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Better Lighting for Improved Human Performance, Health and Well-Being, and Increased Energy Efficiency – A Scoping Study for CIE-UK

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Approved on behalf of the Managing Director, NPL
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FOREWORD

This publication marks a milestone in the work of CIE-UK in that it is the outcome of the first piece of sponsored research that it has undertaken. CIE-UK provides UK representation to the International Commission on Illumination based in Vienna, which has a world-wide membership. Its role is to encourage the development of all aspects of lighting and, where appropriate, to provide recommendations and standardisation. Much of its work has a basis in research but in recent times this has become less and less through a reduction in financial resources, which has led to a depletion in suitably qualified personnel and appropriate facilities, both industrial and academic. This project was aimed at attempting to reverse this decline and to provide a focus for any available resources.

The project set out to identify, in a structured way, those topics that were most necessary to encourage the development of lighting for the benefit of people in terms of effectiveness, comfort and health and to consider this with respect to energy efficiency and sustainability. CIE-UK considered that it was essential that these topics be investigated so that lighting application could be developed. The work has been carried out by the National Physical Laboratory at Teddington, under the direction of Teresa Goodman and identifies topics for development. It is hoped that this will provide researchers and students in the field of lighting and related areas with topics that experts believe require answers. Also, by selecting from projects identified in this report, the necessary funding may be easier to obtain because of its provenance.

One of the weaknesses of some recent research has been a lack of sufficient breadth to the researcher's expertise, which has limited the outcome. Understanding the needs of lighting application and its relationship to the environment requires an understanding of the human response to lighting, including both visual and non-visual processes. These also need to be considered in developing the way lighting is measured. However, it is rare to find all these qualities in one team and therefore it is envisaged that there is a need for collaboration across academic department boundaries, both national and international, for the available research funding to be most effective. For this to succeed will require funding from governments and similar bodies because without this level of involvement it is unlikely that the necessary improvements will be made and hence valuable resources will be lost.

I wish the outcome of this project success and that it will lead to an upturn in the quality and quantity of investigations in the important area of lighting. CIE-UK deserves congratulations in undertaking and sponsoring this project, and in particular Dr Mike Pointer, CIE-UK Chairman for much of the period of the project, as well as his fellow Trustees. Thanks are also due to the members of the research management panel chaired by Ken Scott.

David Loe
September 06.

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ABSTRACT

Light and lighting affects human performance, health, safety and well-being in many different ways, and also accounts for a significant proportion of the World's energy consumption. This report reviews research that has been carried out in these areas and summarises the current state of knowledge and where there are gaps in that knowledge. Additionally, it provides a summary list of proposed topics for future research, which it is hoped will be of assistance to researchers and funding bodies when applying for, or allocating, research funds and gives some suggestions regarding how this research could be organised. Issues relating to the research procedures used are also discussed, with the intention of improving the ability to compare one study with another and increasing confidence in the validity of any conclusions drawn.

EXECUTIVE SUMMARY

We all know we need light in order to see our surroundings and to perform a multitude of daily tasks, ranging from the completely mundane (e.g. choosing a matching pair of socks), to the very complex (e.g. driving in heavy traffic). There is clearly a strong correlation between the lighting conditions and the ability to perform visual tasks safely, effectively and efficiently. But light does not only stimulate vision; it can affect our mood, change our perceptions and directly influence our behaviour in many complex and unexpected ways. It can even control our health and well-being, playing a key role in areas ranging from sleep disorders through to the initial onset and/or subsequent growth rates of various cancers.

In view of the importance of light, it is hardly surprising that a significant proportion of the World's energy budget is devoted to the provision of light and lighting (in excess of 2000 TWh each year). But much of this energy is probably not being used effectively, either being 'wasted' by being directed where it is not actually needed or being used to provide light that is not optimised for the task being undertaken.

Effective and efficient use of lighting requires good lighting design, and that in turn requires an understanding of exactly how light affects human task performance, safety, health and well-being. This report reviews research that has been carried out in these areas, summarises the current state of knowledge and identifies where there are gaps in that knowledge.

An important conclusion that can be drawn from this report is that knowledge of the influence of light on human performance, health and well-being is far from complete and that there are many areas where research is urgently needed. Better understanding of human responses to light will become evermore important as the need to conserve energy resources grows and the requirement for business and technology to operate in a 24 hour economy increases. The report therefore also provides a summary list of critical topics for future research, which it is hoped will be of assistance to researchers and funding bodies when applying for, or allocating, research funds.

