 7.1 that has not been discussed in the text, but it is in fact the easiest of all the concepts to come to terms with. Often it would be true to say that, for lighting designers, the perfect luminaire would be invisible. As it is, designers often strive to eliminate as far as possible any visible intrusion of luminaires into the scenes that they create. Luminaires are recessed into ceilings, tucked above shelves or cornices, or built-in under furniture or handrails. They are, for the most part, regarded as necessary but unwelcome intrusions into the scene.

There are, however, times when the luminaires become features of the design concept. There can be all sorts of reasons for this, but a recurring one is that the space is bland and featureless, and would benefit from the presence of self-luminous, eye-catching objects that add 'sparkle' and interest to the scene. There are no metrics for assessing the perceived effect nor are there procedural steps for incorporating these elements into the design, but when the decision is made that luminous elements are to be part of the scene, it is as well to keep in mind the well-worn adage, "One man's sparkle is another man's glare".

The design product

The spreadsheets that have been used to generate the Boxes shown alongside the text facilitate the translation from envisioned effects to luminaire performance not only by performing the calculations, but by providing the designer with almost unlimited opportunity to explore alternative options. Designers are encouraged to use them as models to develop spreadsheets that serve their own fields of lighting practice. Commercially available 'lighting design' software packages generally fail to address the issues that concern a creative designer.

While most people think of a lighting designer's output being the illumination that users will experience, the realities of life should cause the designer to take a different attitude. It is the specification document, listing lamps, luminaires, circuits and controls, that determines whether or not his or her vision of a space in light will be achieved, and for this reason, the specification should be regarded as the design product. It has been stated above that the ability to envision is the essential design skill, but the ability to translate that vision into a specification document that will not be compromised runs it a close second. Never lose sight of the fact that when the specification goes out to tender, the contractor who will get the job will be the one that puts in the lowest price.

Defining illumination adequacy

While this ‘perception-based approach’ to lighting design is proposed as being appropriate for indoor lighting applications ranging from simple, everyday activities to complex, large-scale projects, it cannot be denied that there will always be some situations for which it would be quite sensible to provide uniform illumination over the time-honoured horizontal working plane, *wp*, which extends wall-to-wall and may be coincident with the floor plane, or elevated above it.

This type of lighting practice is sometimes referred to as ‘lumen dumping’, and the conventions adopted by lumen dumpers for planning their lighting installations include treating every space as a rectangular room measuring $L \times W$, with the lighting installation comprising a regular grid of luminaires located on the luminaire plane, *lp*, which may be coincident with the ceiling or below it, and with only the wall height *H* between *lp* and *wp* being counted as wall area *w*. All of these dimensions are inter-related by the room index, where $RI = L.W/H(L+W)$. (North American practice uses the room cavity ratio, where $RCR = 5H(L+W)/L.W = 5/RI$.)

Clearly this approach contrasts with that adopted by the rest of this book, so let us now imagine what would be the implications for lumen dumpers if the designated lighting standard were to be based on perceived adequacy of illumination, PAI, being prescribed minimum level of ambient illumination, specified in terms of mean room surface exitance, MRSE.

The defining expression states that MRSE equals the first reflected flux FRF divided by the room absorption $A\alpha$, so that:

$$MRSE = \frac{FRF}{A\alpha}$$

and:

$$FRF = MRSE \times A\alpha$$

Room absorption is the sum of products of room surfaces (work plane, luminaire plane, and walls) and their absorptance values:

$$A\alpha = A_{wp}(1-\rho_{wp}) + A_{lp}(1-\rho_{lp}) + A_w(1-\rho_w)$$

It is common in such situations for room surface finishes to be undefined, and for ‘typical’ surface reflectances to be assumed. Providing that assurances are given that ‘light’ finishes will be used, the following surfaces’ reflectances may be assumed as typical:

$$\rho_{wp} = 0.25; \ \rho_{lp} = 0.75; \ \rho_w = 0.5$$

Applying these reflectance values to the above expression gives:

$$A\alpha = L.W + H(L + W)$$

So:

$$FRF = MRSE[L.W + H(L + W)] \tag{7.1}$$

The first step for determining a lighting layout is to use Formula 7.1 to calculate the first reflected flux, after which the next task is to devise a distribution of direct flux from the lighting installation that will provide the required level of FRF, and this presents the lumen dumper with a novel quandary. There is no stipulated illumination distribution. At one extreme, s/he could direct all of the flux onto the work plane, but that might create the dreaded "cave effect". At the other extreme, all of the flux could be directed upwards into the cavity above the luminaire plane, and while that would be a very efficient way of providing the FRF, it would distract attention away from the work plane.

The concept of illumination hierarchy is all about providing controlled distributions of illumination, and for the lumen dumper, the solution would be to nominate the work plane as the target and to work towards a suitable target/ambient illumination ratio, TAIR.

Target illuminance is the sum of direct and indirect components, so that if we assume luminaires that direct all, or at least almost all, of the downward flux onto the work plane:

$$TAIR = \frac{E_{wp(d)} + MRSE}{MRSE}$$

$$= \frac{E_{wp(d)}}{MRSE} + 1 \tag{7.2}$$

From Formula 7.1:

$$TAIR = \frac{E_{wp(d)}[L.W + H(L + W)]}{FRF_{wp} + FRF_{lp}} + 1$$

$$= \frac{L.W + H(L + W)}{0.25L.W + UFFR.0.75L.W} + 1$$

where $UFFR$ = upper flux fraction ratio

$$TAIR = \frac{1 + \frac{1}{RI}}{0.25 + 0.75UFFR} + 1$$

Then:

$$UFFR = \frac{1 + \frac{1}{RI}}{0.75(TAIR - 1)} - 0.33 \tag{7.3}$$

In this way, both TAIR and UFFR are readily predictable for target work planes. If it is decided to use fully recessed luminaires, or any other type of luminaire for which UFFR = 0, then TAIR values can be read from Table 7.1. It can be seen that high values are unavoidable, particularly for low *RI* values.

These high TAIR values can be avoided by use of luminaires that have some upward light component. Figure 7.2 shows how UFFR values relate to TAIR, and this may be

TABLE 7.1 Values of target/ambient illuminance ratio, TAIR, against room index where the horizontal working plane, HWP, is the target surface and all direct flux is incident on the HWP. Light surface reflectances are assumed

RI	*TAIR*
1	9
2	7
3	6.3
4	6
5	5.8

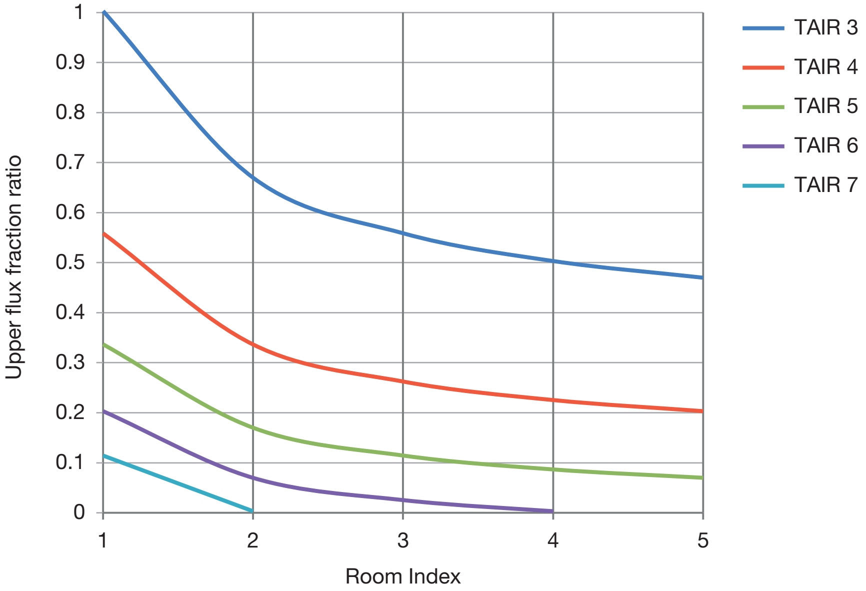

FIGURE 7.2 TAIR values for the horizontal working plane, when it is the target. Except for at low values, room index has only slight effect, but the upper flux fraction ratio is strongly influential.

seen as a simple version of a more comprehensive study reported by Lynes (1974). Jay (2002) has commented that a *BZ3* lighting installation with a 10 per cent upward light component provides a satisfactory appearance in a wide range of workplace applications, and Figure 7.2 shows this to relate typically to a TAIR value around 5 except at low *RI* values. To this I would add my own observation that it needs a TAIR value of at least 3 to impart a distinct difference of appearance to a target, and for a level much less than 2, the difference is unlikely to be noticeable.

The difference between this situation and current general lighting practice is that only the *amount* of light, as it influences assessment of illumination adequacy, is specified, and the distribution of that light is undefined. This means that for anyone to plan a lighting installation, some thought has to be given to the question; What is the purpose of the lighting? Perhaps a grid of luminaires providing uniform work plane illuminance is appropriate, but perhaps not. MRSE specifications may apply to many locations other than workplaces – in fact, the only exceptions would be locations where distinctly dim lighting may be a legitimate design objective. Generally it should be assumed that providing for PAI (perceived adequacy of illumination) does matter, and at the same time, that there needs to be scope for specific targets to be selected so that an illumination hierarchy can be drawn up in terms of TAIR values. It is in this way that an illumination distribution can be created that meets the specific requirements of a space without being compromised by the need to comply with a lighting standard that prescribes uniformity.

The important role of room surface reflectance values

It's time for another thought experiment. Suppose that you are designing a setting in which a white marble sculpture is to be displayed, and you want to achieve a stunning effect. You want the sculpture to stand out from its background so strikingly that it appears to glow. You want the highest possible target luminance contrast. Peter Jay has examined the condition of *maximum attainable contrast* (Jay, 1971) for which every lumen provided is incident on the target, and the background is illuminated only by light reflected from the target.

To simplify the situation, we will assume all surfaces to be diffusing reflectors so we can define maximum attainable contrast in terms of exitance (M) values for a target, *tgt*, seen against a background, *bg*:

$$C_{max} = \frac{M_{tgt} - M_{bg}}{M_{bg}} \tag{7.4}$$

In any enclosed space, the total room surface area, A_{rs}, is the sum of the areas of the enclosing surfaces and any objects contained within the space. If we direct all of the light from the luminaires onto a target area A_{tgt}, then the remainder of the surface area, which forms the background to the target, is A_{bg}, so that $A_{rs} = A_{tgt} + A_{bg}$. As the background receives only indirect illumination, the contrast for this condition will be the maximum attainable contrast, C_{max}. Target and background illuminances and reflectances are E_{tgt}, E_{bg}, ρ_{tgt} and ρ_{bg} respectively.

The target is completely enclosed in a space of exitance M_{bg}, and so the indirect component of its average illuminance will be equal to M_{bg}. The direct component of the target illuminance is therefore $E_{tgt} - M_{bg}$, and the total luminous flux from the luminaires is $A_t(E_t - M_b)$. We apply the conservation of energy principle to state that this flux must equal the rate of absorption by both the target and background areas, so that:

$$A_{tgt}(E_{tgt} - M_{bg}) = A_{tgt}E_{tgt}(1-\rho_{tgt}) + A_{bg}E_{bg}(1-\rho_{bg})$$

So:

$$A_{tgt}E_{tgt} - A_{tgt}M_{bg} - A_{tgt}E_{tgt} + A_{tgt}M_{tgt} = A_{bg}E_{bg}(1-\rho_{tgt})$$

$$A_{tgt}(M_{tgt} - M_{bg}) = A_{bg}E_{bg}(1-\rho_{bg})$$

Divide through by M_{bg}, noting Formula 7.4 and that $M_{bg} = E_{bg}\ r_{bg}$:

$$\frac{M_{tgt} - M_{bg}}{M_{bg}} = \frac{A_{bg}}{A_{tgt}} \times \frac{1-\rho_{bg}}{\rho_{bg}} = C_{\max} \tag{7.5}$$

This is Jay's formula for maximum attainable contrast (Jay, 1971). It shows that C_{max} is the product of two factors, one being the ratio of the surface areas, A_{bg}/A_{tgt}, and the other factor, $(1-\rho_{bg})/\rho_{bg}$, being dependent only on the background reflectance. Now think back to the white marble statue. These two factors tell us that to maximise the contrast, we need to put the statue into a space that is large in relation to the statue, and with low surface reflectance. There is nothing surprising about that, until we notice that there is no mention of target reflectance. If we were to replace the white marble statue with a black one, all the exitance values would be reduced proportionately, but the contrast would be unchanged.

Let's look at this formula a bit more carefully. The target reflectance has dropped out, and $(1-\rho)/\rho$ term is the background absorptance/reflectance ratio, α/ρ, and as shown in Figure 2.9, the inverse of this ratio, ρ/α, describes the influence of reflectance upon ambient illumination. Both of these ratios are plotted in Figure 7.3, where it can be seen that they mirror each other. This figure breaks down into three zones. Where the value of ρ is less than 0.3, room surface exitance will be substantially lower than direct illuminance. Here we have the potential to achieve high target/background contrasts, even where the target area is not much smaller than the background area. Moving to the other side of the chart, where ρ is greater than 0.7, room surface exitance exceeds direct illuminance by some margin, and while this will give an enhanced sense of overall brightness, reasonably high contrasts can be achieved only with targets that are much smaller than their surroundings. In the mid-zone, where ρ values are in the range 0.3 to 0.7, room surface exitance values will be fairly similar to direct illuminance values. This equal balance of direct and diffuse illumination components gives scope for providing noticeable (but not distinct) illumination differences while avoiding strong contrasts. It is also a prescription for practical room surface reflectance values, and guides for good

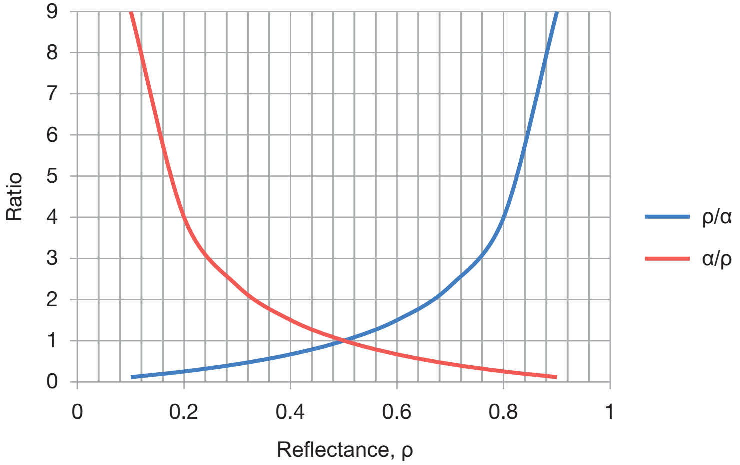

FIGURE 7.3 The influence of room surface reflection properties. For every surface, $\rho = 1\text{–}\alpha$, where ρ is reflectance and α is absorptance. From Formula 2.1 it can be seen that MRSE is proportional to ρ/α, and from Formula 7.3, maximum attainable contrast is proportional to α/ρ. Where overall room surface reflectance, ρ, is either more than 0.7 or less than 0.3, it’s effect upon appearance will be pronounced.

lighting practice invariably recommend reflectances within this range. It may be looked upon as the safe range, in which there is some limited scope for emphasis, but providing sufficient light is put into the space, everything will appear adequately lit. However, this should not inhibit a creative designer. The important thing is for the designer to have developed, through observation of the impact that lighting can have on the appearance of lit spaces, the confidence to step outside the restrictions of recommended practice.

Jay’s study extended beyond a target object surrounded by a background, to examine the limitations for contrast when the target is part of the space itself. Examples might be a demonstration area in a teaching space, or a dance floor in a restaurant. It must not be lost sight of that the formula is based on the assumption that 100 per cent of the provided luminous flux is incident on the target, so that ambient illumination outside the target area is due only to reflected flux. It is, after all, a formula for *maximum attainable* contrast, and so unlikely to be achieved in practice. However, it may be noted that as the target becomes a larger part of the total surface area, so it becomes realistic to assume that spill light onto the background is more likely to be significant, which has the disadvantage of reducing actual target contrasts, and the advantage of reducing the need to supplement the target lighting to provide for safe movement.

Final remarks

The perception-based lighting design approach proposed in this book leaves untouched some aspects of lighting that have traditionally been cornerstones of lighting policy. In particular, the topics of lighting for productivity in workplaces and efficient use of energy for lighting have been barely mentioned, and so we will close by looking at how these two aspects interact with this perception-based approach.

Lighting for productivity in workplaces

We live in an era in which if things need to be seen, they are designed to be seen. Examples of this surround us. Carbon copies were first replaced by photocopies, and then by laser printed materials, before paper-based materials in turn gave way to screen-based displays, originally CRT screens, which in turn have been replaced by high-definition, full-colour LED displays. At least, that is what has happened where material has to be read by a human being. Where the process of reading has been taken over by machines, such as the bar-code readers at supermarket checkouts, the visual task has not simply been eased, but has actually been eliminated, and similar examples can be found in many industrial workplaces.

This revolution in the role of vision has not been accompanied by any serious revaluation of the provision of illumination. Lighting standards and recommended practice documents specify illuminance values for visual tasks, and for anyone who cares to read the cited literature, these are claimed to be based on measured values of the luminance contrast and angular size of the critical detail at the eye. The reality is that while the specified illuminance has climbed during the previous half century, visual task difficulty has eroded or vanished. What has not changed is the notion that providing for illumination adequacy involves lighting the HWP (horizontal working plane) to a specified level, and because this is the basis of lighting standards, it applies to all manner of indoor applications. Every space from a waiting room to a precision machine shop is assessed by someone holding an illuminance meter at around waist height, and wandering around to ensure that at no point does the measured value drop below the specified one.

There are a few exceptions. Some visual tasks cannot be redesigned, and notable examples are surgery, for obvious reasons, and quality control inspection, where the aim is to detect even very slight defects in manufactured products. The common feature of these applications is that they call for specialised solutions that are quite separate from the general lighting. Consider, for example, that you have undertaken a project to light a dentist's premises. You think through the progression of a patient arriving at the entrance, advancing to the reception, and moving through to the waiting room before being called into the surgery. At every stage you have different ideas about the appearance that you want to create, and how you will use lighting to achieve it. However, once the patient is tilted back in the dentist's chair, and the dentist needs a few thousand lux on the patient's back molars, a completely different form of lighting takes over, and the way that that is provided is none of your concern. A luminaire that incorporates a high level of technical expertise is brought into use, but it is a component of the dentist's equipment and does not form part of the lighting installation.

It may be said that, generally, in an indoor space where there is an activity that involves the need for visibility, the surfaces associated with that activity should be designated as target surfaces and incorporated into the illumination hierarchy scheme. Examples would include art galleries, retail stores, industrial assembly lines, and the tellers' counters in banking premises. For activities that are particularly visually demanding, which include the already cited examples of surgery and quality control, specialised lighting solutions that are designed not merely to deliver lumens, but to enhance the visibility of the critical detail, are to be applied. Wherever people are to spend long working periods, whether visually demanding or not, provision for perceived adequacy of illumination requires attention. If high levels of target illumination are to be applied, then keeping TAIR down to modest values will have the effect of ensuring appropriately high levels of MRSE.

Efficient use of energy for lighting

It goes without saying that energy efficient lighting must make use of high luminous efficacy light sources in optically efficient luminaires. Beyond this, the lighting needs to provide for PAI (perceived adequacy of illumination), no more and no less, at all times that the space is occupied. This may involve a control system that can dim the electric lighting to take account of daylight availability, and that will switch it off when the space is unoccupied. The important way in which this differs from good current lighting practice is that it relates to PAI, which means that the lighting sensor is installed so that it responds to MRSE, and not to HWP illuminance. The thinking behind this is that the space should always appear adequately lit without ever being lit to excess, and that instead of the designer working to keep inside a lighting power density limit (W/m^2), the aim would be a genuinely low energy installation, measured in kWh/m^2.yr.

While this scheme seems reasonably straightforward, it could lead to the illumination hierarchy being compromised. Overall dimming to allow for changing levels of daylight would inevitably change the balance of the lighting, particularly in situations where the designer has put together an installation that provides different TAIR values, and involves different types of light sources focussed onto different targets. In such circumstances, it may be an effective policy to maintain the selective target lighting, and to dim only lighting that is provided to boost MRSE, particularly that which washes light over room surfaces close to the source of daylight.

So the question arises, would changing from conventional practice of specifying illumination requirements in terms of minimum HWP illuminance, to basing it upon satisfying PAI, lead to lower energy consumption? The first thing to make clear is that this perception-based approach is not proposed as means for reducing lighting levels. The basic requirement is that a space should appear adequately lit, taking account of the viewer's likely expectations. Conventional practice can, on occasion, lead to the 'cave effect', a dismal appearance brought about by the misguided pursuit of high efficiency. To restate the illumination standards in MRSE values should have the effect of preventing this unfortunate outcome. However, it has to be understood that the prescribed lux (or lm/m^2) values would need to be substantially lower than the current HWP values, not because less light is to be provided, but because of the different way in which the metric evaluates the level of illumination provision.

So if the aim is to come up with the ultimate energy efficient solution that will satisfy the PAI criterion by providing a prescribed MRSE level, what would be the outstanding features of such an installation? The most obvious difference would be the appearance of the space itself. Every surface within such a space would be white or chromium plated! To experience the space would be like stepping into an integrating sphere. Every lumen emitted within the volume of the space would be guaranteed longevity. It would undergo a prolonged life of multiple reflections before eventually being absorbed by the room surfaces. To get an idea of why this would be so, take a look at Figure 7.3. The ρ/α would be so high that it would take the emission of only a few lumens to build up a high lumen density within the space. Of course high efficacy light sources and high efficiency luminaires would be applied, so that only a very low power density would be required to meet any reasonable MRSE value.

Look now at the α/ρ function in Figure 7.3, and it can be seen that as potential for MRSE rockets upwards with increasing room surface reflectance, potential for contrast gets ever lower. We are looking at an environment in which everything is visible, but nothing has distinct visibility. There is no illumination difference, whether a planned illumination hierarchy or an arbitrary outcome of source and distance, and there is no 'flow', and there is no 'sharpness'.