1 INTRODUCTION

Lighting is essential for our normal daily lives. We need light to perform tasks as diverse as reading, driving and operating machinery, and the amount, the spectral qualities and the spatial distribution of that light directly affects our ability to perform these tasks safely and effectively. But light does not only stimulate vision. It also influences our perceptions and behaviour, and has a direct effect on our health and well-being (see Section 3 for an overview of the various interactions). This report reviews the current status of research into the effects and use of light, and summarises where there are gaps in our knowledge and further research would be beneficial.

Visual aspects of light have been studied since the early 1900s and many of the basics are well-understood. This has led to the development of well-defined measurement systems for light and colour under the conditions that we encounter during much of our working lives, and these are reviewed in Section 4. Even here, however, our knowledge is not complete. For example, the way in which the eye's response changes as the light level is reduced is still not fully understood, which has important implications for the safety and efficacy of, for example, night-time driving and emergency exit lighting.

The relationship between lighting and visual task performance has also been studied for many decades, leading to the development of a number of models which relate the ability to perform specific tasks directly to the lighting conditions. These are also examined in Section 4. The primary conclusion that can be drawn from this research is that only changes in lighting conditions that directly affect task visibility have a definite impact on task performance. Furthermore, since most of the models are based on research in the area of office lighting, which involves mainly two dimensional tasks (such as data entry) under fairly well controlled lighting conditions, their applicability is somewhat limited. There has been relatively little research into lighting for industrial environments, such as factories, which typically involve three-dimensional tasks and where uniformity of lighting, for example, may be more difficult to control.

More recently, researchers have investigated how lighting influences our perceptions of a given space and our preferences, or otherwise, for different types of lighting. These studies are reviewed in Section 5 and have highlighted that 'brightness' and 'variety' are two key aspects that drive perception; brightness is related to the amount of light and variety to the degree of non-uniformity. Both these are obviously closely linked to the lighting, but may also be influenced by other factors, such as the reflectance and colour of the walls, floor and ceiling, the amount and type of furniture etc. General extrapolation from the lighting conditions to the overall perception of the space is therefore difficult.

Nevertheless, it is clear that lighting definitely contributes to the perception of an environment. Researchers have therefore also investigated the next obvious question: to what extent can changes in perception influence mood and behaviour and thus produce a change in general (rather than specifically visual) task performance? These studies frequently give inconclusive and conflicting results: changes in the lighting that affect the perception of the space but not visibility may, or may not, affect task performance, depending on the strength of the impact of the lighting on mood and motivation relative to other factors that may also have an influence, such as boredom, ambient noise and time of day.

Psychologists talk of positive and negative 'affect'. Positive affect, or pleasant, positive, feelings, has been shown to increase efficiency in making decisions and to promote innovation and creative problem solving. Negative affect, on the other hand, has the opposite effects. Attractive lighting conditions may generate positive affect, whereas poor lighting will generate fatigue and negative affect. A combination of poor/inappropriate lighting for a task and the need to perform that task over long periods of time will almost certainly lead to eyestrain, fatigue, and negative mood changes and hence result in adverse changes in task performance. But it is difficult to predict exactly what the impact will be, since this depends on the task itself and also on aspects of the environment other than lighting.

Much more research is needed in this area, but the potential rewards are significant: if a clear and consistent relationship between lighting, mood and task performance could be established, which was applicable in a variety of situations, this would lead to new opportunities for enhancing people's positive feelings and for increasing productivity in a wide range of applications.

Although the relationship between lighting, mood, behaviour and task performance is not yet understood, it is certain that light can have a beneficial effect in the treatment of depression and other mood disorders, especially Seasonal Affective Disorder (SAD). Latest developments in this area are also reviewed in Section 5.

The past two decades have seen a major leap forward in our understanding of how light affects our health and well-being, following the identification of a new, novel, photoreceptor in the eye. This has been shown to play a major role in the functioning of the human circadian system, which controls daily rhythms such as the sleep/wake cycle, core body temperature, hormone secretion, other physiological parameters including cognitive function, and immune response. Research in this domain, and the potential implications in areas such as jet lag, shift working and the treatment of sleep disorders, is reviewed in Section 6. This Section also looks at the role of light in the synthesis of vitamin D in the human body and the results of recent research suggesting a link between vitamin D, melatonin and the timing of exposure to light in various cancers, including breast and prostate cancer. The general conclusion is that we need a daily 'light' and 'dark' dose to maintain a healthy circadian system, and that disruption of this system can have serious implications for human health and well-being.

Section 7 looks at specific applications of lighting, such as special requirements for the elderly and visually impaired, office lighting, safety and security, and transportation. It also considers the implications of improved lighting and the greater use of lighting controls in terms of energy efficiency and reduced energy consumption.

Throughout the report, the principal topics requiring further research are identified. Section 8 brings these together under major themes, which it is hoped will be of benefit to researchers and funding bodies when deciding future research directions.

Finally, Section 9 considers how future research should be organised, funded and conducted in order to derive maximum benefit and to encourage its wide application and uptake. Modern lighting research involves practitioners from a range of disciplines, including lighting manufacture, architecture and lighting design, measurement, psychology, psychiatry, physiology and medicine. Effective coordination of these different areas is essential if the ultimate goal is to be achieved i.e. to 'improve' the way in which we use light, in order to:

- increase its effectiveness, thus reducing energy consumption and/or increasing productivity;
- support the 24-hr economy through better understanding of the impact light for shift workers on productivity, motivation and health;
- modify mood or behaviour, for the benefit of individuals or larger communities;
- improve human health, safety and well-being;
- optimise the value of light to the community; and
- improve the quality of life for the elderly and visually impaired.

2 BACKGROUND TO THE STUDY

2.1 RATIONALE

This work was carried out under a contract placed by the CIE-UK (the UK arm of the International Commission on Illumination, CIE) for a study to review the current state of knowledge regarding the impact of light and lighting on human performance, health and well-being and to identify priority areas for future research. The Invitation to Tender for the project highlighted that lighting research in the UK and elsewhere has been in decline for some time, despite the fact that many lighting professionals recognise that current lighting does not provide conditions for optimum performance, cost or energy efficiency. It also emphasised that there is evidence, although much of it is currently unproven, that human performance could be enhanced by a more informed approach to lighting.

For example, there is some research already available to support the view that improved street lighting is perceived to lead to reduced crime. But it is not known what the reasons for this are – in other words what psychological effects related to lighting may be coming into play (do increased lighting levels really act as a deterrent to criminals, or do they merely make people ‘feel safer’ etc.) Nor is it agreed how measurements of street lighting illuminance (which fall in the mesopic region) should be measured. The answers to questions such as these could have a dramatic effect on the recommendations for street lighting and the associated costs.

Furthermore, design issues associated with the lighting of interiors have historically been driven mainly by considerations of utility and energy efficiency. Some recent studies, and a bank of anecdotal evidence, suggest that the accommodation of user needs and preferences may lead to enhanced task performance and occupant well-being. A more rigorous examination of this subject offers the prospect of re-defining the criteria that are used to assess lighting quality, and could also have a direct influence on the future strategy of the CIE Divisions.

Thus the purpose of this report is to:
- evaluate existing research to ascertain what is known about the ways in which lighting affects human well-being and performance;
- review existing practice to determine the extent to which this represents what could optimally be achieved; and
- identify and prioritise potential areas for further research, in order to stimulate research efforts and encourage increased levels of funding for this research.

2.2 HOW THE STUDY WAS CONDUCTED

The current draft of the report was prepared by the authors primarily on the basis of an extensive literature review and discussions at major meetings and symposia, coupled with their existing knowledge. This included:
- review of papers in major lighting publications such as Lighting Research and Technology
- study of key review reports and books on lighting and human behaviour and performance, in particular CIE Publication 158[1] on ocular lighting effects on human physiology and behaviour, Boyce’s book on human factors in lighting[2], and the EPRI report on lighting and human performance[3]

- attendance at CIE meetings and workshops, in particular the CIE 25th Quadrennial meeting and the associated workshop on lighting research[4]
- attendance at relevant CIE Expert Symposia, in particular the Light and Health symposium held in 2004[5].

The structure of the report, its general objectives and the philosophy behind it were discussed with and agreed by a Management Panel, consisting of the Trustees of the CIE-UK and two independent lighting experts: David Loe (Bartlett Graduate School, UCL and Building Research Establishment, retired) and Kenneth Scott (Technical Director of Thorn Lighting, retired). This Panel also approved the final version of the report.