Compared with this outcome, it can be seen that lighting that relates to space, objects, and particularly to people, comes at a cost. Seen in this way, current notions of good lighting practice do, in fact, represent one particular type of energy efficiency compromise. To pursue perception-based lighting concepts is to bring different factors into the equation. Luminaire performance is still there, but the room and its contents are to be seen as the secondary luminaire, whose role is to deliver luminous flux to the viewer. The role of the primary luminaires (the lighting hardware) is to energise the secondary luminaire. This process should be engineered for effectiveness and efficiency.

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APPENDIX

Abbreviations used in the text

α	Absorptance, or vector altitude angle
φ	Vector azimuth angle
ρ	Reflectance
A, $A\alpha$	Area, room absorption (m^2)
CAM	Colour appearance model
CBCP	Centre beam candle power (cd)
CCT	Correlated colour temperature (K)
CGA	Colour gamut area
CQS	Colour quality scale
CMV	Colour mismatch vector
CRI	Colour rendering index
D, D/r	Distance (m), distance/radius correction
E, $E_{s(d)}$	Illuminance, direct illuminance on surface s (lx)
$\mathbf{E}$, $\mathbf{E}_{(x)}$	Vector illuminance, vector illuminance component on x axis (lx)
$\mathbf{e}$, $\mathbf{e}_{(x)}$	Unit vector, unit vector component on x axis
$\sim E$, $\sim E_{(x)}$	Mean symmetric illuminance, symmetric illuminance on x axis (lm)
FRF	First reflected flux (lm)
HCP	Highlight contrast potential
HWP	Horizontal working plane
M_S	Exitance from surface s (lm/m^2)
MRSE	Mean room surface exitance (lm/m^2)
PAI	Perceived adequacy of illumination (MRSE)
RI	Room index
S/P	Scotopic/photopic ratio
TAIR	Target/ambient illuminance ratio
TCS	Test colour sample
VSR	Vector/scalar ratio

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8. OUTCOMES AND EVALUATIONS OF THE PUBLICATIONS

8.1.Responses from the lighting profession

The first submitted document, *Towards the Third Stage of the Lighting Profession*, was accepted for publication in Lighting Research & Technology and published online in February 2009, and the following October, the candidate gave a presentation at University College London, using the title of the paper for the presentation. The presentation was followed by a lively discussion, and soon after, the candidate was interviewed by Jill Entwistle, Editor of the Society of Light and Lighting's bi-monthly Newsletter. The November/December 2009 issue carried a three-page article under the title, *In the Eye of the Beholder*, which was introduced as:

> *In his recent SLL lecture, Kit Cuttle turned current lighting theories on their head. Jill Entwistle talked to him about seeing space in a whole new light.*

This was followed in the January/February issue with Reflections on a New Light Theory, introduced as:

> *In the last issue, author and academic Kit Cuttle outlined his controversial new approach to lighting. Here, leading practitioners and academics respond to his contention that reflected light should supersede horizontal illuminance.*

Seven invited contributors drew attention to the "controversial" nature of the candidate's proposals with a range of contrasting comments. David Loe, formerly Senior Lecturer at UCL, emphasised the *"aim to satisfy the basic requirements of visual function – in other words, sufficient task illuminance with avoidance of discomfort glare"*; and Emeritus Professor Peter Boyce stated that "*The brightness of the space is important, but not as important as the visibility of tasks."* Strikingly different responses were provided by the invited lighting designers. Kevan Shaw (Principal, KSL Design), commented that *"this really is one of those blindingly obvious ideas that we have all missed*", and Nick Hoggett (Partner, DPA Lighting Consultants) added, "*I completely support Cuttle's design philosophy using exit luminance as the primary factor to evaluate the quantity of light needed on a surface … It would be fabulous if Cuttle could develop his approach further, as I believe it has great merit."* Rather more sobering was the comment from Bob Venning (Consultant), *"I think that as a method it will go the way of the luminance design method. An interesting academic approach, but practically hard to implement."* (The luminance design method referred to by Venning is Waldram's 'Designed Appearance Method' [Waldram,1954].)

When the paper appeared in *Lighting Research & Technology* the following year, it was accompanied (unusually) by a discussion comprising comments from three eminent lighting commentators. Lou Bedocs (Thorn Lighting) stated *"Clearly standards and codes must focus on lighting the task, after all, that is what we want to see."* From Kevin Mansfield (University College London) came, *"I welcome further dissemination of the tool as a teaching resource for students and as a device to realign lighting design practice."* To these observations, veteran lighting designer Howard Brandston stated, *"I always light the spaces first, and then supplement for the tasks. I do not light for the tasks, and then supplement for the spaces … It was a foolish premise to believe that task illumination would provide lighting for spaces."*

The second submitted paper, 'A New Direction for General Lighting Practice', was published in LRT three years later, and again included discussion, this time from two invited contributors. Ian Macrae (Thorn Lighting) expressed the view, *"The problem with Kit's proposal is that it would demand a change in process and a lighting design profession that did all lighting design and integrated this with the architect and interior designer, so while the proposal is deserving of merit, we have a long way to go until it can be realised practically."* The other contributor, being a designer, advanced a contrasting opinion. Barry Wilde (MBW Lighting) commented, "*I both welcome and concur with the author's views that it is time to change from a basis of 'visibility' to one of 'appearance'. I would go further and say that in my view it is probably 30 years too late!"*

The other three submitted documents are examples of how the candidate has sought to convey his message not only to the scientific and technical community, but to the broader lighting profession and particularly to the professional lighting designers. With regard to the latter, an interesting development emerged in 2007. The Professional Lighting Designer's Association (PLDA) had been founded in Europe, and proceeded to organise bi-annual conventions (PLD-C). Despite the fact that the PLDA has been disbanded, the PLD-C events have continued and have proved very successful. When reports of the 2007 London convention reached the candidate, he decided that this would be an effective forum for disseminating the MRSE and PAI concepts. The third submitted document, Perceived Adequacy of Illumination, was presented at the 2011 Madrid convention, but prior to that he had had a paper accepted for presentation at the 2009 Berlin convention, and following that, another paper at the 2013 Copenhagen convention. These events have provided valuable opportunities to gain comment and to engage in discussion with the world's leading lighting designers on the MRSE and PAI topics, and some indication of the candidate's success may be gained from the fact that at the Copenhagen convention he was presented with the PLD-C 2013 Lifetime Achievement Award.

It was, by this time, abundantly clear that the candidate's proposals reflect the views of lighting designers, and that if these proposals are to gain appeal throughout the lighting community, then it is the scientific and technical members who will need to be persuaded that the prime purpose of lighting is to enable people to relate to their surroundings, rather than to perform visual tasks. This observation underlies the importance of developing and gaining recognition for reliable lighting metrics.

8.2. Research at DIT

The candidate’s 2010 LRT paper, *Towards the Third Stage of the Lighting Profession* [Cuttle, 2010], attracted international interest, and this has led to the Dublin Institute of Technology initiating PhD research in this area. The candidate was contacted soon after publication of the paper and invited to act as industry supervisor for the first PhD studies to investigate the lighting concepts introduced in the paper. He visited DIT in 2011, where he presented a lecture on the MRSE concept, and discussed opportunities for research studies with Dr Kevin Kelly. Soon after, Dr Kelly recruited James Duff for a PhD focussed on this candidate’s proposals.

It was agreed that there would be collaboration with DIT to enable Duff to undertake research to objectively evaluate the candidate’s theories, and to address the main questions posed. It was agreed to address the following objectives as part of a series of PhD research projects:

- Investigate the relationship between MRSE and spatial brightness;
- Investigate the relationship between MRSE and PAI.
- Test the MRSE formula proposed by the candidate;
- Address the challenge of calculating MRSE through software;
- Develop and evaluate a practical means for measuring MRSE in the field;
- Investigate the use of IH and TAIR in practice
- The setting of criteria for the Code based on appropriate values of MRSE and TAIR.

Initial Research Questions (RQs) with first PhD study by Duff.

- Is the MRSE formula proposed by Cuttle accurate?
- What is the relationship between MRSE and spatial brightness?
- What is the relationship between horizontal illuminance and PAI?
- What is the relationship between MRSE and PAI?
- Can MRSE be calculated through lighting design software?
- Can MRSE be easily measured in the field?

The outcomes of Duff's research are examined in the following chapter, and it may be noted that examination of these RQs is continuing with another PhD candidate.

8.3 Outcomes of DIT research

Duff initiated a series of experimental investigations in which he gained assessments of human subjects' reactions when exposed to a range of MRSE conditions [Duff, 2015]. Two of these studies have been reported in LRT [Duff et al, 2017(a), 2017(b)] and comprised subjects making brightness assessments firstly in a viewing cabinet, and then in a small office. Both experiments exposed subjects to three variables – MRSE, light distribution, and surface reflectances - and involved 26 subjects making surrounding brightness assessments of 27 different viewing conditions. PAI assessments were added for the two experiments in the small office location.

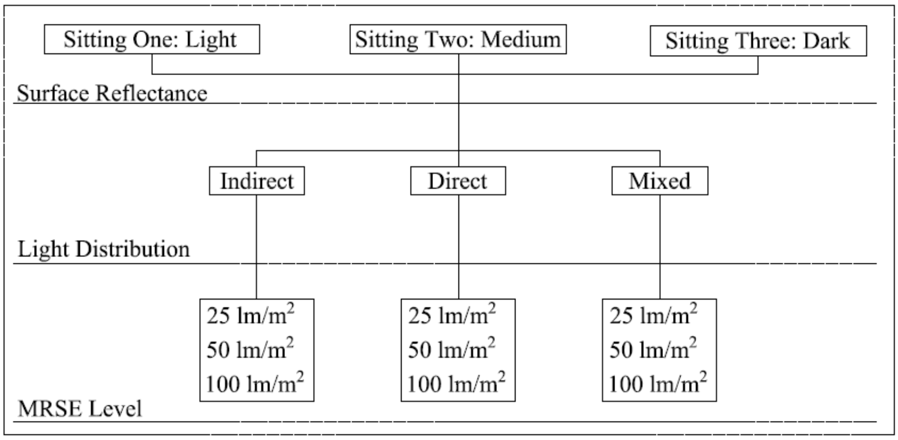

Figure 8.1. Experimental variables for Duff's brightness studies. For each of the two experiments, subjects participated in three sittings for the light, medium and dark surface reflectances. At each sitting, they were presented with nine randomized combinations of the three light distributions and three MRSE levels, giving a total of 27 viewing conditions for each experiment. From Duff et al, 2017(a), 2017(b).

Throughout the series, subjects' assessments of the appearance of the space were recorded on the following seven-point scale:

7. Very bright
6. Bright
5. Slightly bright
4. Neither bright nor dim
3. Slightly dim
2. Dim
1. Very dim

It may be noted that the experiment is described as an examination of 'spatial brightness', but this candidate prefers to use the term 'surrounding brightness'. This is because spatial brightness has been defined in different ways by other researchers, and in particular, it has become quite common for researchers use the term for assessments of a specific field of view, rather than for assessments of how lighting affects the overall appearance of an enclosed space.

For the first experiment [Duff et al, 2017(a)], a laboratory viewing booth was constructed which enabled Duff to exercise control over the necessary range of variables. Each subject was seated and able to view the inside of the cabinet through an aperture that imposed minimal restraint over their viewing direction, and the experimenter presented a randomised sequence of lighting and room surface reflectance conditions that represented a range of visual conditions likely to be encountered in indoor workplaces.

The key findings of this experiment using the viewing booth were:

- A simple linear relationship was found to exist between MRSE and SB.
- A broadly unpredictable relationship was found to exist between horizontal working plane illuminance and SB.
- The linear relationship was of the form:

$$SB = (MRSE/30) + 1$$

where SB is surrounding brightness on the seven-point scale.

The unpredictable relationship between horizontal working plane illuminance and surrounding brightness confirmed the obvious fact that the HWP illuminance metric does not relate to SB assessments. It was devised as a metric for assessing visual performance and may continue to be employed for that purpose, but clearly it has no relevance to this thesis and is not considered further.

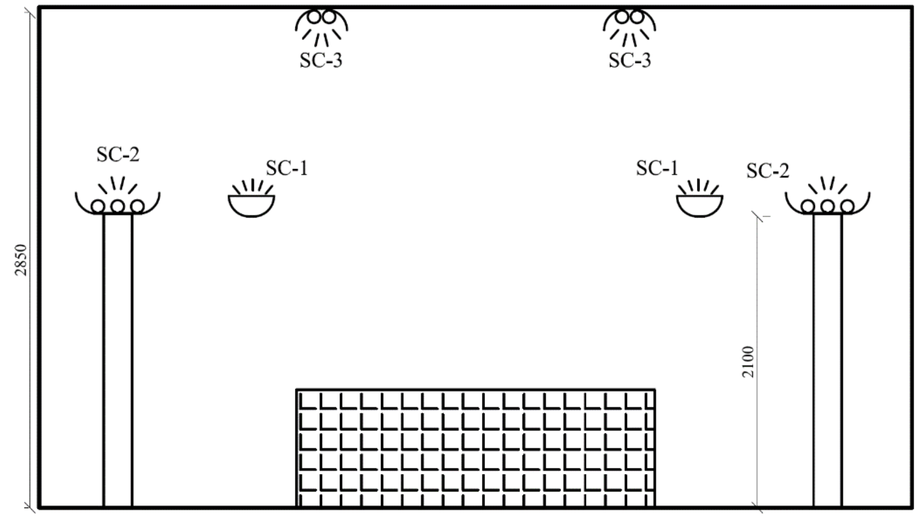

Figure 8.2(a) Vertical section through the small office space used in the second experiment, showing the desk, and wall-mounted uplights SC-1, freestanding uplights SC-2, and ceiling-mounted downlights SC-3. The direct, indirect and mixed lighting distributions were provided by selective switching of the three luminaire types, and all were dimmable to provide the three levels of MRSE. From Duff et al, 2017(b).

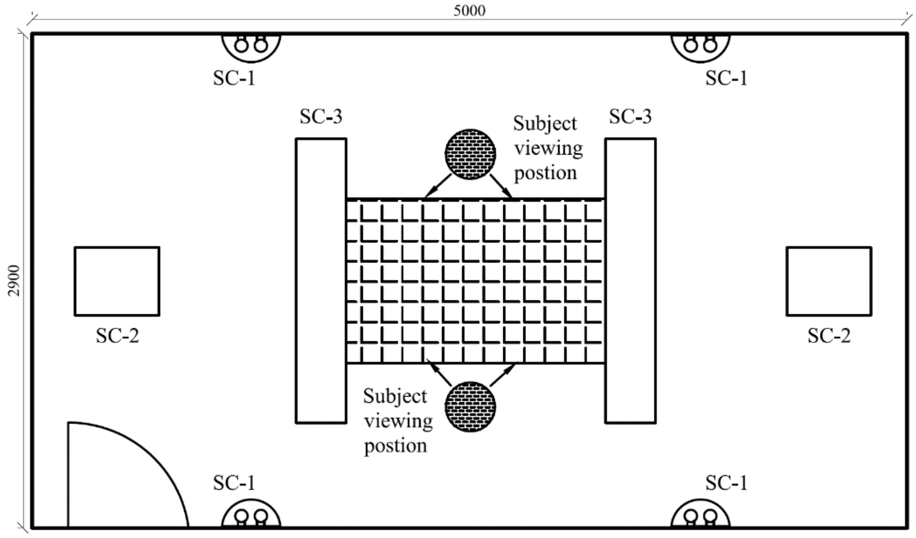

Figure 8.2(b) Plan view, including reflected ceiling view, of office space showing the locations of the two subjects, and of the three luminaire types. From Duff et al, 2017(b).

Duff conducted the second experiment in the office space illustrated in Figure 4.2, where the human activity associated with space was readily recognisable. This stage involved physically changing the reflectance values of the ceiling and walls in the office between the sittings to provide relatively light, medium and dark combinations of room surface reflectance. The percentage reflectance values for ceiling/walls/floor were: Light, 86/84/24; Medium, 69/62/24; and Dark, 44/38/17. As indicated in Figure 8.1, each sitting presented subjects with nine randomised combinations of light distribution and MRSE level, and the three sittings repeated those nine viewing conditions with the light, medium and dark room surface reflectance values, to give a total of 27 viewing conditions.

The procedure used in the first experiment was followed and the results confirmed the previous findings, including the linear relationship. This experiment also included assessments of perceived adequacy of illumination, PAI, for which subjects were instructed to respond ‘yes’ or ‘no’ to whether they assessed the lighting to be adequate for the location.

Duff recorded an additional finding:

- Assessments of SB were strongly correlated with levels of PAI assessments.

From the data, it is noted that the result of this experiment may be may be expressed as a simple linear relationship of the form:

$$PAI = 15(SB - 1) + 5 \qquad \text{percent}$$

While conducting these investigations, Duff encountered a range of practical issues that were outside the scope of conventional procedures.

The available lighting software was (and still is) directed towards calculating illuminance on room surface planes (including the horizontal working plane). He developed a script that facilitates calculation of MRSE using the RADIANCE program, this being readily available freeware. This represents an important development for accurate prediction of MRSE. Taking the small office shown in Figure 8.2, which he had surveyed in detail while conducting his experimental studies, he made comparisons of MRSE based on: point-by point measurements of surface luminance; manual calculations using alternative formulae; and his own computer-based calculations. His data confirmed the accuracy and effectiveness of his procedure, and he included the script in his paper describing the development of his calculation tool, so to make it available for other researchers [Duff et al, 2016].

In the same paper, he dealt with the issue of measurement. While MRSE is a straightforward concept, it’s measurement creates a problem. MRSE involves either the tedious process of measuring the exitance of every significant room surface and calculating the area-weighted mean, or alternatively, measuring the indirect luminous flux density at a point within the space for the entire surrounding sphere, but this requires the measuring instrument to have facility to distinguish between incident diffusely reflected light from surrounding surfaces and direct flux from the luminaires or windows.

Duff had conducted his experiments by dividing surfaces into grids of points, at which he measured luminance values that he converted into exitance values. The process was painstaking, and convinced him that a practical instrument capable of measuring the indirect luminous flux density at a point in space would be necessary for MRSE to become accepted for general lighting practice.

The first task was to devise a means for separating direct and indirect light. He achieved this by applying high dynamic range imaging, basing his work on a procedure developed by Mardaljevic [2009], which provides photometrically accurate two-dimensional digital images. He developed a procedure by which an operator reviews an on-screen image, and adjusts a luminance threshold to identify light sources within the field of view. When satisfied that all sources of direct light have been correctly identified, MRSE from the remaining field is automatically calculated.

The next task was to deal with making measurements over the entire three-dimensional sphere. This requires multiple images, the number depending upon the angular subtence of the camera lens. The most suitable lens that Duff was able access required eight images to be taken in spatially separated directions from the measurement point, but as he noted, a full-field lens that covers an entire hemisphere (such lenses are available) would require only two images to provide reliable measurement of MRSE from a specified point [Duff et al, 2016].

In a separate publication [Duff, 2016], he examined alternative predictive calculation procedures for mean room surface exitance. The defining formula for MRSE is:

$$MRSE = \sum M_{rs}\, A_{rs} \,/ \sum A_{rs} \qquad (1)$$

Where: M_{rs} is the exitance of room surface rs lm//m^2

A_{rs} is the area of room surface rs m^2

Calculation procedures that provide for accurate prediction of inter-reflected light within an enclosed space involve multiple iterations of reflections until the level of reflected light reduces to an insignificant level. This candidate had proposed an alternative formula that substantially simplifies calculations [Cuttle, 2010, 2015]:

$$MRSE = \sum E_{rs(d)}\, A_{rs}\, \rho_{rs} \,/ \sum A_{rs}\,(1-\rho_{rs}) = FRF/A\alpha \qquad (2)$$

Where: $E_{rs(d)}$ is the direct component of the illuminance of room surface rs lm/m^2

P_{rs} is the reflectance of room surface rs

FRF is the total first reflected flux lm

Aα is the room absorption m^2

Duff investigated the extent of error incurred by formula (2), comparing MRSE values calculated by both formulae (1) and (2) for two different luminaire distributions, a downlighter and an uplighter, located at the centre of a room for which the five different reflectance combinations shown in Table 8.1 were specified [Duff, 2016].

Table 8.1. Reflectance combinations for Duff's comparison of formulae (1) and (2), the results of which are shown in Figure 8.3. In every case the average room surface reflectance is 0.5, and the five combinations represent increasing levels of surface reflectance diversity [Duff, 2016].

	Ceiling reflectance	Wall reflectance	Floor reflectance
1	0.5	0.5	0.5
2	0.6	0.5	0.4
3	0.7	0.5	0.3
4	0.8	0.5	0.2
5	0.9	0.5	0.1

The result of this comparison is shown in Figure 8.3. It can be seen that formula (2) tends to overestimate MRSE for uplighting, and to a lesser extent, to underestimate MRSE for downlighting. Luminaires that provide a balance of upward and downward flux incur errors between these levels, with the extent of error increasing as the diversity of reflectance values increases.

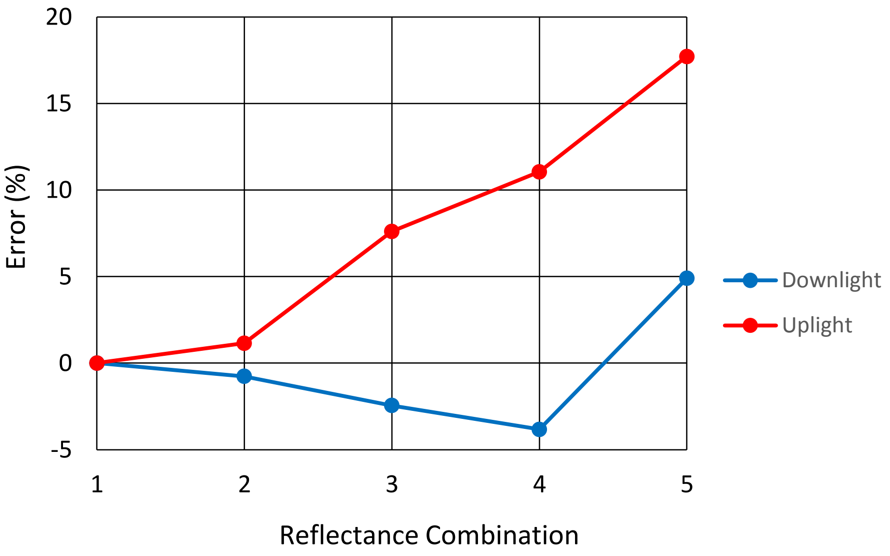

Figure 8.3. Levels of error incurred using formula (2) rather than formula (1) in Duff's comparison[6] for downlight and uplight luminaires illuminating a room with the five reflectance combinations shown in Table 8.1.

For practical applications, the difference between these formulae is that application of Duff's procedure, based on formula (1), requires the use of a computer to deal with the iterations of room surface interreflections, while this candidate's procedure, based on formula (2), can be carried out on the back of an envelope. The underestimation incurred by using formula (2) may be acceptable depending upon the circumstances. In practice, predictive calculations can never be exact as they are liable to be upset, at least to the extent indicated here, by factors such as changes of furniture, to which MRSE would be more susceptible than horizontal illuminance. For example, it should be recognised that when a person enters a room, the level of diffusely inter-reflected light declines as the person's body and clothing have increased the level of room absorption. Of course, nobody notices the decline, but the effect would be detectable and predictable. Also, it may be noted that for luminaires that emit combinations of upward and downward flux, the actual error can be expected to fall between these extremes. While the candidate's procedure may prove useful for initial estimates and for comparing alternative lighting strategies, for finalising installation specifications, the Duff et al calculation procedure [2016] based on formula (1) should always be applied.

8.4 Other research outcomes

In a study by Rea, Mou and Bullough [2016], subjects viewed the interior of a laboratory cabinet with their head movement restrained by a chin rest, and they were directed to assess 'scene brightness'. The variables included not only illumination level but also the spectral power distribution of the illumination. The study recorded brightness assessments for two correlated colour temperatures (CCT 2700 and 5400K) of lighting, two levels of horizontal illuminance (100 and 350 lx) measured on the cabinet floor, and two values of wall reflectance (0.2 and 0.7). The study found that the spectral sensitivity of brightness perception is not well characterised by the photopic luminous efficiency function V(λ), for which the authors made proposals for a better metric, and, of interest to this thesis, brightness was better characterised by illuminance at the eye on a vertical plane, than by horizontal illuminance. Vertical illuminance at the eye could be expected to correlate with MRSE, suggesting that for these viewing conditions, ‘scene brightness’ would correlate more closely with MRSE than horizontal illuminance.

Raynham [2016] has conducted a computer-based study of the impact of adding MRSE to the current criteria for lighting spaces where there is no defined visual task. He noted that the candidate had proposed that a MRSE level of 100 lm/m^2 may be required to satisfy the PAI criterion [Cuttle, 2010], and he examined how energy requirements would be affected if this requirement was to be added to the general lighting criteria specified in the British Lighting Standard, BS EN 12464-1 2011. These include minimum requirements for average wall illuminance, ceiling illuminance, mean cylindrical illuminance at head height, and a ‘modelling’ requirement specified in terms of both minimum and maximum values for the ratio of cylindrical to horizontal illuminance, and of these, he selected the minimum cylindrical illuminance level as being the “most onerous”. He produced 27 tables of data to demonstrate that, in a typical office spaces, conventional installations of luminaires that emit only downward flux would have to emit more flux to provide 100 lm/m^2 MRSE than to meet the requirements of the standard, and on this basis, he found that “the adoption of an MRSE target of 100 lux would require a significant increase in the luminous flux used.” [Raynham, 2016]

It is considered that this finding does not withstand scrutiny. MRSE is not being proposed as another metric to be added to the range of current specifications to increase their effectiveness, but as an alternative metric that would have the effect of changing lighting practice. To be useful, this study should have examined light distributions that provide efficiently to satisfy either the British Standard requirements, or the MRSE level for PAI.

8.5 Analysis and assessment of research findings

8.5.1 The SB/MRSE relationship

Duff’s experiments [Duff et al, 2017(a), 2017(b)] both required subjects to make their assessments of the overall brightness of their surroundings on a seven-point scale, and in Figure 8.4 these responses form the scale of surrounding brightness, SB. Duff reported them as ‘spatial brightness’, which might cause confusion with other reported studies of luminance distributions within a specific field of view, but Duff’s experimental conditions do in fact correspond with the author’s definition of SB. Each point on the chart is the average of 26 subjects’ responses to nine combinations of luminaire distribution and room surface lightness. While the SB/MRSE trends are strongly significant, the differences of luminaire distribution and room surface lightness were found to be not significant. Duff also recorded levels of horizontal working plane illuminance, which showed only weak correlation with SB.

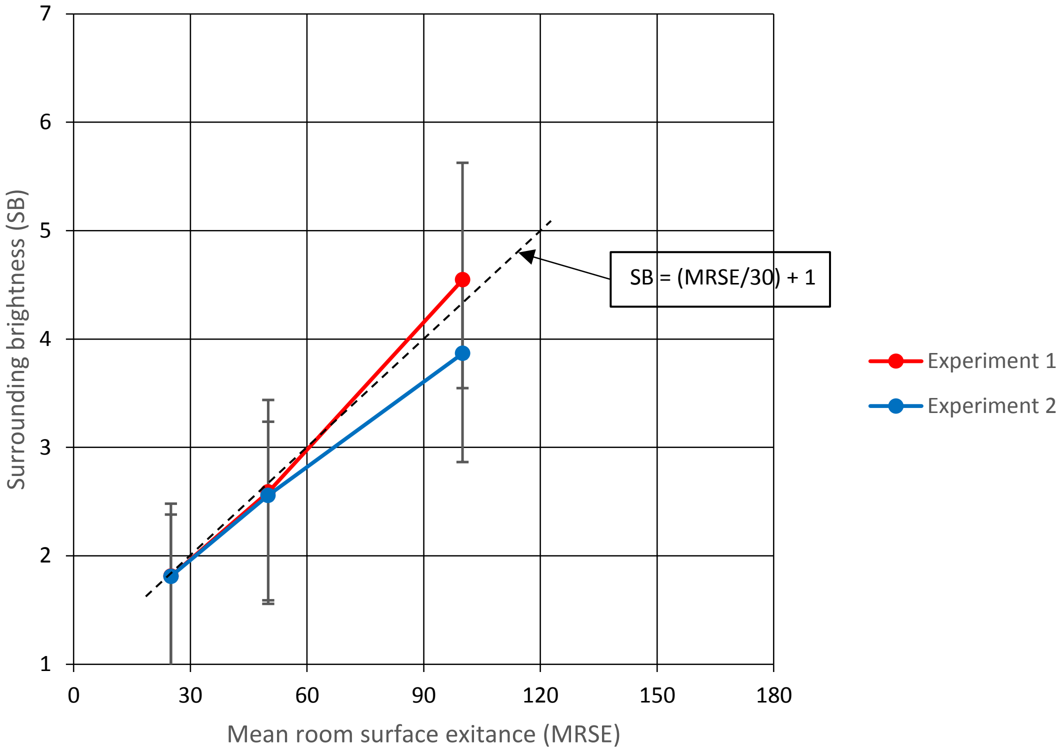

Figure 8.4. Mean values and SDs for surrounding brightness responses relative to mean room surface exitance, for Duff's Experiment 1 (lighting booth) and Experiment 2 (small office) [Duff et al, 2017(a), 2017(b)]

There is strong indication here of a linear SB/MRSE relationship expressed by the indicated trendline, but some caution needs to be applied. The limited range of MRSE levels, 25 – 100 lm/m^2, has effectively restricted SB responses to the range of 2 (dim) to 4 (neither dim nor bright). It is a distinct limitation that there are no responses that rate even slightly bright.

These brightness assessments should not be confused with the classical brightness studies for which subjects viewed target surfaces presented against uniform backgrounds leading to brightness/luminance relationships defined in terms of logarithmic functions, which have been successfully applied to situations such as specifying the brightness of roadway warning signs [Boyce, 2014]. Duff's assessments concern how brightly-lit, or dimly-lit, an enclosed space may appear, and the seven-point scale relates directly to this aspect of appearance. However, it should not be assumed that the intervals on this scale are uniform, that is to say, that the difference between 'dim' and 'slightly dim' is the same as the difference between 'bright' and 'very bright', and for that reason it is important that research is extended to cover the entire range of the scale. As it stands, the linear trend shown here suggests that MRSE needs to be reduced to zero for the average response to be 1 (very dim) which seems improbable, and much less likely, a 7 (very bright) response would occur at merely 180 lm/m^2, this being a value that may be commonly exceeded in practice. It would seem likely that an extended range of MRSE conditions would indicate some departure from a linear function.

It would seem reasonable to conclude that SB and MRSE are related, as the finding that the relationship was unaffected by the flux distribution of the luminaires or the room surface lightness values provides reasonable support for the notion that MRSE may serve as a reliable metric for specifying SB in lighting practice. This would enable typical assessment of how lighting affects the overall appearance of how brightly-lit, or dimly-lit, a space appears to be, to be specified on a descriptive scale that would be equally understandable to lighting designers and to the people that they provide their services for. It may be noted that the recorded values of horizontal illuminance showed only weak correlation with SB, with substantial scatter due to the flux distribution and surface lightness variables, indicating that horizontal illuminance would not serve as a reliable metric for specifying SB. Even so, further research studies are needed before the SB/MRSE function can be reliably applied in practice.

8.5.2 The PAI/SB relationship

For the second experiment, which was conducted in the small office, subjects made the binary assessment, ‘yes’ or ‘no’, as to whether the lighting was perceived to be adequate [Duff et al, 2017(b)]. They were seated at a desk, and the activity associated with the space was obvious.

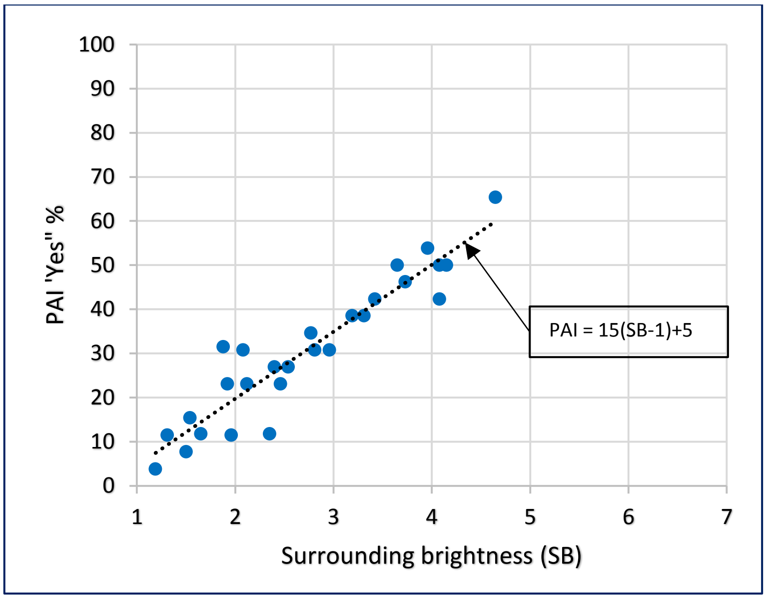

Figure 8.5. Percentage of 'Yes' perceived adequacy of illumination (PAI) responses relative to surrounding brightness (SB), from Duff's experiment in the small office [Duff et al, 2017(b)].

Figure 8.5 shows the percent positive perceived adequacy of illumination (PAI) responses relative to average surrounding brightness (SB) assessments for the 27 viewing conditions. The trend rates strong statistical significance and suggests a linear relationship as indicated [Duff *et al*, 2017(b)], but again, the limited range of MRSE and SB levels restricts the findings that can be drawn. Also, Duff has commented that the number of subjects was insufficient to reliably define a relationship of this nature. As noted previously, SB assessments generally did not exceed 4 (neither dim nor bright), and as a consequence, PAI 'Yes' ratings were limited to around 50%, which is far too low for setting a lighting criterion. While it is never practical to set standards to ensure 100% satisfaction, a criterion of at least 90% is necessary to provide for an acceptable level of satisfaction.

It is, perhaps, an interesting comment on peoples' changing expectations that 50% of the subjects rated a MRSE level assessed as 'neither dim nor bright' to be adequate for office work. This application has long been regarded as the illuminance level benchmark for task lighting, and this response might be seen as recognition of the changing nature of office work, together with expectations for office lighting.

There will need to be discussion to determine an appropriate adequacy criterion for PAI, and as Duff has comments, it is not possible to identify an appropriate value from the reported research. Also, there needs to be more research to include activities other than office work.

8.5.3 Utilization of direct flux for providing MRSE

As has been mentioned, utilization of direct flux is one of several factors that determine the efficiency of a lighting installation, but if lighting practice is to shift its focus from the horizontal working plane to room surfaces, then a substantial re-evaluation of flux utilization needs to occur. Duff's data has provided this candidate with an opportunity to conduct an initial study of direct flux utilization.

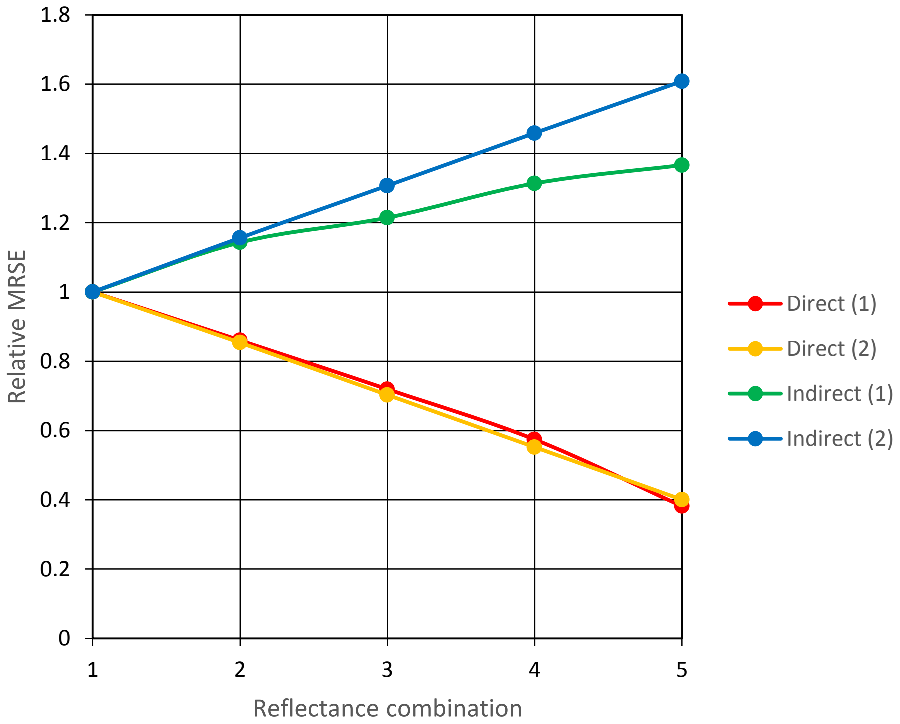

Figure 8.6. Mean room surface exitance due to two luminaires, one providing direct lighting and the other indirect lighting, both having the same flux output, in a room where the room surface reflectance combination is varied, but the average reflectance is always 50 percent. MRSE calculations were made using Duff's definitive procedure (1), and Cuttle's formula (2), and are shown relative to the value for reflectance combination 1. Ceiling/wall/ floor reflectance combinations are: 1. 50/50/50; 2. 60/50/40; 3. 70/50/30; 4. 80/50/20; 5. 90/50/10.[10]

As part of Duff's assessment of the accuracy of alternative predictive formulae [Duff, 2016] he compared mean room surface exitance values calculated for a reference room by his own definitive procedure (1) [Duff et al, 2016] with values calculated by Cuttle's formula (2) [Cuttle, 2010, 2015], as shown in Figure 8.6. The relative values shown in the chart indicate that if all room surfaces are of the same reflectance, then for providing MRSE, it makes no difference how the flux is distributed. For conventionally decorated spaces, where ceilings are lighter and floors are darker than walls, then as reflectance diversity increases, so the efficiency of indirect lighting to provide MRSE increases, and the efficiency of direct lighting reduces. It may be noted that while both formulae show these effects, Cuttle's formula deals satisfactorily with the direct luminaire, but tends to over-rate the utilance advantage of indirect lighting.

The first striking feature of Figure 8.6 is the extent of the difference between the direct and indirect light distributions. Clearly, when the objective is to provide for surrounding brightness, room surface reflectances are far more influential than they are when providing for illuminance-based metrics. Perhaps reflectance combination 5 is somewhat extreme, but for the more typical combination 4, the indirect luminaire achieves more than double the utilance of the direct luminaire, which turns conventional understanding of luminaire efficiency upon its head. Anyone who has experience of providing standards-compliant lighting knows that while uplighting may be a rather attractive way of providing illumination, it is far too inefficient for everyday applications. What that mindset fails to recognise is that while downlighting is the efficient way to illuminate the horizontal working plane (and a light meter located on it), direct flux travels through space without visible effect until it undergoes a reflection, so that in a conventionally decorated space, it would be typical for three-quarters of the flux to be absorbed on contact with the floor without having caused any visible effect. On the other hand, for uplighting, it would be typical for three-quarters of the direct flux to be usefully reflected back into the space.

Nonetheless, it needs to be recognised that these assessments are over simplistic. The rate of reflection (and its counterpart absorption) of luminous flux within a space is determined by all the room surfaces, including the furniture, the windows, and the pictures hanging on the walls. It should not be overlooked that after the luminaires have emitted their flux, they become light absorbers, whether set into the ceiling or hanging from it. It is traditional in lighting practice to assume an empty room for determining the utilization factor, but for the levels of reflectance used for exitance calculations to have reasonably reliable correspondence with those that will apply in practice, it is necessary for consideration to be given to the likely effects of the actual room contents.

This understanding of light within an enclosed space challenges the very notion of 'an efficient luminaire'. It requires the purpose of the luminaire to be understood as providing the first stage of light distribution control, which involves directing flux onto selected surfaces to initiate the second stage of generating the inter-reflection process, which creates the illumination distribution that stimulates the eye. If the furnishings are changed, or if the room is redecorated, the lighting is changed. In fact, whenever someone walks into a room, the mean room surface exitance drops. The person's body has increased the room absorption, and thereby, the rate at which lumens are being absorbed. While the difference caused by one person may be safely discounted, the difference between an empty reception area and the same space full of people would certainly be noticeable. Designers will need to make sensible judgements as to the level of detail for which they define room surface reflectance values.

This way of understanding the behaviour of light in an enclosed space may be explained by rearranging Cuttle's formula [Cuttle, 2010, 2015], MRSE = FRF/Aα, where FRF is the variable affected by flux distribution. The underlying principle is: *For efficient flux utilization to provide for mean room surface exitance, maximise first reflected flux by directing direct flux onto high reflectance room surfaces*.

8.5.4 Providing for visual emphasis

The alternative to designing for illumination efficiency is to apply direct flux onto selected objects or surfaces to provide for visual emphasis, this being the perceived effect of direct illumination being applied selectively to chosen objects or surfaces. Generally, this will be for the purpose of making them appear more conspicuous or to provide for enhanced discrimination of detail, but inevitably it will produce first reflected flux that will contribute to the inter-reflected light field. It is in this way that the designer develops an illumination hierarchy.

The proposed measure of the perceived extent of visual emphasis is target/ambient illuminance ratio (TAIR) [Cuttle, 2013, 2015], where the TAIR value for a target object is the ratio of target illuminance to the ambient illumination level indicated by mean room surface exitance, so that:

$$TAIR = \frac{E_{ts}}{MRSE} = \frac{E_{ts(d)} + MRSE}{MRSE}$$

Where $E_{ts(d)}$ is the direct component of illuminance on the target surface.

Visual emphasis should not be confused with luminance contrast. Under controlled viewing conditions, such as where subjects are presented with a uniform disc seen against a uniform background, precise functions relating subjective contrast to luminance contrast can be defined, and in fact, researchers can even demonstrate objects being made to disappear into their backgrounds as luminance contrast approaches zero. This does not happen in ‘real’ situations. Consider the situation of a dark grey sculpture that is to form a feature in a reception foyer. If it is sited so it will be seen against a light grey wall, a distinct luminance contrast will occur, but this does not comprise visual emphasis. If selective lighting is now directed onto the sculpture, then as the light level is increased, the luminance contrast is reduced, and visual emphasis is created: but no matter how much fiddling is done with the dimmer control, the sculpture will never disappear into its background. As the luminance contrast approaches zero, the sculpture would appear as a brightly-lit object seen against a neutral background. This would have the effect of drawing attention to it and revealing its form and texture, and giving it visual emphasis. In terms of lighting metrics, this would be a situation of low luminance contrast, and high TAIR.

Table 8.2 indicates the author’s tentative proposal for the relationship between visual emphasis and TAIR, which is based on his own observations and measurements, coupled with the outcomes of student projects. So far, this relationship has not been subjected to formal research.

Table 8.2. Approximate guide to visual emphasis related to TAIR, being the ratio of target illuminance (the sum of direct illuminance and mean room surface exitance) to mean room surface exitance [Cuttle, 2013,2015].

Visual emphasis	Target/ambient illuminance ratio, TAIR
Noticeable	1.5:1
Distinct	3:1
Strong	10:1
Emphatic	40:1

This table calls for some careful consideration. Brightness studies have shown that under controlled conditions, subjects are able to reliably detect luminance ratios as low as one percent, but these data indicate that TAIR values need to be as high as 1.5:1 to be ‘noticeable’. This is because this table refers to observations in real environments, in other words, to complex, non-uniform visual environments. It should not be supposed that such a criterion could ever be defined precisely for practical application irrespective of circumstance, nonetheless, it is offered as useful guidance for practical application, and the same thinking applies to the other visual emphasis criteria listed on the table.