3 OVERVIEW OF THE ROUTES THROUGH WHICH LIGHT AND LIGHTING IMPACTS ON HUMAN PERFORMANCE, HEALTH AND WELL-BEING

Lighting affects human performance, health and well-being through three systems: the visual system, the perceptual or cognitive system, and the non-image-forming system. The effect of light on the visual system depends on the size, luminance contrast and colour difference of the task and the amount, spectral distribution and spatial distribution of the lighting (see Section 4). The impact of lighting on the perceptual system depends on the 'message' it sends (see Section 5). The effect on the non-image forming system depends on the amount and spectral distribution of the lighting and the timing and duration of the exposure (see Section 6). These systems do not act in isolation, but interact with one another in complex, and often unexpected, ways (Figure 1).

Research aimed at developing a clear understanding of the relationship between light and task performance is complicated by the facts that most tasks have three components – visual, cognitive and motor - and that the balance between these depends on the task. Tasks with a large visual component are more sensitive to changes in lighting than those with only a small visual component, but all tasks may be significantly influenced by perception. This means it is very difficult to identify the effects of changes in lighting on task performance in general, to make predictions of performance in specific situations, or to generalise from one task to another. Most studies of the effect on lighting conditions on work have therefore concentrated on the impact via the visual system, and the models that have been developed apply only to tasks of large visual size, with high luminance contrast between the task and the background and with high background luminance.

Although studies into perceptual and non-image-forming effects of light are still at a relatively early stage, it is already clear that light falling on the retina has many important consequences for human health and well-being and the ability to perform tasks, beyond simple task visibility. As the understanding of these effects improves and mechanisms for the broader impacts of lighting on health, well-being and performance become clearer, there will be increasing opportunities for tailoring lighting for these effects as well as for vision. Lighting recommendations will need to be revised, new measurement systems and instruments might be necessary, and new lighting (lamps and luminaires) may well be required. There are huge opportunities for all involved in the area of lighting research, which potentially will lead to important and significant benefits to people and the economy.