It is the range of the TAIR values that should attract attention. To achieve visual emphasis that will be assessed as ‘strong’, let alone ‘emphatic’, requires carefully a controlled distribution of direct flux. In fact, if the target surface area is anything more than a quite restricted proportion of the total room surface area, and particularly if its reflectance is high, the FRF generated by the direct flux directed onto the target is likely to raise mean room surface exitance to an extent that makes a high value of TAIR unattainable.

Consider a space in which a selected target surface (ts) is the only surface to receive direct light, so the total room surfaces (rms) are lit only by reflected light, then from Cuttle’s formula:

$$MRSE = \left(E_{ts(d)}\, A_{ts}\, \rho_{ts}\right)/A_{rms}(1-\rho_{rms})$$

So from the previous expression:

$$TAIR = \frac{E_{ts(d)} + MRSE}{MRSE}$$

$$= 1 + \left(\frac{A_{rms}}{A_{ts}} \times \frac{1-\rho_{rms}}{\rho_{ts}}\right)$$

It can be seen that, for this situation, TAIR depends on firstly, the ratio of total room surface area to the target area, and secondly, on the ratio of total room surface absorptance to the target reflectance. It is, therefore, independent of the quantity of direct flux on the target. In this way, where the aim is to impart visual emphasis to a target object, *the principle for maximising target/ambient illuminance ratio, is to present the object in a relatively large space, to concentrate the direct flux onto it, and to keep reflectances low*.

This topic is to be the focus of ongoing research at DIT aimed at continuing the investigations of Duff. Dr K Kelly, with Dr J Duff as an industry advisor, is supervising PhD candidate Durante, with this candidate enrolled as an advisor.

9. CONCLUSIONS

From the examination of the evolution of general lighting practice (Section 1.2) it is concluded that the concept that underlies general lighting practice is that the prime purpose of lighting is to provide for efficient performance of visual tasks. Conversely, the underlying concept on which the candidate bases his proposals (Chapters 3 – 7) for a new lighting design methodology is that the prime human response to illumination in indoor locations is based on assessment of how illumination affects the appearance of the surrounding room surfaces, and objects within the space. For lighting practitioners, this difference of purpose may be expressed as the difference between providing illumination to satisfy human visual needs, and seeking to meet (or exceed) peoples' expectation for the appearance of their surroundings. While it is noted that neither of these concepts has been subjected to research examination, the thesis examines the basis of the candidate's proposals, and considers what might be the implications of his new interior lighting design methodology being adopted as the basis for general lighting practice.

The proposed methodology involves the designer in specifying lighting design criteria relating to how the quantity and distribution of illumination affect the appearance of an enclosed space and its contents. The four response functions examined in Sections 9.3.1 to 9.3.4 identify the relationships between human response and illumination that are central to the methodology. Human response to light is defined in terms four novel criteria, these being *surrounding brightness* (SB); *perceived adequacy of illumination* (PAI); *visual emphasis* and *illumination hierarchy*. Illumination quantity and distribution are specified in terms of two unfamiliar metrics, these being *mean room surface* *exitance* (MRSE), and the *target/ambient illumination ratio* (TAIR). These terms are defined in the Terminology section.

Duff's research studies [Duff, 2017(a), 2017(b)] examined the candidate's proposals and found that:

- A functional relationship exists between *surrounding brightness* (SB) and *mean room surface exitance* (MRSE), indicated by the linear expression:

  $$SB = (MRSE/30) + 1$$

  However, as noted in the examination of Duff's findings in Section 9.3, the range of MRSE conditions to which subjects were exposed was from 25 to 100 lm/m^2, corresponding to SB values ranging from 1.83 to 4.33, or brightness assessments ranging from 'dim' to 'neither dim nor bright'. It is a significant limitation that the experimental conditions did not include any conditions assessed to be even slightly bright, and as has been discussed, it is possible that extended data would indicate a non-linear functional relationship.

  Nonetheless, the fact that the SB responses in a laboratory viewing booth were closely reproduced in a 'real' office situation, and that these responses were not significantly affected by the changes of light distribution or of room surface lightness, indicate that MRSE may have potential to serve as a useful indicator of "how brightly lit, or dimly lit, a space appears to be." [Cuttle, 2010, 2015]

  It may also be noted that within the range that is covered by the experimental data, the above expression indicates that a surrounding brightness level of 4 (neither dim nor bright) corresponds to a MRSE value of 90 lm/m^2. This is interesting, as a SB level of 4 could serve as the response level that defines the minimum level of illumination for general lighting practice, as it represents the lowest level that is not perceived to be even slightly dim, while avoiding the unnecessary extravagance of providing a level perceived as slightly bright. More research will be needed to establish this important value, but identification of a MRSE level that would serve as a reliable indicator of a SB4 response would be potentially useful research finding.

- A functional relationship exists between *surrounding brightness* (SB) and *perceived adequacy of illumination* (PAI). The experimental research data [Duff et al, 2017(a), 2017(b)] is reviewed in Section 9.1, and the relationship is described by the linear expression:

  $$PAI = 15(SB - 1) + 5 \qquad \text{percent}$$

  The limitations of the data noted in the previous sub-section are equally relevant to this relationship. From the above expression, a SB value of 4 corresponds to a PAI level of 50%, indicating that for the small office situation, half of the subjects assessed this level of surrounding brightness to be inadequate. More research will be needed to specify a SB level that a substantial majority (such as 95%) of people would assess to be adequate for office work, but as SB4 occurs at the upper end of the research data, it can only be concluded at this stage that people expect an office to the illuminated to provide a surrounding brightness level that is greater than ‘neither dim nor bright’. It should be noted that the PAI concept represents a way of associating illumination levels with types of human activities that is quite different from current practice, and it would not be restricted to work places.

It is noted that Duff’s research also included investigations and proposals for new procedures for calculations and measurement of MRSE [Duff *et al*, 2016; Duff, 2016], and while these are not examined in this thesis, other findings relevant to the thesis may be derived. Devising a lighting installation to provide a specified level of MRSE with a high level of *flux utilance* requires an understanding of light distribution that is quite different from providing for horizontal working plane (HWP) illuminance. Instead of selecting luminaires to deliver their flux outputs directly onto the

HWP, luminaires to provide MRSE efficiently need to be chosen according to the distribution of room surface reflectances, the principle being that flux should be directed onto room surfaces of relatively high reflectance, with the objective of maximising *first reflected flux*. As is explained in Section 9.3, this finding is supported by Duff's research [Duff, 2016], where it is shown that in a conventionally decorated room, flux utilization may be substantially increased by directing flux onto the ceiling rather than onto the floor or working plane.

The concept *illumination hierarchy*, being an ordered distribution of direct flux, involves flux being distributed for the purpose of achieving selective *visual emphasis*, rather than for efficiency. This involves target objects and surfaces being selected to receive direct flux, and the candidate has tentatively proposed a relationship (see Table 8.2) between visual emphasis and *target/ambient illuminance ratio* (TAIR). It has been demonstrated in Section 9.3 that TAIR may be maximised by restricting target surfaces to a small proportion of the total room surface area, and keeping surface reflectances low. Again, this principle represents an understanding of flux distribution that is different from current practice, but so far, the relationship between and TAIR has not been subjected to research examination.

The acceptability of candidate's proposal for a new interior lighting design methodology may be seen to depend firstly, upon the four response functions relationships between the aforementioned criteria and the metrics being proved to be valid, and secondly, on the development of design procedures that enable practitioners to apply the methodology in practice.

More research is needed to establish response functions that would serve as reliable predictors of the proposed new criteria applicable to the broad range of practical lighting applications. In particular, research needs to be extended to include:

- Identification of the prime responses of people to the quantity and distribution of illumination in typical categories of indoor spaces.

- A range of MRSE values that corresponds to surrounding brightness assessments ranging from ‘very dim’ to ‘very bright’.
- Assessments in a range of ‘real’ locations that includes a variety of types of indoor activities.
- Assessments in daylit spaces.
- Examination of energy-use implications of switching lighting specifications from horizontal working plane illuminance to mean room surface exitance.

The candidate has demonstrated application of the methodology by use of an Excel Spreadsheet (Cuttle, 2015), but this is seen to be no more than a demonstration of feasibility. It will require the development of professional software for the methodology to be considered for adoption by general lighting practice.

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APPENDICES

Appendix A: Responses of the lighting profession to first submitted publication

In the eye of the beholder, SLL Newsletter, Nov/Dec 2009; 2(6): 6-7.

Reflections on a new light theory, SLL Newsletter, Jan/Feb 2010; 3(1): 6-8.

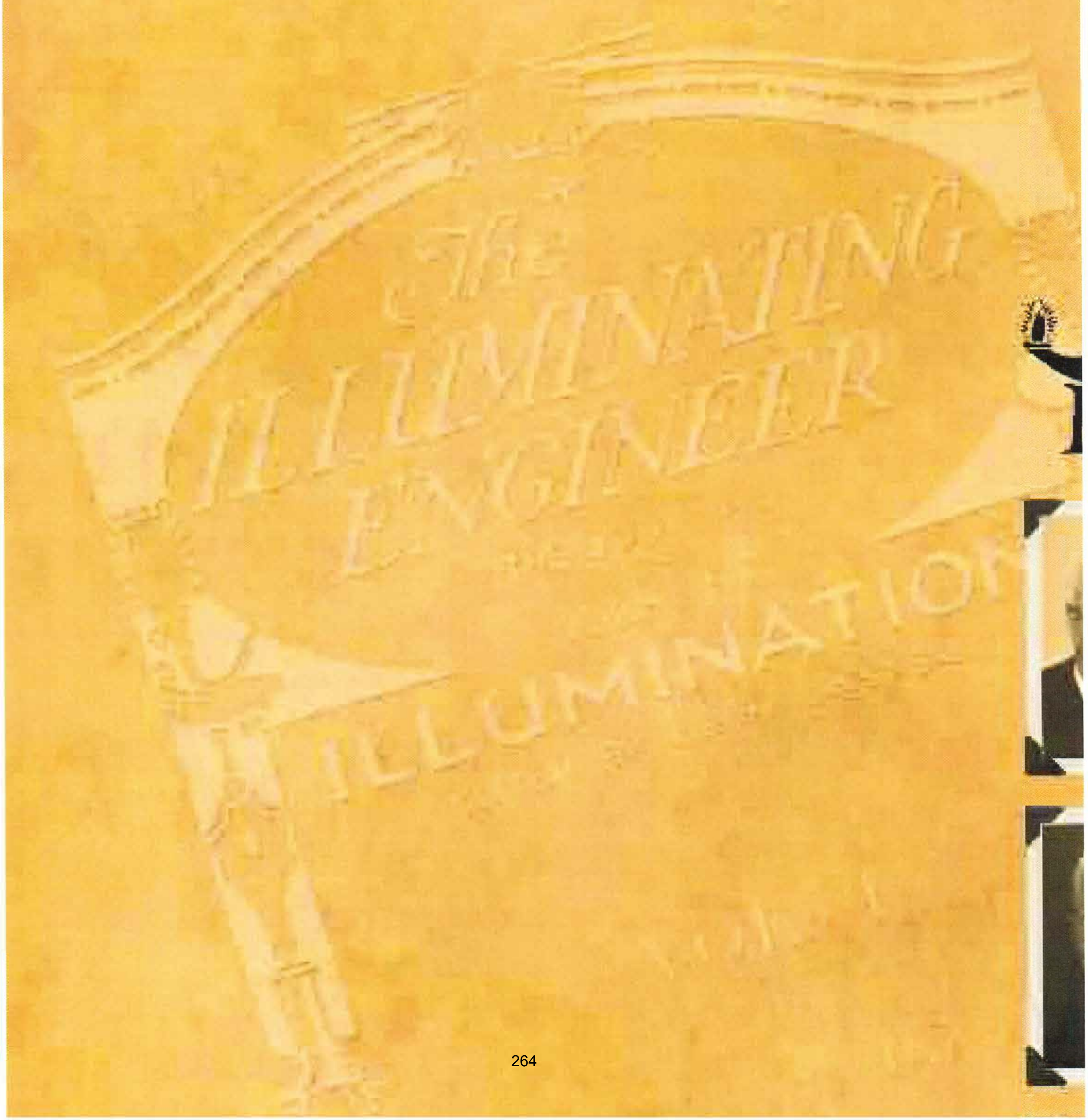
Viewed in a different light, SLL Newsletter, Mar/Apr 2010; 3(2); 8-9.

[illegible]

Newsletter

The Society of Light and Lighting

Part of the Chartered Institution of Building Services Engineers



In the eye of the

In his recent SLL lecture, Kit Cuttle turned current lighting theories on their head. Jill Entwistle talked to him about seeing space in a whole new light

The way we currently measure lighting, maintains Kit Cuttle, is outdated, inappropriate and quite simply wrong. It is time, he says, that we turn the old thinking on its head and start looking at lighting from a totally different perspective. 'We're measuring in the wrong way, we're calculating in the wrong way and we're specifying in the wrong way,' says Cuttle. 'We have lost touch with the determining factor for the level of light we should be providing for various activities in various locations.'

In an SLL lecture held at the Bartlett in October, Cuttle advocated that the preoccupation with horizontal illuminance should end. Instead we should be concerned with reflected light, the apparent brightness of a space, the light that reaches the eye rather than the horizontal plane. It is what he has termed the third stage of lighting design. However, it is important, he says, to understand what those first two stages are and why in his view they have taken our approach to lighting in the wrong direction.

'The first stage is an engineering approach to lighting. The 'first stage' professionals wanted to be able to produce uniform illuminance over large areas. That's a concept that's still very much with us and dominates a lot of our thinking. We have modern light meters which are technically sophisticated instruments, but they still measure exactly the same aspects and quality of lighting that they were trying to measure in the 19th century – Illuminance regardless of the direction of the incidence of light on a horizontal, two-dimensional plane.

'Then they started thinking about how to decide how much light to provide. The whole notion of building this around providing light for human need and the concept of visual performance caught on. I've no doubt that at the time it made a lot of sense. If we go back to the 1920s and 1930s there were eminent people in lighting saying that for a typical reading task we need one foot candle, approximately 10 lux. Therefore when we have difficult visual tasks we should provide additional illuminance in order to compensate for that. But of course that's laughable now, we wouldn't dream of providing 10 lux for any indoor activity. We even light corridors and plant rooms to much higher levels than that.'

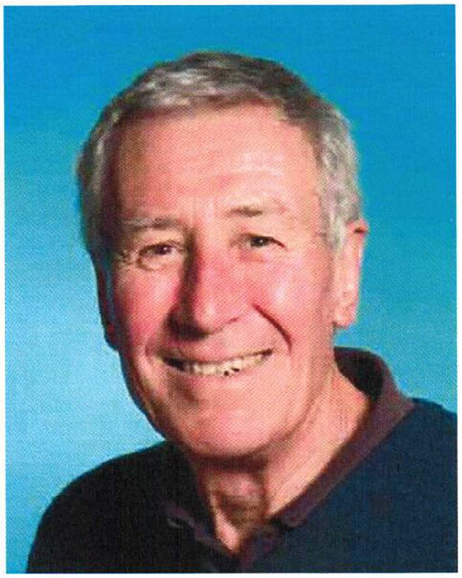
Both stages led to a misplaced concern with horizontal illuminance in Cuttle's view. 'The direct component of illuminance has no visual effect. It is not until the light has undergone a reflection that it has a visual effect upon the appearance of the things around us. Therefore, particularly when we have environments where we direct light and control it very intensely to achieve high efficiency on certain planes and surfaces, we get a quite misleading impression of how useful and how effective that light is going to be for vision. We have got to allow the light to undergo at least one reflection before it becomes effective at the eye.'

Among the negative results of the old approach is overlighting, according to Cuttle. General levels of illumination are calculated on the basis of worst possible case which, given that task lighting can supplement light levels for people and tasks that need it, is 'inefficient and unnecessary'. This concern to produce high levels of illumination on the horizontal surface also overlooks the fact that technology has moved on. In the workplace, most people use near-vertical, self-illuminated screens. In the supermarket, the person at the checkout no longer has to read the prices because a bar code scanner does it for them. 'But it doesn't stop them putting strong lighting right over the checkout to give high levels of illuminance on the horizontal work plane because that's what the codes specify.'

The switch of focus to reflected or indirect light turns previous thinking about issues such as efficiency upside down. 'As soon as we start measuring light arriving at the eye, we get a completely different impression of what is effective lighting,' says Cuttle. 'Techniques such as wallwashing or uplighting have always been thought of as inefficient lighting because when we measure illuminance by

'If codes, standards and recommended practice documents specifiyed lighting in terms of how it gives people a sense of brightness in a space this would completely change the way we think about efficient, effective and economical lighting installations. Gone would be the low brightness fully recessed louvre, with mirror optics that direct 95 per cent of the light on to the horizontal work plane. All of that is, I believe, quite misleading.'

beholder



Achieving the third stage:

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holding out a light meter on the horizontal plane, uplighting and wallwashing make little impact.

'We have to completely rethink the ways in which we distribute light. Washing the walls with light can be an extremely effective way of giving people a sense of a bright, well-lit space and a good sense of the ambient illumination. It becomes efficient and effective to put light on to surfaces that are going to reflect a high proportion back into the space because that is what gives our sense of brightness within the space. It is a complete turnaround, not only for how we measure lighting but how we even think about lighting.'

Crucial to Cuttle's theory, of course, are the nature and colour of the surfaces and objects within a space. Lighting design already accounts for the reflectance and colours of materials within a space, but many a scheme has been compromised because the architect/interior designer subsequently changed their mind after the lighting had been predicated on different surfaces. The closer bonding of the lighting specifier with the overall design process would be essential if indirect lighting was to play the key role. It is here that Cuttle is addressing the lighting engineer in particular, pointing up the gap that still persists between lighting design and lighting engineering.

'I think we're moving into an era where architects find that they're getting on better with people who call themselves lighting designers rather than lighting engineers. They like working with them better. I want to see lighting engineers getting involved in this area much more. I don't see that there should be this distinction. Illumination engineering has a lot to offer and a long way to go.

'I would like to see the architects and interior designers talking to lighting engineers because the way they distribute their materials around the space has got a lot to do with how it should be lit and how the distribution of light should work with it. I would like to see lighting engineers becoming much more conscious of that. By and large lighting engineers don't give much attention to reflectances.'

Cuttle still believes in measurement of light, and has developed a process for quantifying reflected light based on Mean Room Surface Exitance (MRSE).

'Iluminance is the density of the lumens arriving at the surface. Exitance is the density of the lumens coming off the surface. The average room surface exitance does not include direct light from the luminaires or from the windows, it's just light from the room surfaces. It doesn't matter if it's uplighting, downlighting, sidelighting, or daylight or electric lighting, MRSE gives a good indication of the overall impression of how brightly lit the space appears to be.'

It's possible to get an approximate measure by taking a conventional light meter, holding it up to the eye, shielding

> **'You have wall and ceiling illuminance relative to the horizontal plane illuminance. Abandon that. It is not the central issue. The central issue is, as we look around ourselves, how much reflected light is available.'**

the light sources and taking a reading, says Cuttle, though he acknowledges that this is obviously an imprecise method. He has also taken it to the next stage of using a web cam, again holding it at eye level. It's a crude instrument and hasn't got a good dynamic range, he says, but it conveys some idea of what's possible. 'You bring up your image on the screen, you click on the light sources to delete those, and you could then develop a programme that would give an average value of the exitance of all the other surfaces. In other words, MRSE is quite capable of being measured. At the same time, of course, you could also get a measure of the UGI (unified glare rating).'

All that is actually needed, says Cuttle, is a photo sensor that could be plugged into the USB port of a laptop and with the appropriate software the rest would be straightforward. 'We could transform the whole thing into a much more simple process. Portable, easily manageable and potentially it's all there. We could bring the process of light measurement right up into the 21st century.'

Cuttle is not contending that direct light should be ignored altogether. 'We need to give thought to how we take control of the amount of direct light relative to the indirect light because if we only have reflected light, and every light source is completely concealed, it becomes a rather dull world. We need a bit of brightness, a bit of liveliness, a bit of sparkle here and there, but it's important to get that balance right. I think this would be a lovely avenue for people to explore a good deal more thoroughly, that direct light from a luminaire is glare.'

Neither is Cuttle suggesting any precipitate changes without careful thought and further exploration of the theory. 'To really move in this direction we do need some good research,' he says. 'I don't want to see people rushing into print with completely revised codes and standards until we have actually got some good research and can show that this whole approach is valid and has been investigated.

'We need to have sound values by which we can specify what is perceived adequacy of ambient illumination. Then we can revise our documents and teaching. Lighting manufacturers, I trust, would be pretty quick to get on board and realise the market is shifting and they have to adapt to it.'

Responses to Kit Cuttle's lecture will be published in the next issue of the newsletter (Jan/Feb). If you would like to contribute, please email the editor at: jentwistle@cibse.org

Kit Cuttle's paper, Third Stage of the Lighting Profession, is published in the March 2010 issue of LR&T, also available online to members at www.sll.org.uk

The second edition of Cuttle's book, Lighting by Design, has just been published in the UK by Architectural Press, and is available through Amazon and specialist outlets, price £34.99

Dynamic

Could digital cameras transform luminance measurement?

Liz Peck reports

Luminance, as we all know, is traditionally measured using a luminance meter which gives a single spot reading. A high resolution image from a digital camera contains around 10 million pixels, effectively 10 million spot readings. So does this mean that digital cameras could be the answer to a more effective measure of luminance? It was this question that was addressed by Axel Jacobs, John Mardaljevic and Birgit Painter at a recent London SLL meeting.

The human eye is capable of adapting to luminances as high as 1,000,000 cd/sq m and as low as 0.000,000,1 cd/sq m. Once adapted, the eye can cope with a luminance range of 1:1000, but for a part of the scene, this can be as high as 1:10,000. However, most digital image formats have been designed with the capabilities of computer graphics displays in mind and therefore the typical contrast for a TFT screen is currently about 300:1.

This means that computer display technology is a long way from being able to display images that have a luminous range even close to what the human eye can process. On top of that, the information stored in the image files is not expressed in photometric terms. Instead of describing the luminance of a pixel in cd/sq m, pixels can only be expressed as a brightness comparison to another pixel.