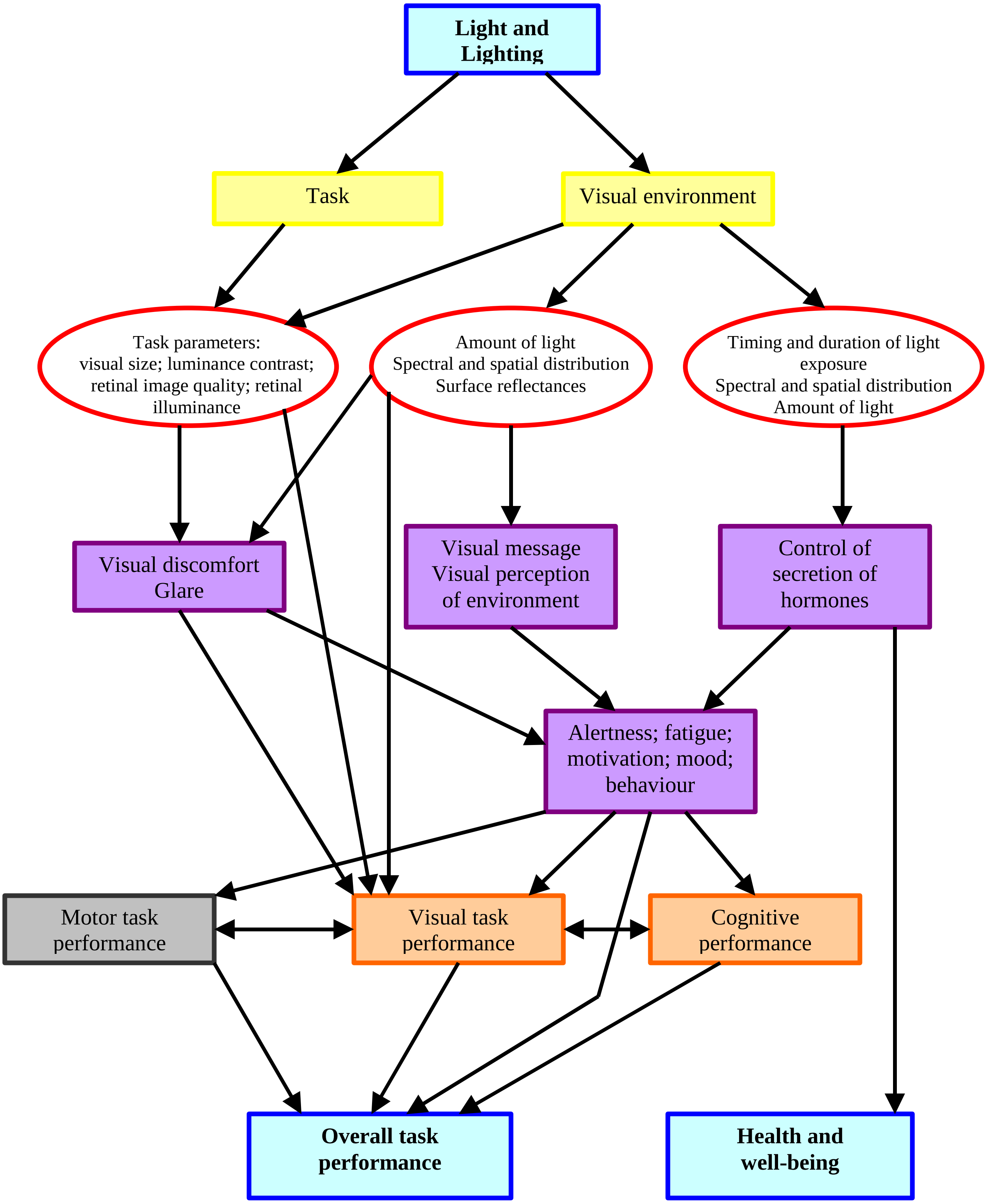

Figure 1. Relationships between Light and Lighting, Task Performance, Health and Well-Being

4 LIGHT FOR VISION

4.1 INTRODUCTION

The effect of lighting on the ability to see is the most obvious impact of light on humans. The optics of the eye form an image of the outside world on the retina, which is then processed through two different channels to the visual cortex in the brain. The magnocellular channel processes information rapidly, but with little detail or colour information, whereas the parvocellular channel processes information more slowly and provides details of brightness, colour and texture. The human visual system also shows differences in spatial performance: the foveal region provides discrimination of fine detail in the image, whereas in the periphery, detail is missing. The physiology of the eye and the visual system all influence the ability to perform visual tasks and lighting therefore has a direct bearing on task performance in many situations.

As mentioned in the previous Section, tasks can generally be sub-divided into three components: visual, cognitive and motor. These interact to produce a complex relationship between stimulus and response, with the balance between the components depending on the actual task. Tasks in which the visual component is large are more sensitive to changes in lighting than those where this component is small. Lighting can affect our ability to perform visual tasks in two main ways. Firstly, it can change the stimulus presented by the task by modifying the luminance and colour of the task. This in turn can affect both the luminance contrast and colour contrast of the task. (Luminance contrast is defined as the difference between the task luminance L_t and the background luminance L_b, as a percentage of the background luminance.) Secondly, lighting can affect the operating state of the visual system. As retinal illuminance increases, the speed with which the information is transmitted along the neural pathways increases. Additionally, as the adaptation luminance of a task increases, the detail that can be resolved by the visual system becomes finer. However, the answer to improved task performance, even for tasks with a high visual content, is not simply to increase the illuminance; beyond a certain point no further improvements in performance are possible, and glare effects may even degrade task visibility.

The perceptual system takes over once the retinal image has been processed by the visual system (see Section 5). Although perception does not have a direct influence on the ability to perform a visual task, it is important to remember that different influences can interact and affect performance in unexpected ways, for example, trying to work on a task that is poorly lit can cause adverse changes in mood, so performance may be further degraded. This makes it extremely difficult to make definitive predictions of performance.

In order to isolate individual effects, studies into the relationship between lighting and work often involve subjects conducting specific tasks under specific conditions, but these results cannot be easily applied in other situations. Another approach is to study a well-characterised, visually simple task, which does not relate to a real-work situation. This enables a mathematical model for that particular task to be developed, but applying this in a real-life work situation involves considerations of interactions between the various relevant tasks. Another complication is that eye performance changes with light-level (illuminance), age, contrast, target eccentricity etc., all of which affect the ability to perform tasks and can compromise experimental findings from task performance studies.

4.2 VISUAL SCALES AND MEASUREMENT SYSTEMS

4.2.1 Introduction

In order to be able to communicate information about light and lighting, whether it be to compare one product with another, to provide specifications and recommendations regarding lighting requirements, or to enable the energy efficiency of any given light source to be calculated, it is essential to use appropriate, internationally-agreed, measurement scales and systems. However it is important to recognise that the complexity and flexibility of the human visual system means that although photometric and colorimetric measurements have been carried out for more than a century, and the basic scales were defined by international agreement more than 80 years ago, they invariably provide only an approximation to the actual visual effect for any given individual in any given situation. This means that although the numerous metrics used to characterise lighting can be precisely determined, they provide only an inexact representation of the true visual effect; their apparent precision can be deceptive. One of the key drivers behind research in the area of visual scales and measurements systems is therefore to enable measurements to match the actual visual outcome more precisely, particularly for those situations where measurements currently provide only a poor approximation to visual effectiveness.