How is it possible, then, for a digital image to give a measure of luminance? The answer, it seems, could lie in High Dynamic Range Imaging (HDRI).

HDR images are created from a set of photographs taken at differing exposure levels. A minimum of three images is required: under-exposed, normal and over-exposed. The more exposure settings that can be added in between, the better the HDR image. The HDR computing software uses

Further information and reading:

London Metropolitan University WebHDR site http://luminance.londonmet.ac.uk/webhdr
Transmission Illuminance Proxy HDR imaging a new technique to quantify luminous flux
J Mardaljevic PhD, B Painter PhD and M Andersen PhD
Lighting Research and Technology 41:1, 2009
High Dynamic Range Imaging and its Application in Building Research
A Jacobs
Advances in Building Energy Research. Vol 1 No 1. 2007

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Newsletter

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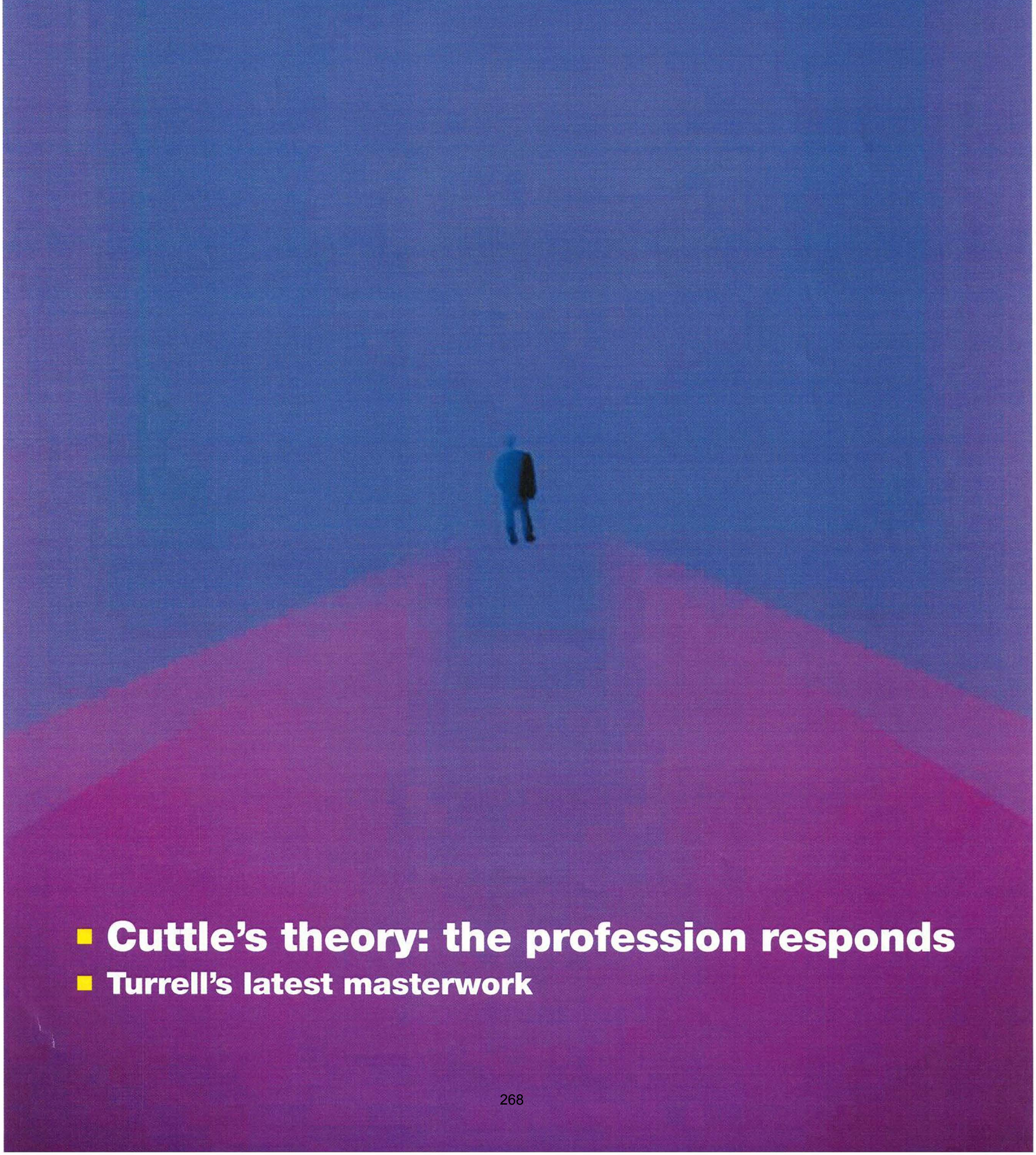
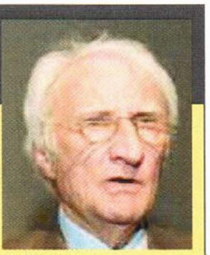


- **Cuttle's theory: the profession responds**
- **Turrell's latest masterwork**

Reflections on a

In the last issue, author and academic Kit Cuttle outlined his controversial new approach to lighting. Here leading practitioners and academics respond to his contention that reflected light should supersede horizontal illuminance

David Loe
Independent consultant



Kit Cuttle touches on a number of interesting issues relating to the lack of development in lighting design quality, a plea with which I have much sympathy. Most lighting installations aim to satisfy the basic requirements of visual function – in other words, sufficient task illuminance with the avoidance of discomfort glare, either direct or reflected – and by using the minimum amount of electricity. All of these are of course important, but if they are prescribed without considering the lit appearance of the room then the illumination is likely to be less than ideal for the occupants. And, if I understand Cuttle correctly, this is what he feels too.

My question is, how does luminous exitance help solve this problem? My experience and research have led me to see that people like working spaces to appear visually light and visually interesting, with areas of light and shade, which indicates to them that they have appropriate functional illuminance and a pleasant working environment. These signals may be psychological, but are likely to have positive effects on health and performance. For this I believe that luminance is the best measure that we have at present. Luminance combines illuminance and reflectance which the designer can specify and measure.

A further issue that Cuttle raises is the question of functional and amenity lighting. In my view both are important, but perhaps a room should be provided with amenity lighting, which responds to the architecture and the daylighting, leaving the client, with help, to then determine the necessary task illumination for the particular application. (Bearing in mind, of course, that the two lighting elements will need to be integrated.) Perhaps this could be a better way to proceed?

Peter Boyce
Author and academic

Given that visual tasks have become easier over time, there is clearly an opportunity to reduce recommended illuminances and thereby reduce the energy used for lighting, without deterioration in visual performance. Kit Cuttle's emphasis on spatial brightness as the main design criterion seems to neglect this opportunity. I think that a better approach would be to consider how to maintain a suitable perception of spatial brightness while minimising energy consumption.

A related matter is the assumption that what people now care about is the brightness of the space. I do not believe this to be their primary concern. First and foremost, what people want from lighting in a workspace is to be able to see what they need to see, in comfort. It may be that the perception of the brightness of the space is used as a marker as to whether or not they will be able to see what they need to see anywhere in the space, but if this correlation breaks down – which it might do if the main design criterion is mean room surface exitance – then dissatisfaction will inevitably result.

The brightness of the space is important, but not as important as the visibility of the tasks. For this reason, I believe an approach in which the lighting is first designed to provide the desired level of spatial brightness, leaving any task visibility problems to be overcome solely by ad-hoc measures, is misguided.

In addition, I believe that mean room surface exitance is a crude measure of brightness perception. The range of luminances present in the space and the spectrum of the light are also important.

Having said all that, I believe Cuttle is to be congratulated on pointing out the value of mean room surface exitance as a design criterion and the implications that would carry for the type of lighting adopted.

new light theory

Bob Venning

Consultant

I always find Kit Cuttle's work challenging and to some extent he is right in what he says. However, Waldram propounded the luminance design method, which never caught on, and I suspect that Cuttle's model will suffer from the same problems – lack of detail knowledge at tender stage as to the exact type of materials being used, their finish, colour and texture. All these are equally important to the design if it is to be progressed. We have always suffered the problem that architects or interior designers think about these elements far too late.

We try to integrate the lighting into the structure and finishes, and with other services. To do this means it has to be flexible enough to respond to changes to the design as the building is going up. Rarely does the designer have the luxury of designing the lighting with all the information he or she needs to hand.

Then there is the case of the office. How many people use 70/50/20 as surface reflectances? Maybe 70/25/35 would be a better estimate as there is invariably more glass wall and less solid wall than is generally considered.

I think that as a method it will go the way of the luminance design method. An interesting academic approach, but practically hard to implement.

Kevan Shaw

Kevan Shaw Lighting Design

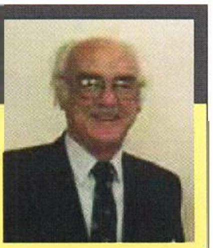
This was an excellent and well-explained proposal. Kit Cuttle's explanation clearly expresses what we all know to be the major limitations of considering lighting measured as the quanta of light falling on a surface. His well-thought out and excellently delivered paper ran so well together that it could have seemed almost too obvious or even glib. However, having read the published paper, and the comments and Cuttle's response, this really is one of those blindingly obvious ideas that we have all missed.

Using mean room surface exitance (MRSE) as a method of assessing the real appearance of a lit room has the potential to provide calculated values that have real meaning to, and a direct relationship between, a lighting calculation and visual appearance. Obviously the method requires some research to prove its effectiveness, and also refinement to enable calculation of spaces that are not box shaped or that don't have absolutely consistent surface reflectance. At a time when freshly MSc'ed lighting designers are finding it difficult to secure jobs this is an excellent PhD subject.

We are also all aware of how our existing method of working towards a target illuminance on a horizontal plane is often extremely wasteful of energy while not necessarily creating a good lit appearance to a room. MRSE appears to provide a tool that will allow us to demonstrate how to achieve an adequately lit space with the minimum of energy – a really valuable goal for lighting design now.

Kevin Poulton

K Poulton and Associates, lighting industry consultant, Australia



Kit Cuttle is quite right, horizontal illuminance (Ehor) is an obsolete and out of date illuminance metric. In fact it is both meaningless and nonsensical in the 21st century.

Cuttle's thesis that the illuminance at the plane of the eye is a more relevant indicator of the visual scene to which the eye will respond, for better or worse, is long overdue.This is particularly so in the case of non-task specific areas, such as public spaces, foyers or passageways, and even if a task is particularly difficult or small in detail then perhaps Ehor or Evert could be relevant as a supplementary metric.

For decades we have had two metrics that have largely been ignored: mean cylindrical illuminance (Ecyl) and half-mean cylindrical or semi-cylindrical illuminance (Esc). They are easy to calculate and they can be measured by means of a simple adaptor to the standard lux meter.

My own anecdotal evidence is that in public spaces an Ecyl of 100 lux and in task areas an Ecyl of 200 lux will produce a very pleasant visual environment. Obviously other parameters, such as suitable reflectances and the UGR, must be considered. No one metric is going to be the complete indicator of a satisfactory visual environment.

We should also include the work done by Kit and Joe Lynes in the 1960s on vector and scalar illuminance. What a pity these metrics are not in common usage, especially in these days of computerised calculation methods.

At the present time when the world's focus is on energy usage and efficiency, the lighting industry should be reviewing its specification and calculation methodologies and not be stuck, as Cuttle says, 'in the 1920s or 1930s'.

I would like to thank him for raising a most important and timely matter. I hope it will be the beginning of a debate we should have had years ago. In my opinion, our lighting standards and codes, in terms of illuminance recommendations, are archaic and should be revised.

Peter Raynham

Lecturer at the Bartlett, UCL

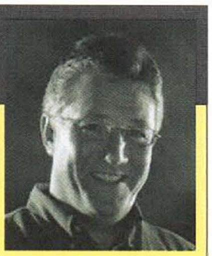
In the introduction to his paper Cuttle goes through the previous stages of the lighting profession where we have learnt to predict and control how much light a given installation will create and know how much light to provide for a particular task. He then correctly points out that we are providing more than enough light for our visual tasks and what we are really doing is lighting so that spaces look sufficiently bright. He then goes on to develop some ideas about the importance of luminous exitance and then uses Sumpner's principle to show how simple changes in room reflectances can have a big impact on the amount of light that bounces around the space.

His proposal that mean room surface exitance should be the key parameter for lighting designers is a little questionable. Clearly the amount of light coming from room surfaces is important to our perception of lightness within a space but it is a long way from being the be-all and end-all of lighting design. The problems are twofold. First of all the concept carries no information about the light pattern within the space, and tells us very little about the way objects will appear in the space. These two factors are intimately linked and, coupled with the direct distribution from the light sources, can make a big difference to the way a space appears.

What Cuttle's paper does do is provide a wake-up call to everybody who slavishly follows the schedule of the SLL Code without thinking about the distribution of light in the space, or worrying about the lit appearance of a space. The paper is very thought-provoking but it leaves us with more questions than answers.

Nick Hoggett

Partner, DPA Lighting Consultants



This theory is not only really interesting, but challenges current thinking in a way we need to do more often. Cuttle's methodology of considering the exit luminance from a surface is a totally valid and appropriate way of approaching lighting design. I have said for many years now that lux is a meaningless unit of light as far as human emotion is concerned. I think it is excellent that Cuttle has started to formalise some analytical data to support this method.

I believe that what he is suggesting is actually not new at all, and is in fact exactly the approach that we take to our work and have done so for many years, but we do it more instinctively than mathematically. When we are briefed for a project, once we understand the basic structures and usages, some of the first questions we ask are about the colour and texture of the materials that will be used.

His method, which I support, needs excellent knowledge of the materials and colours of surfaces, therefore, which it's often difficult to fix at the early stages of a project. If the wrong assumptions are made, spaces could be left over or underlit. This is the case with any lighting design approach, but perhaps more so when using only exit luminance. Cuttle's desire to engage architects to understand the importance of defining room surfaces early is an excellent goal. Other factors such as the introduction of furniture into a space also have greater relevance with this design philosophy, which is why it is so important to understand everything about a space when considering the lighting.

We do, however, have to ensure that the lighting solutions we conceive are not so rigid that they leave building owners and users with inflexible spaces, limited by the original colours. We have to ensure that a reasonable level of flexibility is achievable to allow for future changes.

I am not sure how feasible it will be to generate meaningful values for real projects using exit luminance because room surfaces are far more complex than just a single colour in a lot of instances. I can give many examples of this, but will quote two. First of all, what about a wall that is partly panelled, partly painted and then has a substantial part of its area covered with artwork? What about a room that has a highly decorated historic ceiling, where some parts are light, others are dark, some reflective and some not?

To adopt Cuttle's method and link it back to finite numbers will be an immensely complicated challenge, and one that I suspect will prove impractical to implement in anything other than simple rooms in terms of their surface treatments. Cuttle has quite rightly reiterated that this method is not just for the workplace, but for all building types and this again, in my opinion, is absolutely correct. We should consider the brightness of surfaces that humans experience as being of prime importance, rather than designing to standards related to task.

I am also sympathetic to Cuttle's opinion that many tasks can be carried out in relatively low light levels, and certainly lower than some current standards call for. However, again I think the subject is complex and issues such as duration of task need to be considered carefully. We want to use light to invigorate, enliven, stimulate, excite, relax or calm as is appropriate for that particular circumstance, at that particular moment in time. To achieve this needs human consideration as well as mathematical solutions.

Another area that Cuttle discusses which I entirely agree with, and talk about regularly, is how by lighting the surfaces that we need to light and not lighting other surfaces, tremendous savings in energy can be achieved.

To conclude, I completely support Cuttle's design philosophy using exit luminance as the primary factor to evaluate the quantity of light needed on a surface. But I do believe the complexities of most interior and external spaces, together with the aspirations of using light creatively, will make it very difficult to produce finite values that produce a definitive code for such an approach. It would, however, be fabulous if Cuttle could develop his approach further, as I believe it has great merit and is better than the current methodologies generally employed.

Volume 3. Issue 2. March/April 2010

Newsletter

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- **Simpson on the CIBSE presidency**
- **The 2010 Lighting Design Awards**

Viewed in a different light

Kit Cuttle comes back on the questions and issues raised by respondents to his proposed new lighting theory based on mean room surface exitance

It was, I suppose, inevitable that seeking to dethrone the visual task from its traditional role would arouse some ire. Peter Boyce has expressed the injured sentiment succinctly: 'First and foremost, what people want from lighting in a workplace is to be able to see what they need to see, in comfort.' However, my argument, which Peter Raynham supports, is that if normal-sighted people have nothing more difficult to see than a typical reading task, then the lighting levels that we conventionally provide for adequately lit environments are more than sufficient to meet their visual performance requirements. It is well established that providing high lighting levels does not improve the performance of easy visual tasks.

David Loe sees sufficient task illuminance, with concern for comfort and efficiency, as the primary objective, but he adds that the lit appearance of the room also needs consideration and wonders whether this is my view also. I have to say that my priorities are different. For me the primary objective is that the people who use the spaces that we illuminate should consider them to appear adequately lit. Furthermore, I want to see an end to visual task difficulty being quoted as the principal determinant of how much light we provide.

Boyce claims that, 'the brightness of the space is important, but not as important as the visibility of tasks', so let us take a look at lighting for visibility. Whether we are lighting for commercial display, or for an exhibition of art, or for quality control in industry, or for the law office clerk who has to read the small print, the aim is to reveal certain visible attributes of the illuminated objects. Seen in this way, the paper-based reading task is a special case: it is two-dimensional, and it is diffusely reflecting, with the result that visibility is inevitably a function of illuminance.

This is not the general case. For three-dimensional objects the aim is likely to be to reveal form or texture; or for surfaces that are not diffusing reflectors, it may be revealing gloss or creating highlights. Despite these and many other variations of object attributes for which lighting may be designed to impart visibility, the reading task forms the entire basis for the research-based knowledge we have for visual performance. It is this deficiency in our knowledge that has given rise to three generations of lighting professionals being deluded into believing that provision for task visibility comprises application of an appropriate level of illuminance on to a notional task plane. Should any reader fail to feel convinced on this point, I challenge them to propose a commonly occurring difficult visual task for which the best solution is to provide a high level of overall workplane illuminance.

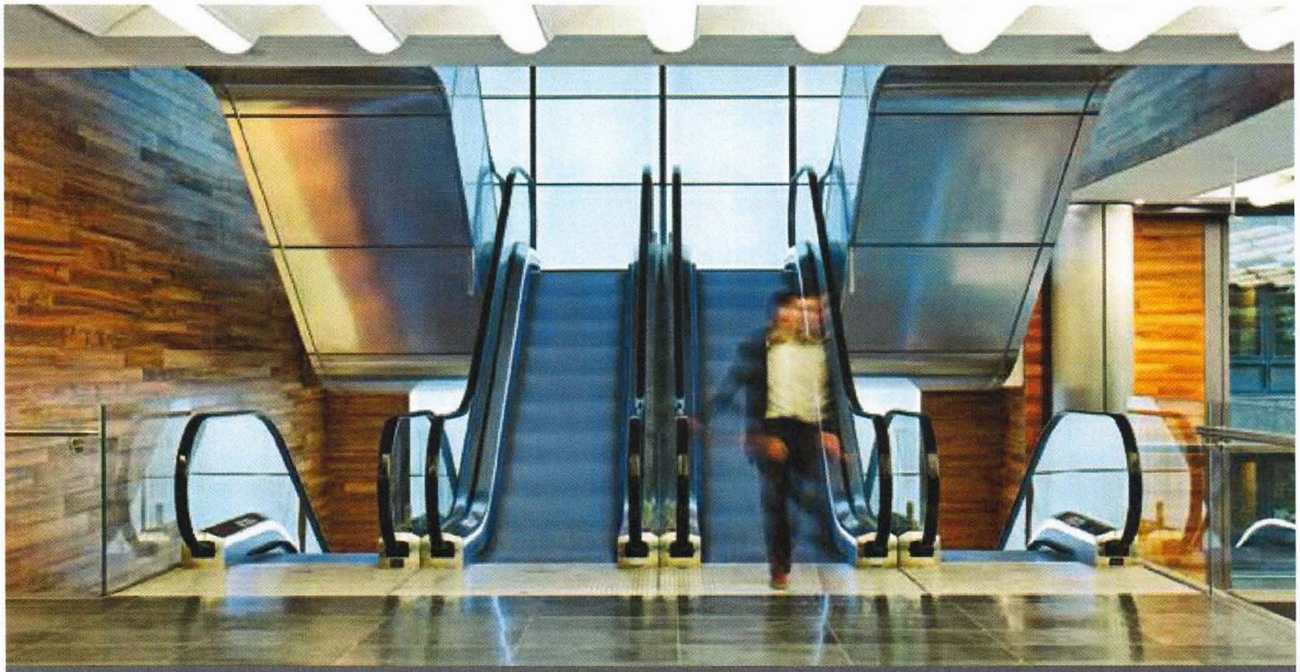
Kevin Poulton is adamant that workplane illuminance schedules are obsolete, and of course I support him in this. He recounts how he has been giving thought to alternative illumination metrics and, as he points out, this is an area that has interested me for many years. However, the mean room surface exitance (MRSE) concept has an important difference. It takes account only of reflected light, as it excludes all direct light from luminaires or windows. My reasoning for this is that direct light arriving at the eye is glare, which does not contribute to the perception of an adequately lit room.

However, research may indicate that simply ignoring this component is not the right approach. It may be postulated that glare has the effect of raising the visual adaptation level, causing surroundings to appear darker, so that for high UGR locations it would be necessary to provide higher values of MRSE to achieve perceived adequacy of illumination. This would be an interesting development, as it would indicate that the benefits of glare control are not restricted to avoidance of visual discomfort, but also open up opportunities for higher levels of energy efficiency.

> **'I persist in the belief that change is inevitable. The open question is whether the motivation for change will come from within the profession or from outside'**

The opportunities offered for improved efficiency are not wasted on Kevan Shaw and Nick Hoggett, whose comments are welcome not just for their enthusiasm, but even more so because they see that this is not simply an alternative way of measuring lighting, but a changed way of thinking about lighting. Whereas Bob Venning comments that, 'Rarely does the designer have the luxury of designing the lighting with all the information he or she needs to hand', these designers know that it is not possible to deliver lighting suited to a particular location without having the information to predict how light will interact with the surrounding surfaces.

Shaw makes the comment that MRSE has the potential to provide 'real meaning to, and a direct relationship between, a lighting calculation and visual appearance.' How have we stumbled along for so long without this? Hoggett sees this approach not to be new, but to be closely in line with the procedure that he and his colleagues would engage in with their clients to develop design strategies. The notion that it might become general practice for the



Ropemaker Place, City of London. Image courtesy of Zumtobel

It's important to recognise that room surfaces are as much a part of lighting as luminaires and windows, says Cuttle. 'For this to become explicit in our codes and standards would be a step forward for the profession.'

engineers, architects and interior designers involved in either specifying or planning lighting installations to start from the same set of basic concepts could totally transform attitudes towards the role of lighting in buildings.

Nevertheless, even the enthusiasts do not see plain sailing ahead. Hoggett worries that we will need to make allowances for what may happen later, but it is a simple fact of life that if a building owner or operator changes the room surface reflectances, they will change the lighting distribution. If they do this without consulting anyone who knows anything about lighting, there is a high probability that the result will be disappointing. If standards come to be specified in MRSE, they might also find that they are out of code compliance, and I do not see how lighting professionals could, even if they wished to, make allowance for that.

Venning acknowledges that lighting decisions are often based on assumed surface reflectances, but at the end of the day, we all need to recognise that room surfaces are as much a part of lighting as luminaires and windows. For this to become explicit in our codes and standards would be a step forward for the profession.

The aim of this proposal is to specify the level of provision of illumination for general lighting practice in a way that corresponds with assessments of whether or not a space appears to be adequately lit. We should expect that a level of illumination that may be found adequate in a waiting room or hotel lounge is likely to be assessed as inadequate in a workplace, sports hall, or fast-food outlet. The justification for a level specified for a particular context would be: 'If the lighting fails to measure up to this level, it is likely that a significant number of occupants will assess the space to appear dull, gloomy and inadequately lit.' It should be obvious that this is not a condition that could be prescribed with a high level of precision. Nonetheless, the crux of my argument is that this concept provides a far more valid basis for lighting standards than does visual performance. As explained above, there is no generally applicable relationship between illuminance and visual performance.

To be practical, we need a measure of 'perceived adequacy of illumination' that is both simple and reliable. MRSE certainly is simple (divide first reflected flux by room absorption – you can't get more simple than that) but is it reliable? Hoggett worries about non-uniform surfaces; Raynham is concerned about the light pattern in the space; Loe considers that luminance values are necessary, and Boyce believes the lamp spectrum also has to be specified.

In your mind's eye, imagine a plain, uniform-reflectance wall. Now replace that wall with one that has the same overall average reflectance, and is reflecting the same total amount of light towards you, but in this case the reflectance is non-uniform. Why should this wall appear any more, or any less, adequately lit? The two walls will look different, but I can think of no good reason to suppose that one may appear adequately lit but not the other. We need to keep in mind that we are not seeking, to use Raynham's term, the 'be-all and end-all of lighting design', but simply an indicator of adequacy. We do not expect a building code to ensure good architecture, and we should not expect our lighting code to ensure good lighting design. The purpose is to specify for adequacy and fitness for purpose without compromising design objectives. The problem is that our illuminance schedules fail to do this.

So where will all of this discussion lead us? Venning sees the status quo to be so dominant that even good ideas, such as JM Waldram's proposals, could have no chance of changing the basis of lighting practice. Nonetheless, I persist in the belief that change is inevitable. The open question is whether the motivation for change will come from within the profession or from outside, as other practitioners become increasingly aware of the deficiencies in the theoretical basis of the illuminance schedules that are perceived to form the core of our recommendations for general lighting practice.

Kit Cuttle's paper, Third Stage of the Lighting Profession, is published in the March issue of LR&T (Vol 42, no 1), also available online to members at www.sll.org.uk. See NL Nov/Dec 2009 for the original article and NLJan/Feb 2010 for responses from the lighting profession. ■

Appendix B: Candidate's recent publications

Cuttle C, 2017. A fresh approach to interior lighting design: The design objective – direct flux procedure. *Submitted for publication in Lighting Research and Technology,* June 2017.

Cuttle C, 2017. Integrating useful lighting metrics into the design process. *Submitted for presentation at the Professional Lighting Designers Convention, Paris, 1-4 November 2017.*

A fresh approach to interior lighting design:
The design objective – direct flux procedure

C Cuttle MA, FCIBSE, FIESANZ, FIESNA, FSLL
Wellington, New Zealand

Short title: A fresh approach to interior lighting design

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A procedure is proposed to guide the design process from devising a combination of lighting design objectives relating to human response to lit environments to developing a direct flux distribution that specifies how luminaires are required to direct flux onto selected target surfaces to optimally satisfy the design objectives. A selection of previously-published lighting concepts is reviewed in the light of recently-published research, and based on these concepts, the procedure takes the form of a downloadable spreadsheet that enables users to prioritise between efficient flux utilization and the achievement of design-oriented objectives. While it is recognised that more research is needed before the procedure could be adopted for general application, the aim of this paper is to demonstrate the opportunities offered by a practical alternative to current lighting practice.

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Terms and acronyms used in the text

Ambient Illumination
The diffusely inter-reflected flux field within the volume of an enclosed space. The average flux density of ambient illumination may be specified by a MRSE value.

Direct flux distribution (DFD)
A specification of the direct flux received from luminaires or windows (ie, excluding inter-reflected flux) by each target surface ($F_{ts(d)}$) to optimally satisfy a lighting design objectives (LDO) combination.

First reflected flux (FRF)
The total quantity of direct flux that is reflected back into a space from all room surfaces. More specifically, it is the summation of direct surface illuminance, surface area, and surface reflectance, $FRF = \sum E_{rs(d)} A_{rs}\, \rho_{rs}$. FRF may be estimated by rearrangement of Cuttle's formula (see *MRSE*), $FRF = MRSE\ .A\alpha$

Flux utilization (U_F)
The efficiency with which direct flux is applied for achieving mean room surface exitance. Specifically, $U_F = \sum M_{rs} A_{rs} / \sum F_{ts(d)}$, where $\Sigma F_{ts(d)}$ is the total direct flux.

Illumination efficiency
An ordered distribution of target/ambient illuminance ratio (TAIR) to optimally satisfy a lighting design objectives (LDO) combination that prioritises flux utilization. (See Section 3.4)

Illumination hierarchy
An ordered distribution of target/ambient illuminance ratio (TAIR) to optimally satisfy a lighting design objectives (LDO) combination that prioritises visual emphasis. (See Section 3.5)

Lighting design objective (LDO)
Describes a specific aspect of lighting to be provided. Whenever practical, a LDO is not only described, but also specified quantitatively. The overall purpose for which lighting is to be provided for a specific application is defined by a LDO combination.

Mean room surface exitance (MRSE)
The average luminous flux density of the diffusely inter-reflected light field within the volume of an enclosed space. Equal to the area-weighted average of exitance levels of room surfaces, $MRSE = \sum M_{rs} A_{rs} / \sum A_{rs}$. Serves as the measure of ambient illumination within an enclosed space. MRSE may be predicted by Duff's precise method,[9] or estimated by Cuttle's formula,[1-3] $MRSE = FRF/A\alpha$.

Perceived adequacy of illumination (PAI)
The ambient illumination level (MRSE) assessed by a (high) proportion of people to provide for the appearance of a space being adequately lit for its associated activity.

Room absorption (Aα)
A measure of the capacity of a space to absorb flux. More specifically, it is the summation of room surface areas and their absorptance values, $A\alpha = \sum A_{rs} (1 - \rho_{rs})$

Room surfaces
The surfaces that form the boundaries of the light field within an enclosed space or room. Typically, room surfaces include furnishings and the areas of ceiling, walls and floor not obscured by furnishings. *Abbreviations: rs, an individual surface; rms, all room surfaces.*

Surrounding brightness (SB)
Assessment of how brightly-lit, or dimly-lit, room surfaces appear to be. May be rated on a seven-point dim/bright scale (See *Section 3.2, The SB/MRSE relationship.)*

Target/ambient illuminance ratio (TAIR)
The ratio of illuminance incident on a selected target surface relative to the ambient inter-reflected light level. Using mean room surface exitance as the measure of ambient illumination level, $TAIR = E_{ts}/MRSE = (E_{ts(d)} + MRSE)/MRSE$

Target illumination
The sum of direct and ambient illumination received by target surfaces.

Target surfaces

Room surfaces or objects selected to receive direct flux (see DFD). May be selected to raise MRSE, or to achieve visual emphasis. *Abbreviations: ts, a target surface; tgs, all target surfaces.*

Visual emphasis

The perceived effect of direct illumination being applied selectively to chosen objects or surfaces, usually for the purpose of making them appear more conspicuous, or to provide for enhanced discrimination of detail.

1. Introduction

Lighting practice as it developed during the first half of the last century was based on the notion that the prime purpose of lighting was to enable visual tasks to be performed efficiently. It is for this reason that interior lighting practice continues to be directed towards providing uniform illumination over the horizontal working plane, irrespective of the nature of human activity. The author has argued that this is seldom appropriate, and that the community at large would be better served if lighting practice was based on meeting (or exceeding) peoples' expectations for how lighting affects the appearance of lit spaces and their contents.[1-3]

The author has proposed that peoples' assessments of how brightly-lit, or dimly-lit, an enclosed space appears to be may be related to the average exitance of the visible surfaces within the space, where exitance is the density of luminous flux (lm/m^2) exiting, or emerging from the surfaces. The lighting metric proposed as relating to this perceived effect is mean room surface exitance,[1-3] where:

$$MRSE = \frac{\sum M_{rs} A_{rs}}{\sum A_{rs}} \qquad (1)$$

Where: M_{rs} = exitance of room surface rs
A_{rs} = area of room surface rs

While equation (1) appears straightforward, prediction involves iterative calculations of diminishing quantities of inter-reflected flux, and to avoid this complication, the author has employed Sumpner's principle[4] for a simplified expression (referred to as Cuttle's formula):

$$MRSE = \frac{FRF}{A\alpha} = \frac{\sum E_{rs(d)} A_{rs}\, \rho_{rs}}{\sum A_{rs}(1-\rho_{rs})} \qquad (2)$$

Where: FRF = first reflected flux lm
$A\alpha$ = room absorption
$E_{rs(d)}$ = direct illuminance on room surface rs lx
P_{rs} = reflectance of room surface rs

While this expression might appear more complicated, it is in fact simpler to calculate, and it gives insight into the nature of MRSE. Light emerging from the luminaires travels through the space without visible effect until it undergoes its first reflection. In an enclosed space, the first reflected flux (FRF) then undergoes multiple reflections until it is completely absorbed, and the greater the room absorption (Aα), the more rapidly this process occurs. In this way, MRSE serves as the measure of the density (lm/m^2) of the diffusely inter-reflected light field within the volume of an enclosed space.

MRSE forms the basis of a procedure (henceforth referred to as 'the procedure') for devising lighting solutions that relate to peoples' assessments of how the appearance of their surroundings are affected by the quantity and distribution of illumination. Please note that when terms defined in the *Terms and Acronyms* section are used for the first time in the text, they are shown in bold italics.

2. The procedure

Lighting Design may be described as the process of defining a combination of ***lighting design objectives*** (LDOs) for an application, and devising a lighting system to optimally satisfy the LDO combination. While individual LDOs may relate to a broad range of criteria covering aspects such as light source colour characteristics and discomfort glare control, the procedure considers specifically LDOs that relate to either the quantity or the distribution (spatial, not spectral) of illumination in indoor spaces.

The lighting design process may be seen as comprising three stages. The first stage involves specifying the lighting design objectives; the second stage involves specifying the required lighting installation performance to satisfy the objectives; and the third stage involves selection of luminaires and development of a layout to meet the performance requirements. The procedure relates to the first two stages of the design process. For the first stage, it identifies aspects of how the quantity and distribution of illumination that affect the appearance of lit spaces may be specified in quantitative terms as LDOs, and then in the second stage, it leads to the development of a ***direct flux distribution*** (DFD). The DFD is the distribution of direct flux from the lighting installation (which may comprise luminaires or windows) onto selected target surfaces that will produce the required overall quantity and distribution of illumination within the space, including effects of inter-reflected flux. The purpose of the DFD is to optimally satisfy those lighting design objectives (LDOs) that address how lighting is to influence the appearance of surrounding room surfaces, furnishings, and other objects within the space. The outcome is that the designer has to hand a specification of the direct luminous flux to be delivered onto selected surfaces that will generate the overall ***ambient illumination*** and the distribution of ***target illumination*** to optimally satisfy the lighting design objectives.

It should be noted that the procedure does not form a complete design process. However simple or complex, the design process starts with the designer selecting, or envisaging, a concept for how the appearance of a space is to be affected by lighting, and developing a combination of lighting design objectives to achieve the concept. The procedure then provides a bridge between this LDO combination and a specification of how light is to be distributed within the space to achieve it. From this point, the designer is able to select luminaires (or devise daylighting controls) with knowledge of how their performance contributes towards achieving the concept. It may be noted that this is a reversal of the procedure employed by the time-honoured lumen method. That procedure involves selecting a luminaire, devising a layout, and performing a calculation to assess the performance. This procedure involves determining the required performance, devising a flux distribution to provide it, and selecting luminaires to achieve it. In fact, this is the procedure is widely used by those lighting designers who never have accepted the constraints of the lumen method.

For simplicity, the examples in the following text relate to lighting provided by luminaires, but the same principles would be equally applicable to daylighting practice.

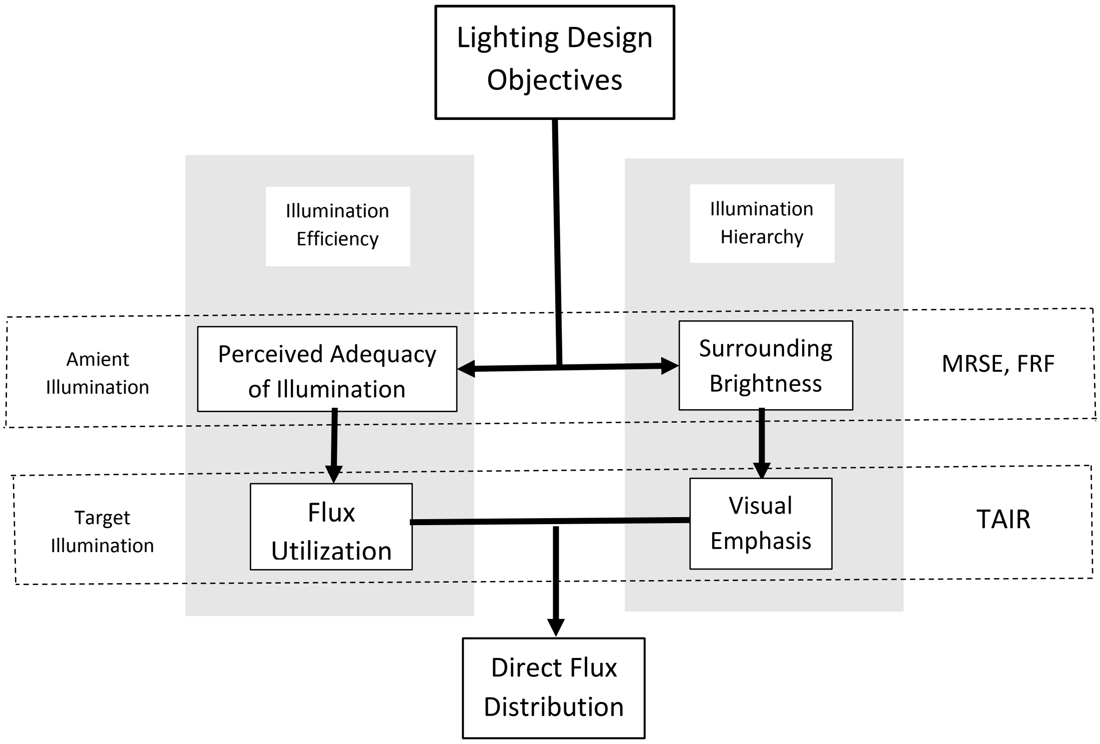

Figure 1. The LDO – DFD Procedure guides the lighting design process from a combination of lighting design objectives to a direct flux distribution. See text for explanation.

2.1 Ambient illumination

Figure 1 shows the outline of the procedure. When the designer has determined the combination of lighting design objectives, the first step of the procedure is to determine the ambient illumination, which concerns how brightly-lit, or dimly-lit, the space is to appear, and this confronts the designer with a decision that is crucial throughout the design process. The left-hand track gives priority to ***illumination efficiency***, which concerns the efficiency with which flux is applied to satisfy the LDO combination, and the right-hand track gives priority to ***illumination hierarchy***, which concerns the development of a structured distribution of illumination to satisfy (or exceed) peoples' expectations for a well-lit indoor space.

Illumination efficiency is always a concern, and where this is given high priority, the aim will be to specify a lighting installation that provides efficiently for the ***perceived adequacy of illumination*** (PAI) criterion. In due course, regulators may choose to specify minimum levels of PAI in lighting standards that relate to various indoor human activities. Alternatively, the designer may choose to give higher priority to the illumination hierarchy, in which case the ambient illumination may be determined by selecting a level of ***surrounding brightness*** (SB), which may range from very dim to very bright, according to the lighting design objectives. Whether the LDOs prioritise PAI or

SB, ambient illumination is specified by ***mean room surface exitance*** (MRSE), from which the ***first reflected flux*** (FRF) to provide the mean room surface exitance level within the space is determined.

The specification of ambient illumination defines the density of diffusely inter-reflected flux within the volume of the space. The difference between exitance-based and luminance-based metrics is an important distinction. Exitance, being the density of luminous flux exiting, or emerging from a surface, is independent of viewing location or direction, and as applied in the procedure, relates to an overall impression of surrounding brightness within an enclosed space. Luminance is a directionally specific quantity, and is the metric used to specify brightness distribution within a defined field of view from a specific location.

2.2 Target illumination

Referring back to Figure 1, the next step is to determine the ***target illumination***. Sufficient direct flux needs to be applied to surrounding surfaces to provide the first reflected flux to generate the required mean room surface exitance, and in deciding how this flux is to be distributed, the designer again prioritizes between illumination efficiency and illumination hierarchy. Where high priority is given to illumination efficiency, the aim will be to distribute flux to maximize the ***flux utilization*** to provide the required FRF, but where the LDOs call for selective ***visual emphasis***, priority is given to creating an illumination hierarchy.

For maximising the utilization of direct flux, the guiding principle is to direct flux onto high reflectance surfaces, and this is discussed in Section 3.4. Alternatively, designing for visual emphasis involves identifying objects or surfaces for selective illumination, and for this the LDOs depend upon the human activity. In a workplace, it is likely to be visual tasks that are identified; in a retail situation, it will be merchandise; in a public area, it might be displayed objects or the architectural features of the space. Designing for such LDOs is discussed in Section 3.5, but whatever the priorities, target illumination is specified by ***target/ambient illuminance ratio*** (TAIR) values.

The overall procedure may be facilitated by an interactive spreadsheet (an example is given in Section 5.3) which guides the designer from the LDOs to the direct flux distribution (DFD). The situation in which this outcome places the designer is: *The specified quantities of direct flux are to be directed onto the identified objects and surfaces, and this will achieve the predetermined overall surrounding brightness, together with the intended balance of priority for either efficiency or visual emphasis.*

3. Functional relationships

The workings of the procedure depend upon definition of four functional relationships that are not part of conventional lighting methodology. These functional relationships are crucial.

There have been past proposals to replace horizontal working plane illuminance specifications with luminance-based lighting metrics, most notably Waldram's 'designed appearance method',[5] more recently followed by 'spatial brightness',[6] and 'scene brightness'.[7] Generally these assume a fixed viewing position and direction of view, enabling the field of view to be specified as a luminance distribution, except in the case of scene brightness, for which it is specified by illuminance measured at the eye normal to the viewing direction.

The exitance-based metrics[1-3] on which this paper is based are distinctly different, as exitance, being the density of luminous flux exiting, or emerging, from a surface, is independent of viewing direction. While the *mean room surface exitance* (MRSE) within a space is defined by the area-weighted average exitance of all room surface surfaces, it is a single value which specifies the average density of diffusely inter-reflected flux within the volume of the space. Similarly, *surrounding brightness* (SB) is a single overall assessment of how brightly-lit, or dimly-lit, the space appears to be. It is independent of viewing location and direction, and assumes that the assessment is made by a person who has had an opportunity to look around within the space and to gain an overall impression.

To date, only one research study specifically related to the author's initial proposal of exitance-based metrics[1-3] has been reported. Between 2011 and 2016, James Duff completed his PhD research studies[8] investigating the author's concepts at the Dublin Institute of Technology, under the supervision of Dr Kevin Kelly, and with the author enrolled as advisor.

3.1 Duff's research

The scope of Duff's studies of exitance-based metrics is extensive. He developed procedures for measurement and calculation;[9] he compared the accuracy of alternative prediction formulae;[10] and he conducted experiments which involved subjects making subjective assessments of their surrounding environments.[11,12] The outcomes of these experiments are examined in the following section, and are shown to be particularly relevant to this paper.

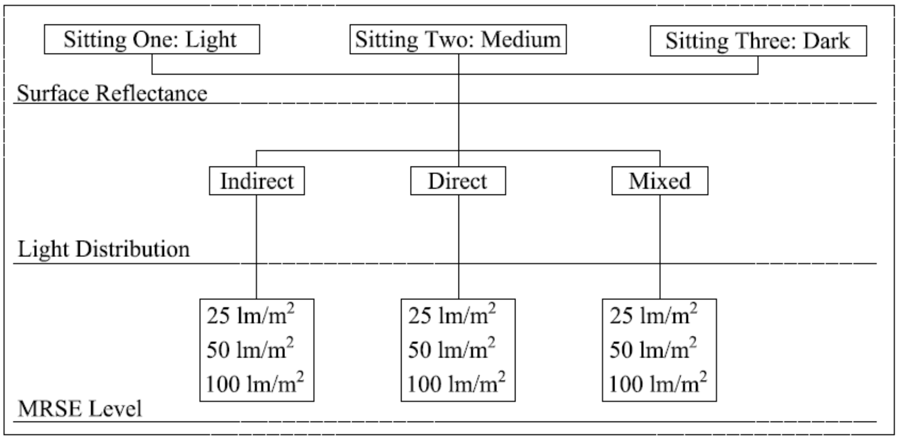

Figure 2. Duff employed the same format for both experiments,[11,12] with 26 subjects attending three sittings. At each sitting they were presented with a different set of surrounding surface reflectances, where they assessed nine combinations of three light distributions, and three mean room surface exitance levels.

The first experiment involved subjects making brightness assessments while looking into a laboratory lighting booth,[11] and for the second experiment, they were seated in a small office and they assessed both brightness and illumination adequacy.[12] A feature of these experiments was the consistency with which the experimental conditions were maintained. For both experiments, the same group of 26 subjects was presented with 27 viewing situations, nine at each of three sittings. As indicated in

Figure 2, for each sitting, the variables comprised three levels of mean room surface exitance - 25, 50 and 100 lm/m^2 - and three distributions of luminaire flux - direct, indirect, and a mixture of the two. The nine combinations of these variables were presented in randomised order, and then, for each of the sittings, the reflectance values of the room surface surfaces were changed. The décor maintained the convention of ceilings being of higher reflectance than walls, and floors of lower reflectance, and both experiments presented a sequence of relatively light, medium and dark room surface surfaces, in that order.

3.2 The Surrounding brightness / Mean room surface exitance (SB/MRSE) relationship

Throughout all three experiments, subjects assessed the overall brightness of their surroundings after two minutes of exposure on a seven-point surrounding brightness scale:

7. Very bright
6. Bright
5. Slightly bright
4. Neither dim nor bright
3. Slightly dim
2. Dim
1. Very dim

In Figure 3, these responses form the scale of surrounding brightness, SB. Duff reported them as ‘spatial brightness’, which might cause confusion with other reported studies of luminance distributions within a specific field of view,[6] but Duff’s experimental conditions do in fact correspond with the author’s definition of surrounding brightness (see Terms and acronyms). Each point on the chart is the average of 26 subjects’ responses to nine combinations of luminaire distribution and room surface lightness. While the SB/MRSE trends are strongly significant, the differences of luminaire distribution and room surface lightness were found to be not significant. Duff also recorded levels of horizontal working plane illuminance, which showed only weak correlation with SB.[10,11]

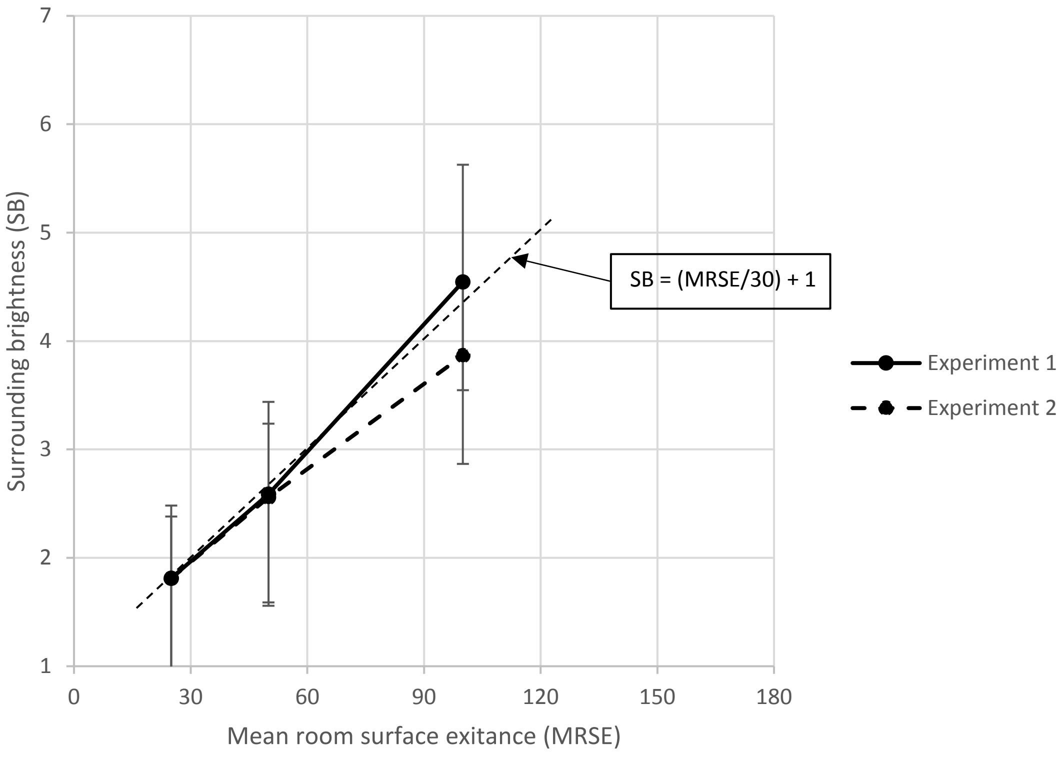

Figure 3. Means and standard deviations for surrounding brightness responses relative to mean room surface exitance, for Duff's Experiment 1 (lighting booth) and Experiment 2 (small office).[11,12]

There is strong indication here of a linear SB/MRSE relationship expressed by the indicated trendline, but some caution needs to be applied. The limited range of MRSE levels, 25 – 100 lm/m^2, has effectively restricted SB responses to the range of SB2 (dim) to SB4 (neither dim nor bright). While the responses may be seen to accord reasonably well with the author's earlier proposal that a MRSE of 100 lm/m^2 is "the lowest level for acceptably bright appearance", and that 30 lm/m^2 corresponds to a "dim appearance",[1,3] it is a distinct limitation that there are no responses that rate even slightly bright.

These brightness assessments should not be confused with the classical brightness studies for which subjects viewed target surfaces presented against uniform backgrounds leading to brightness/luminance relationships defined in terms of logarithmic functions, which have been successfully applied to situations such as specifying the brightness of emergency 'Exit' signs or roadway warning signs.[6] Duff's assessments concern how brightly-lit, or dimly-lit, an enclosed space may appear, and the seven-point scale relates directly to this aspect of appearance. However, it should not be assumed that the intervals on this scale are uniform, that is to say, that the difference between 'dim' and 'slightly dim' is the same as the difference between 'bright' and 'very bright', and for that reason it is important that research is extended to cover the entire range of the scale. As it stands, the linear trend shown here suggests that MRSE would need to be reduced to zero for the average response to be SB1 (very dim) which seems improbable, and much less likely, a SB7 (very bright) response would occur at merely 180 lm/m^2, this being a value that may be commonly exceeded in practice. It would seem likely that an extended range of MRSE conditions would indicate a sigmoid form of function.

`It would seem reasonable to conclude that SB and MRSE are related, as the finding that their inter-relationship was unaffected by three levels of both luminaire flux distribution and room surface lightness values, provides reasonable support for the notion that MRSE may serve as a reliable metric for specifying SB in lighting practice. This would enable typical assessment of how lighting affects the overall appearance of how brightly-lit, or dimly-lit, a space appears to be, to be specified on a descriptive scale that would be equally understandable to lighting designers and to the people that they provide their services for. It may be noted that the recorded values of horizontal illuminance showed only weak correlation with SB, with substantial scatter due to the flux distribution and surface lightness variables.[11,12]

Even though further research studies are needed before the SB/MRSE function can be reliably applied in practice, the SB4 level (neither dim nor bright) is of particular interest for regulators as it may be seen to represent the lowest surrounding brightness level that is not perceived to be even slightly dim. As such, regulators may find that the corresponding MRSE value of 90 lm/m^2 serves as an appropriate amenity level for specifying lighting standards, but again, more research will be needed to confirm this value.

3.3 The Perceived Adequacy of Illumination / Surrounding brightness (PAI/SB) relationship

For the second experiment, which was conducted in the small office, subjects made the binary assessment, ‘yes’ or ‘no’, as to whether the lighting was perceived to be adequate.[12] They were seated at a desk, and the activity associated with the space was obvious.

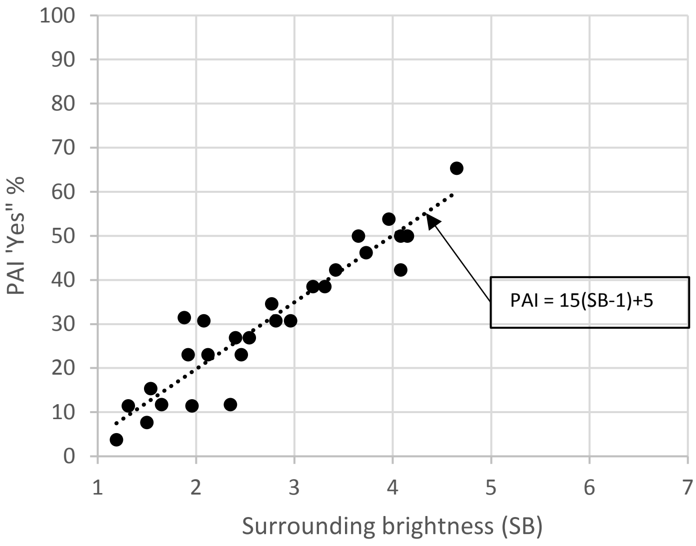

Figure 4. Percentage of ‘Yes’ perceived adequacy of illumination (PAI) responses relative to surrounding brightness (SB), from Duff’s experiment in the small office.[12]

Figure 4 shows the percent positive perceived adequacy of illumination (PAI) responses relative to average surrounding brightness (SB) assessments for the 27 viewing conditions. The trend rates strong statistical significance and suggests a linear relationship as indicated,[12] but again, the limited range of MRSE and SB levels restricts the conclusions that can be drawn. As noted previously, SB assessments generally did not exceed SB4 (neither dim nor bright), and as a consequence PAI ‘Yes’ ratings were limited to around 50%, which is far too low for setting a lighting criterion. While it is never practical to set standards to ensure 100% satisfaction, a criterion of at least 90% (or better, 95%) is necessary to provide for an acceptable level of satisfaction.

It is, nonetheless, interesting to note that 50% of the subjects rated the SB4 level to be inadequate for office work. This indicates that as the subjects were aware of the nature of the activity in this space, their responses indicated that it would require a level of surrounding brightness distinctly higher than an amenity level to achieve an acceptable PAI rating. This application has long been regarded as the illuminance level benchmark for task lighting, and there will need to be discussion to determine an appropriate adequacy criterion for PAI. It is not possible to identify an appropriate value from the reported research, and also, research needs to be extended to include activities other than office work.

3.4 Utilization of direct flux for providing surrounding brightness

As has been mentioned, utilization of direct flux is one of several factors that determine the efficiency of a lighting installation, but if lighting practice is to shift its focus from illuminating the horizontal working plane to providing surrounding brightness, then a substantial re-evaluation of flux utilization needs to occur.

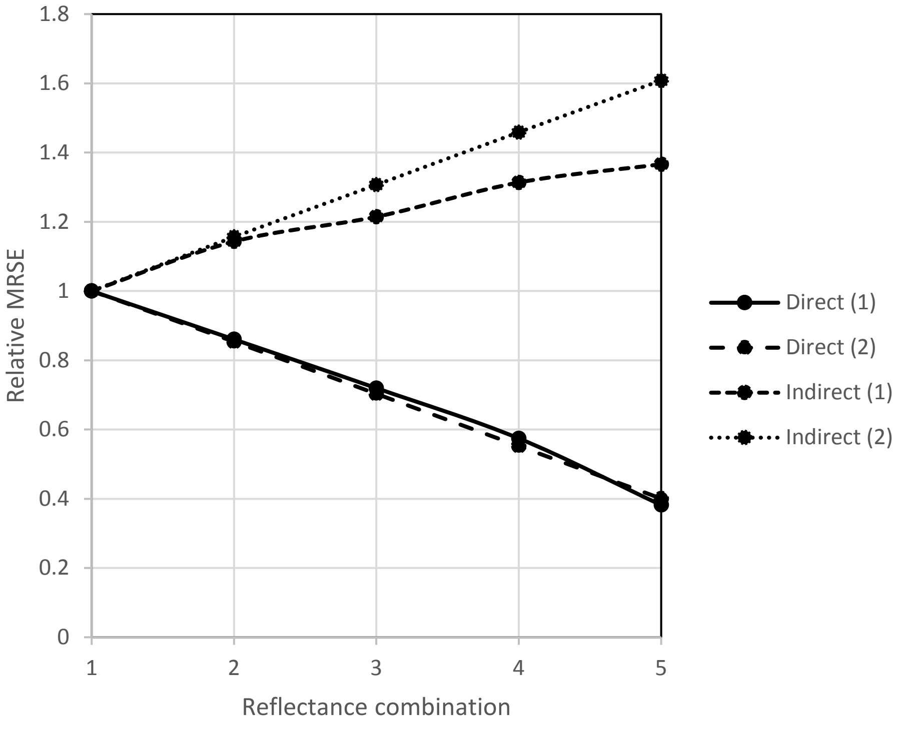

Figure 5. Mean room surface exitance due to two luminaires, one providing direct lighting and the other indirect lighting, both having the same flux output, in a room where the room surface reflectance combination is varied, but the average reflectance is always 50 percent. MRSE calculations were made using Duff’s definitive procedure (1), and Cuttle’s formula (2), and are shown relative to the value for reflectance combination 1. Ceiling/wall/ floor reflectance combinations are: 1 = 50/50/50; 2 = 60/50/40; 3 = 70/50/30; 4 = 80/50/20; 5 = 90/50/10.[10]

As part of Duff's assessment of the accuracy of alternative predictive formulae,[10] he compared mean room surface exitance values calculated for a reference room by his own definitive procedure (1)[9] with values calculated by Cuttle's formula (2),[1,3] as shown in Figure 5. The relative values shown in the chart indicate that if all room surfaces are of the same reflectance, then for providing MRSE, it makes no difference how the flux is distributed. For conventionally decorated spaces, where ceilings are lighter and floors are darker than walls, then as reflectance diversity increases, so the efficiency of indirect lighting to provide MRSE increases, and the efficiency of direct lighting reduces. It may be noted that while both formulae show these effects, Cuttle's formula deals satisfactorily with the direct luminaire, but tends to over-rate the utilance advantage of indirect lighting.

The first striking feature of Figure 5 is the extent of the difference between the direct and indirect light distributions. Clearly, when the objective is to provide for surrounding brightness, room surface reflectances are far more influential than they are when providing for visual task illuminance. Perhaps reflectance combination 5 is somewhat extreme, but for the more typical combination 4, the indirect luminaire achieves more than double the utilance of the direct luminaire, which turns conventional understanding of luminaire efficiency upon its head. Anyone who has experience of providing standards-compliant lighting knows that while uplighting may be a rather attractive way of providing illumination, it is far too inefficient for everyday applications. What that mindset fails to recognise is that while downlighting is the efficient way to illuminate the horizontal working plane (and a light meter located on it), direct flux travels through space without visible effect until it undergoes a reflection, so that in a conventionally decorated space, it would be typical for three-quarters of the flux to be absorbed on contact with the floor without having caused any visible effect. On the other hand, for uplighting it would be typical for three-quarters of the direct flux to be usefully reflected back into the space.

Nonetheless, it needs to be recognised that these assessments are over simplistic. The rate of reflection (and its counterpart absorption) of luminous flux within a space is determined by all the room surfaces, including the furniture, the windows, and the pictures hanging on the walls. It should not be overlooked that after the luminaires have emitted their flux, they become light absorbers, whether set into the ceiling or hanging from it. It is traditional in lighting practice to assume an empty room for determining the utilization factor, but for the levels of reflectance used for exitance calculations to have reasonably reliable correspondence with those that will apply in practice, it is necessary for consideration to be given to the likely effects of the actual room contents. For this reason, the term ***room surfaces*** is introduced (see Terms and acronyms), and this concept should always be applied for quantification of mean room surface exitance.

This concept of *room surfaces* challenges the very notion of 'an efficient luminaire'. It requires the purpose of the luminaire to be understood as providing the first stage of light distribution control, which involves directing flux onto selected surfaces to initiate the second stage of generating the inter-reflection process, which creates the distribution of target illumination that stimulates the eye. If the furnishings are changed, or if the room is redecorated, the lighting is changed. In fact, whenever someone walks into a room, the mean room surface exitance drops. The person's body has increased the room absorption, and thereby, the rate at which lumens are being absorbed. While the difference caused by one person may be safely discounted, the difference between an empty reception area and the same space full of people might be noticeable, and a thoughtful designer could take this into account. Designers will need to make sensible judgements as to the level of detail for which they define room surface reflectance values, but meanwhile, lighting-conscious people might choose to identify themselves as such by wearing white clothing, although the author's observation of the clothing favoured by professional lighting designers suggests that they seem to aim to cause maximum lighting disturbance!

This way of understanding the behaviour of light in an enclosed space may be explained by rearranging Cuttle's formula[1-3] as $MRSE = FRF/A\alpha$, where FRF is the variable affected by flux distribution. The underlying principle is: *For efficient flux utilization to provide for mean room surface exitance, maximise first reflected flux by directing direct flux onto high reflectance room surfaces.*

3.5 Providing for visual emphasis

The alternative to designing for illumination efficiency is to apply direct flux onto selected objects or surfaces to provide for ***visual emphasis***, this being the perceived effect of direct illumination being applied selectively to chosen objects or surfaces. Generally this will be for the purpose of making them appear more conspicuous or to provide for enhanced discrimination of detail, but inevitably it will produce first reflected flux that will contribute to the inter-reflected light field. It is by selecting objects and surfaces for target illumination that the designer develops an ***illumination hierarchy***.

The proposed measure of the perceived extent of visual emphasis is ***target/ambient illuminance ratio*** (TAIR),[2,3] where the TAIR value for a target object is the ratio of target illuminance to the ambient illumination level indicated by mean room surface exitance, so that:

$$TAIR = \frac{E_{ts}}{MRSE} = \frac{E_{ts(d)} + MRSE}{MRSE} \tag{3}$$

Where $E_{ts(d)}$ is the direct component of illuminance on the target surface.

Visual emphasis should not be confused with luminance contrast. Under controlled viewing conditions, such as where subjects are presented with a uniform disc seen against a uniform background, precise functions relating subjective contrast to luminance contrast can be defined, and in fact, researchers can even demonstrate objects being made to disappear into their backgrounds as luminance contrast approaches zero. This does not happen in 'real' situations. Consider the situation of a dark grey sculpture that is to form a feature in a reception foyer. If it is sited so it will be seen against a light grey wall, a distinct luminance contrast will occur, but this is not visual emphasis (see Terms and acronyms). If selective lighting is now directed onto the sculpture, then as the light level is increased, the luminance contrast is reduced, and visual emphasis is created: but no matter how much fiddling is done with the dimmer control, the sculpture will never disappear into its background. As the luminance contrast approaches zero, the sculpture would appear as a brightly-lit object seen against a neutral background. This could have the effect of drawing attention to it and revealing its form and texture, enhancing its colour, and giving it visual emphasis. In terms of lighting metrics, this would be a situation of low luminance contrast, and high TAIR.

Table 1 indicates the author's tentative proposal for the relationship between visual emphasis and TAIR, which is based on his own observations and measurements, coupled with the outcomes of student projects. So far, this relationship has not been subjected to formal research.

Table 1 calls for some careful consideration. Brightness studies have shown that under controlled conditions, subjects are able to reliably detect luminance ratios as low as one percent, but these data indicate that TAIR values need to be as high as 1.5:1 to be 'noticeable'. This is because this table refers to observations in real environments, in other words, to complex, non-uniform visual environments. It should not be supposed that such a criterion could ever be defined precisely for practical application irrespective of circumstance, nonetheless, it is offered as useful guidance for practical application, and the same thinking applies to the other visual emphasis criteria listed on the table.

It is the range of the TAIR values that should attract attention. To achieve visual emphasis that will be assessed as 'strong', let alone 'emphatic', requires not only a carefully controlled distribution of direct flux, but also restricted ambient illumination. In fact, if the target surface area is anything more than a quite restricted proportion of the total room surface area, and particularly if its reflectance is high, the FRF generated by the direct flux directed onto the target is likely to raise mean room surface exitance to an extent that makes an 'emphatic' level of TAIR unattainable. Consider a space in which a selected target surface (ts) is the only surface to receive direct light, so the room surfaces (rs) are lit only by reflected light, then from Cuttle's formula:

$$MRSE = \left(E_{ts(d)}\, A_{ts}\, \rho_{ts}\right) / A_{rs}(1 - \rho_{rs}) \qquad (4)$$

So from equation 3:

$$TAIR = \frac{E_{ts(d)} + MRSE}{MRSE}$$

$$= 1 + \left(\frac{A_{rms}}{A_{ts}} \times \frac{1 - \rho_{rms}}{\rho_{ts}}\right)$$

This equation deserves careful consideration. It can be seen that, for this situation, TAIR depends on firstly, the ratio of room surface area to target area, and secondly, on the ratio of room surface absorptance to target reflectance. It is, therefore, independent of the quantity of direct flux on the target. In this way, where the aim is to impart visual emphasis to a target object, *the principle for maximising target/ambient illuminance ratio, is to present the object in a relatively large space, to concentrate the direct flux onto it, and to keep both target and room surface reflectances low.*

4. Design decisions

The proposed procedure directs designers towards determining firstly, the level of ambient illumination, and then a distribution of target illumination, at both stages prioritising between illumination efficiency and illumination hierarchy (see Figure 1).

For determining the ambient illumination, what matters is a person's likely assessment of how brightly lit, or dimly lit, the space will appear. It may be concluded from the previous section that while there is reasonable evidence that relationships exist both between surrounding brightness (SB) and mean room surface exitance (MRSE), and between perceived adequacy of illumination (PAI) and SB, these relationships have not been defined to the point where they could be recommended for application in professional lighting practice. This need not deter a designer who gives high priority to illumination hierarchy and has sufficient experience to avoid inappropriate decisions, but for designers who want clear guidance on just how much light needs to be applied to ensure that the illumination will be assessed as adequate or appropriate for a particular activity, the SB/MRSE relationship indicated in Figure 3 cannot be relied upon. More research investigations are needed.

For determining target illumination, the guiding principle expressed in Section 3.4 is that for efficient flux utilization, the flux needs to be directed onto high reflectance surfaces would serve well for designers who place high priority on illumination efficiency. However, designers who prioritise illumination hierarchy have other objectives. If the aim is to provide for detail discrimination, then current procedures for devising task lighting to achieve high levels of relative visual performance should serve well.[6] If the aim is to provide for visual emphasis, then the TAIR values given in Table 1 may serve as a helpful guide, but inevitably, there will always be differences of judgement as to how a level of visual emphasis may be described, and more research is needed for clarification. Meanwhile, the remainder of this section discusses application of the procedure *assuming that the four functional relationships will be acceptably well defined in due course*. This is done with the aim of illustrating how lighting practice might be changed by adoption of the proposed procedure.

The procedure would present designers with options, and the decision-making process could be as simple or as complex as the designer chooses. While the first step of selecting an appropriate MRSE level would usually be fairly straightforward, the second step could be similarly simple, or it could be distinctly complex, depending upon the lighting design objectives (LDOs). As the MRSE value for an enclosed space is a single value that represents the average flux density of the diffusely inter-reflected light field within the space, it presents the designer with complete freedom (and also total lack of guidance) on how the direct flux might be distributed. After all, there has been a recent fashion for painting ceilings matt black, so that anyone who blindly follows the findings of Section 3.4 regarding the efficiency of uplighting would be hopelessly adrift. Central to resolving the target illumination is how to engage general lighting practice in prioritising the 'illumination hierarchy – illumination efficiency' balance.

Illumination efficiency will always be a concern, and where it is given high priority, satisfying the PAI criterion becomes the principal, if not the only, LDO. In due course, this could be supported by lighting standards specifying minimum MRSE levels based on PAI. Such standards would limit design freedom only insofar as they restrict designers from specifying MRSE levels likely to be assessed as inadequate, indicating that the space would appear insufficiently lit for the activity associated with it. It is not proposed that minimum PAI levels should be specified for all activities, as there are some applications for which designers should be free to exploit distinctly dim lighting to advantage, providing of course, that safety concerns are addressed. However, this should not be thought of as an illumination issue: as the airlines have demonstrated, there are effective ways of providing for safe movement at very low SB levels. Otherwise, where a minimum PAI is specified, a designer would be able to choose to satisfy the specified level, or to exceed it to provide for a greater sense of surrounding brightness. However, if the designer has opted for the illumination efficiency track, the PAI-based minimum MRSE level would specify the LDO that determines ambient illumination.

Illumination efficiency involves the entire process of lighting provision – including light source efficacy; luminaire efficiency; and flux utilization. While it is only this last part that is accounted for in the procedure, designing for efficient provision for MRSE invokes ways of thinking about efficient lighting that are quite different from conventional understanding, as has been discussed in Section 3.4.

The first difference in giving priority to the illumination hierarchy approach would be that determining ambient illumination involves the designer in considering peoples' likely assessment of how brightly-lit, or dimly-lit, the space will appear to be. The designer would define a surrounding brightness LDO using the SB1 – SB7, dim-bright scale, specified in terms of MRSE. Where no minimum MRSE standards apply, the designer has freedom to select the level of diffusely inter-reflected flux density within the volume of the space as it affects peoples' likely assessment of how the lighting provides for an overall sense of surrounding brightness.

The designer's choice of how the direct flux which provides the FRF that generates the MRSE is to be distributed within the space will be guided primarily by creating TAIR distributions that address LDOs concerned with visual emphasis. As has been mentioned, in workplaces the LDOs could be expected to include provision for visual performance; in retail stores, with giving visual emphasis to merchandise displays; and in public areas, with drawing attention to selected displays and features of the space. These situations call for selective lighting, which is specified by the direct flux distribution, DFD.

5. The procedure in use

Practical application of the procedure is demonstrated in Section 5.3 by use of the Illumination Hierarchy Spreadsheet, and should the procedure become adopted for general use, it may be expected that professionally-produced lighting design software based upon this form of application of the procedure would become available. In the meantime, this spreadsheet (which is based on Cuttle's formula) demonstrates application of the procedure with a level of accuracy likely to be acceptable in many applications.

Referring back to Figure 1, the design process starts with the designer developing a combination of lighting design objectives (LDOs) for the lighting application, and this is the precursor to application of the LDO - DFD procedure. Section 5.1 gives a step-by-step description of the procedure for a designer who accords priority to the illumination efficiency track, and Section 5.2 does the same for a designer who opts for the illumination hierarchy track. Illumination efficiency will always have some level of priority as a design objective, so Section 5.1 will inevitably have some level of relevance, and the level of priority that the LDO combination accords to illumination hierarchy determines the relevance of Section 5.2. These two sections enable the reader to follow each stage of the procedure.

The procedure leads to the designer defining the direct flux distribution DFD. This is a powerful specification. Its function is to: *Deliver the indicated quantities of luminous flux onto the* *corresponding surfaces, and the quantity and distribution of illumination that will optimally achieve the lighting design objectives will be achieved.*

Section 5.3 gives an example of application of the Illumination Hierarchy Spreadsheet. Readers who are not interested in following the detail of the procedure may choose to proceed directly to 5.3.

5.1 The Illumination Efficiency Track

The procedure is as follows:

1. Specify ambient illumination as a mean room surface exitance (MRSE) value. Perhaps one day this may be done by referring to an appropriate lighting standard and looking up the specified MRSE level to satisfy the perceived adequacy of illumination (PAI) criterion for the activity. Until that day, it needs to be done by applying the appropriate PAI/SB function for the activity (see Section 3.3) to determine the surrounding brightness to satisfy a specified proportion of people, and then applying a SB/MRSE function (see Section 3.2) to determine the design MRSE level.
2. Calculate the room absorption, $A\alpha = \sum A_{rs} \, (1 - \rho_{rs})$
3. Determine the required first reflected flux from all room surfaces, $FRF_{rms} = MRSE \, . A\alpha$
4. Examine the distribution of room surface reflectances, and maximise flux utilization (see Section 3.4) by selecting high reflectance target surfaces to receive direct flux, $F_{ts(d)}$.
5. Determine levels of $F_{ts(d)}$ onto specific target surfaces to match the sum of first reflected flux from all target surfaces to the required first reflected flux from all room surfaces, so that $FRF_{rms} \approx \; FRF_{tgs} = \sum F_{ts(d)} \, \rho_{ts}$. This defines the direct flux distribution (DFD).
6. Devise a luminaire layout to deliver the DFD.

5.2 The Illumination Hierarchy Track

The procedure is as follows:

1. To determine ambient illumination, consider how brightly-lit, or dimly-lit, the space is to appear. Select a value of surrounding brightness on the seven-point scale (SB1. very dim – SB7. very bright), and apply a SB/MRSE function (see Section 3.2) to determine the design level of mean room surface exitance (MRSE).
2. Check whether a minimum MRSE level is specified, and adjust if necessary.
3. Calculate the room absorption, $A\alpha = \sum A_{rs} \, (1 - \rho_{rs})$
4. Determine the required first reflected flux from all room surfaces, $FRF_{rms} = MRSE \, . A\alpha$
5. Select target surfaces or objects for visual emphasis and designate TAIR values (See Section 3.5 and Table 1).
6. Determine the illuminance due to direct lighting to be applied to each target, $E_{ts(d)} = (TAIR \, . MRSE) - MRSE$
7. Determine the total FRF due to selective target lighting, $FRF_{tgs} = \sum E_{ts(d)} \, A_{ts} \;\, \rho_{ts}$
8. To provide the MRSE, the value of FRF_{tgs} needs to match the required FRF_{rms} value. So,
   (a) If $FRF_{tgs} \approx FRF_{rms}$, then serendipity: the distribution of direct target illuminance, $E_{ts(d)}$, defines the direct flux distribution, DFD.

(b) If $FRF_{tgs} < FRF_{rms}$, the FRF difference is to be made up by adding more target surfaces to raise the value of FRF_{tgs}, and so define the DFD. Follow steps 4 and 5 from Section 5.1. *(Care needs to be taken to avoid creating TAIR values that compete with visual emphasis LDOs.)*
(c) If $FRF_{tgs} > FRF_{rms}$, then MRSE will exceed the design level and the TAIR values will not be achieved. Some revision of the selection of target surfaces is called for to reduce FRF_{tgs}.

9. Devise a luminaire layout to deliver the DFD.

5.3 The Illumination Hierarchy Spreadsheet

The Illumination Hierarchy Spreadsheet[3] shown in Figure 6 facilitates application of the procedure. It follows quite closely the layout of the worksheet that Waldram developed for his Designed Appearance Method,[5] but unlike Waldram's pre-computer version, it requires the user only to fill in the cells shown shaded; all the rest of the data are generated automatically. The Illumination Hierarchy Spreadsheet is one of four spreadsheets introduced in the author's book, *Lighting Design: A perception-based approach.*[3] (The spreadsheets can be downloaded from the publisher's website. Go to: http://www.routledge.com/books/details/9780415731973/ and click on eResource/Downloads).

ILLUMINATION HIERARCHY SPREADSHEET							
170806							
Project Name:	Hotel Reception Area						
MRSE	120	lm/m^2					
Room Surface	**Ars**	**(rho)rs**	**A(alpha)rs**	**TAIR**	**Ets(d)**	**DFD**	**FRFts**
	m^2				lx	lm	lm
Ceiling	81	0.8	16.2	1.9	108	8748	6998
Wall 1	32.8	0.45	18.0	1.5	60	1968	886
Wall 2, excl. mural	29.7	0.45	16.3	1.5	60	1782	802
mural	14	0.65	4.9	5	480	6720	4368
Wall 3, solid	6.6	0.45	3.6	1	0	0	0
Wall 3, glazed	26.2	0.1	23.6	1	0	0	0
Wall 4	43.7	0.32	29.7	1.5	60	2622	839
Reception counter	4.8	0.25	3.6	5	480	2304	576
Circulation	28.6	0.15	24.3	1.5	60	1716	257
Water feature	4.6	0.7	1.4	10	1080	4968	3478
Lounge	38.4	0.2	30.7	3	240	9216	1843
Bar counter	4.6	0.4	2.8	5	480	2208	883
		A(alpha)rms	175.2	m^2	Ftgs(d)	42252	lm
		FRFrms	21021	lm	100	%	
		FRFtgs	20930	lm	100	%	
		FRFrms-FRFtgs	90	lm	0	%	

Figure 6. The Illumination Hierarchy Spreadsheet, illustrating an example of application for a hotel reception area described in the text. Only the shaded spaces are filled in by the user; all other data are generated automatically. See Terms and acronyms for symbols, and note that (alpha) is α, and (rho) is ρ.

After filling in the project name, the designer enters the three columns of working data, comprising the surrounding surfaces, their areas (Ars), and their reflectances ((rho)rs). This is done with as much detail as circumstance demands. At its simplest it would comprise three rows - ceiling, walls and floor – and this could be sufficient for a simple illumination efficiency priority application such as a corridor or lift lobby. The example shown comprises a moderately intricate project for the evening illumination of the reception area of a small hotel. Alternative lighting schemes probably would be needed for daytime and overnight. As these data are entered, the spreadsheet shows the total room absorption, (A(alpha)rms), which takes account of all the room surfaces.

The designer enters a mean room surface exitance level chosen to satisfy the lighting design objectives, in this case, 120 lm/m^2, which is taken to correspond to a ‘slightly bright’ assessment of surrounding brightness. Instantly, the spreadsheet shows the total first reflected flux (FRFrms) required from the room surfaces.

Now comes the creative bit. The designer works down the TAIR column entering values of target/ambient illuminance ratio. At this stage, every surface is shown to have a TAIR value of 1, which means that it receives no direct flux. Ignoring the ceiling for the moment, it is decided that the appearance of walls 1 and 2 would benefit from some modest level of wallwashing, and so TAIR values of 1.5 are entered, corresponding to a ‘noticeable’ level of visual emphasis (see Table 1). Instantly, the direct illuminance to be applied to each target surface (Ets(d)), the direct flux, and the first reflected flux (FRFts) appear alongside.

Moving on to the mural on wall 2, this needs to attract attention, and so a TAIR value of 5 is chosen, corresponding to visual emphasis somewhere between ‘distinct’ and ‘strong’. Employing this pattern of decision making, the designer would continue down the column, and upon reaching the end, the total first reflected flux from target surfaces (FRFtgs) would be shown to be 13,932 lm, comprising 66% of the required FRFrms value (this stage is not shown in Figure 6). These data indicate that when the listed values of direct flux are applied to all target surfaces, 66% of the total required first reflected flux will be generated.

So how is the other 34% to be provided? The designer now switches from Illumination hierarchy priority to illumination efficiency priority. The efficient way to provide FRF is to direct flux onto high reflectance surfaces, and the obvious surface for that is the ceiling. The designer tentatively enters a TAIR value of 2 for the ceiling, and that raises FRFtgs to 103%. A little more experimentation and, as shown in Figure 6, a TAIR value of 1.9 does the trick. When every target surface receives the direct flux level listed in the DFD column, the FRFrms from all of these surfaces will provide the mean room surface exitance (MRSE) level of 120 lm/m^2.

Figure 6 now comprises the blueprint for a lighting installation that will provide for both the ambient illumination and the target illumination that will achieve both the intended surrounding brightness and the balance of visual emphasis to satisfy the lighting design objectives. After this, luminaires and their locations have to be selected, and applying the specified levels of direct illuminance onto the target surfaces is a matter of straightforward illumination engineering.

5.4 A path between the tracks

In practice, it would usually occur that neither one track nor the other would be followed exclusively, and that the designer would steer a path between the tracks. An exception to this might occur where a single LDO is specified, such as an LDO prescribing for “A MRSE standards-compliant installation at minimum initial cost.” Achieving an LDO of this sort would involve efficient utilization of the direct flux to provide the design level of MRSE. As has been discussed in Section 3.4, the principle is that the flux needs to be directed onto high reflectance surfaces, so that in any conventionally decorated room, upward-lighting luminaires that wash the ceiling with light would enable the designer to satisfy the criterion with minimum direct flux. While this would be a turn-around in thinking for those practitioners who are accustomed to ambient illumination being assessed in terms of horizontal working plane illuminance, it would hardly represent a step forward in general lighting design practice that repetitive sequences of downlighter installations should be replaced by repetitive sequences of uplighter installations.

It is the designer's selection of LDOs that determines the extent to which the attainment of an illumination hierarchy is prioritized relative to illumination efficiency. The decision to select objects and room surfaces for visual emphasis lies at the heart of designing lighting rather than providing illumination, and this is captured by the direct flux distribution (DFD). The ability to envisage a lit space and to determine the DFD that will provide it is the essence of lighting design, and it is the DFD specification that enables the designer to achieve an envisioned distribution of visual emphasis within a space of prescribed surrounding brightness.

While application of the procedure is greatly facilitated by use of the illumination hierarchy spreadsheet (Section 5.3), it could be facilitated even more by professionally-produced lighting design software. However, for that to happen, the functional relationships discussed in Section 3 need to be defined.

6 Conclusions and potential outcomes

In the past, the author has argued that the lighting profession is poorly served by current lighting methodology and that change is overdue.[1-3] This extends from lighting standards throughout lighting practice, including the widely-used high-tech lighting design software, as well as the conventions and attitudes that are widely shared among those involved in the provision and application of lighting.

One objection to the proposed procedure that has been expressed to the author is that as lighting design comprises the creation of artistic and inspiring visual experiences, it cannot be reduced to a procedure or method. While this argument may be valid for various art forms, it overlooks that a lighting design solution comprises a specification of wattages, beam spreads, mounting locations, aiming angles, circuits and controls. As the LDO – DFD procedure acts to link lighting design objectives to technically achievable distributions of target illumination, there is no reason why the proposed procedure should compromise the creative component of the design process. Its purpose is to provide a flexible tool that may be used either to efficiently satisfy the most basic lighting design objectives, or to serve as a basis for exploring options for more demanding objectives.

Another objection coming from a different direction is that the proposed procedure lacks a scientific basis. The validity of the task illumination criterion that is widely identified as the basis of lighting standards may be demonstrated by application of the relative visual performance method,[13] this being a research-based procedure that enables task illuminance to be related to human performance for the broad range of practical activities involving vision. For example, speed and accuracy of reading can be directly related to task difficulty and illuminance, but it needs to be recognised that brightness lacks any such justification. Researchers have it on record that when lighting levels are increased, subjects respond with assessments of increased brightness, enabling brightness/luminance functions to be defined, but this does not establish a relationship between brightness assessments and any aspect of human performance. More basically, there seems to be no basis for establishing such a relationship, or in fact, for relating brightness to any measure of satisfaction other than discomfort glare. There is no case for claiming that more surrounding brightness is better.

The author's argument centres on the point that that, during the past century, lighting practice became divorced from application of visual performance procedures. The illuminance levels specified in lighting standards increased to exploit the greatly improved efficiency in light production to provide for people's preferences for surrounding brightness, rather than providing for performance needs encountered in general practice. In fact, it was found again and again that simplifying the visual task (such as the introduction of screen-based reading tasks) or eliminating tasks (as with bar-code readers) is more effective than increasing task illuminance. Otherwise, for those situations where sometimes this approach is not practical, localised task lighting is the preferred option (for example, surgery, and quality-control inspection). It may be concluded that the claim that general practice is based on application of scientific knowledge lacks validity, but that does not justify replacing the current system with an equally invalid system.

The claimed justification for the proposed procedure is that it relates to aspects of how people assess the quantity and distribution of illumination in indoor spaces. Consider the designer who has prepared the illumination hierarchy spreadsheet shown in Figure 6, and is now approaching the hotel owner. He or she can discuss the overall effect of lighting in terms of surrounding brightness, and its distribution in terms of visual emphasis. These are readily understood concepts as they relate directly to how lighting influences the appearance of lit spaces. In this way, both parties can share in a process of devising a lighting solution, and this opportunity could be greatly enhanced by professionally-developed design software based on the foregoing procedures.

While mean room surface exitance (MRSE) is a reasonably straightforward concept, its measurement does create difficulty as it requires an instrument that distinguishes between diffusely reflected light from room surfaces and light directly incident from luminaires or windows. This has been addressed by Duff *et al*,[9] who have applied commercially available high dynamic range imaging equipment to perform MRSE measurements, and while these researchers have demonstrated the feasibility of a practical MRSE light meter, it again requires acceptance of the concept for suitable instruments to become available.

The proposed procedure is capable of development, and one envisaged way in which this might be done concerns target illumination. As it stands, the procedure involves directing flux onto selected fixed objects to achieve visual emphasis, but this omits what may often be the principal objects of regard – the people. The way in which lighting reveals the human features should never be disregarded, and in some instances, such as for a preacher or a receptionist, it should rate highly on the list of lighting design objectives. However, it once again involves a different way of thinking about target illumination. Instead of distributing light onto surfaces, it involves creating a three-dimensional light distribution within the volume of a space that will interact with the human form to reveal it in a way that suits the activity associated with the space. This visual effect of a spatial lighting distribution has been described by Lynes as "the flow of light",[14] and for measuring and analysing the relevant metrics, the cubic illumination concept may be usefully applied.[15] It is considered that this would form a worthwhile development of the proposed procedure, and also, the procedure needs to be extended to include daylighting practice.

Once the process of changing the basis of general lighting practice starts, other aspects would be likely to come under scrutiny. Rea has pointed out that while the $V(\lambda)$ weighted lumen works well for evaluating radiant flux as it affects visual performance at photopic levels, the spectral response for brightness evaluation is weighted more strongly towards shorter visible wavelengths.[16] This indicates that the reliability of the functional relationships discussed in Section 3, upon which the LDO – DFD procedure is based, would be improved by incorporating the evaluation procedures that have been proposed by Rea and Bierman.[17]

The discussion in Section 3 of the limited research into the four fundamental relationships on which the procedure depends identifies scope for further research needed to ensure reliable application of the procedure, and it is hoped that this might catch the attention of some topic-hungry researchers. However, the essential need for change is that lighting practitioners become dissatisfied with the current situation. Until that happens, nothing will change.

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Figure captions

Figure 1. The LDO – DFD Procedure guides the lighting design process from a combination of lighting design objectives to a direct flux distribution. See text for explanation.

Figure 2. Duff employed the same format for both experiments,[11,12] with 26 subjects attending three sittings. At each sitting they were presented with a different set of surrounding surface reflectances, where they assessed nine combinations of three light distributions, and three mean room surface exitance levels.

Figure 3. Means and standard deviations for surrounding brightness responses relative to mean room surface exitance, for Duff's Experiment 1 (lighting booth) and Experiment 2 (small office).[11,12]

Figure 4. Percentage of 'Yes' perceived adequacy of illumination (PAI) responses relative to surrounding brightness (SB), from Duff's experiment in the small office.[12]

Figure 5. Mean room surface exitance due to two luminaires, one providing direct lighting and the other indirect lighting, both having the same flux output, in a room where the room surface reflectance combination is varied, but the average reflectance is always 50 percent. MRSE calculations were made using Duff's definitive procedure (1), and Cuttle's formula (2), and are shown relative to the value for reflectance combination 1. Ceiling/wall/ floor reflectance combinations are: 1 = 50/50/50; 2 = 60/50/40; 3 = 70/50/30; 4 = 80/50/20; 5 = 90/50/10.[10]

Figure 6. The Illumination Hierarchy Spreadsheet, illustrating an example of application for a hotel reception area described in the text. Only the shaded spaces are filled in by the user; all other data are generated automatically. See Terms and acronyms for symbols, and note that (alpha) is α, and (rho) is ρ.

Table 1. Approximate guide to visual emphasis related to TAIR, being the ratio of target illuminance (due to the combined effect of direct and ambient illumination) to mean room surface exitance.[2,3]

Visual emphasis	Target/ambient illuminance ratio, TAIR
Noticeable	1.5:1
Distinct	3:1
Strong	10:1
Emphatic	40:1