Photometric measurements are intended to provide a method by which to quantify light in terms of the visual sensation it produces. Measurements are generally made, and lighting levels specified, in terms of the photopic response function. However, the operational state of the eye changes as the light level is reduced, moving from a photopic adaptation state for luminances above about 10 cd m^{-2} through the mesopic region (where eye response characteristics change rapidly) to a scotopic adaptation state below about 0.01 cd m^{-2}; this changing state is ignored in all current lighting recommendations.

Metrics for characterising colour properties are widely used but imperfect. Colour rendering is a particular issue, because of the desire to use a single number to represent a complex spectral power distribution. This reduction to a single number leads to a considerable loss of information. More complex descriptions may be preferable, but currently it seems that these are unlikely to find wide acceptance. A similar problem occurs with the widespread use of ‘colour temperature’ as an index of the colour appearance of light sources, where sources with similar numerical values can often appear very different.

4.2.2 The Photometric Measurement System

The photometric measurement system is intended to provide a method by which to quantify light in terms of the visual sensation it produces. One of the fundamental premises of any measurement system is that it is additive; for example, if two lengths of string each 1 m long are placed end to end, the total length is 2 m. In the case of photometric measurements, this principle of additivity is taken a step further and it is assumed that if a blue light of x photometric units is added to a red light of y photometric units, the combination of the blue and red light will be (x+y) photometric units; this is often referred to as Abney’s law. Based on this assumption, it is possible to determine the effect of a polychromatic stimulus by performing an integration across the visible spectrum: the spectral power distribution of the stimulus is weighted by an appropriate function, to take account of the differing visual effect produced by radiation of different wavelengths, and then summed. The photometric measurement system is therefore based on the use of spectral luminous efficiency functions, each of which is intended to represent how the average human eye responds under defined conditions, and which have been internationally agreed and standardised by the International Commission on Illumination[6] (CIE).

The CIE has defined spectral luminous efficiency functions for the photopic ('normal' lighting levels) and scotopic ('low' lighting levels) regions; these are called the $V(\lambda)$ and $V'(\lambda)$ functions respectively[6]. These two functions have been adopted by the International Metre Convention as an intrinsic part of the SI system. No function, or set of functions, has yet been defined for the mesopic region ('intermediate' lighting levels) although it is widely recognised that this is of critical importance in a number of areas, such as night-time road lighting (see below). In practice, the huge majority of practical lighting measurements are made using meters designed to approximate the $V(\lambda)$ function.

The $V(\lambda)$ function was determined in the 1920s, primarily using the technique of flicker photometry, with small fields of view (subtending 2° to 3° at the eye) and with central (foveal) fixation. Some brightness matching experiments were included, but in this case only small hue differences were used. Later experiments showed that for the blue region of the spectrum, below 460 nm, the $V(\lambda)$ values were too low to represent the spectral sensitivity of most colour-normal observers and a modified function was proposed, $V_M(\lambda)$[7]. This was adopted by the CIE as a supplement to (not a replacement for) $V(\lambda)$ in 1988. However, despite the deficiency in $V(\lambda)$, it is this function, and not the modified version, that is currently used for all photometric measurements. Furthermore, the modified function has not been adopted by the Metre Convention and hence there are no 'official' units based on it. Although a move to the use of the $V_M(\lambda)$ function for practical measurements could have implications for the energy efficiency rating of some lamps, notably those such as white LEDs (which actually have strong blue emission), the effects would typically be small (<10%) and there therefore appears to be little enthusiasm at present for change. It has been noted that the $V(\lambda)$ function has served the lighting industry well for more than 80 years, without major problems becoming apparent in 'real' lighting installations[8]. Furthermore, since sensitivity in the blue tends to decrease with age, and experiments to determine $V_M(\lambda)$ have used mainly 'young' observers, it can be argued that the $V(\lambda)$ function may actually be a better representation of the visual response of an ageing population than $V_M(\lambda)$.

4.2.3 Mesopic Photometry

One of the most serious shortcomings in the current system of photometry, particularly in relation to evaluating the efficacy of different types of light source, is the lack of an agreed method for measurements in the mesopic region. Ever since the CIE defined the photopic spectral luminous efficiency curve, $V(\lambda)$, in 1924, researchers have been grappling with the difficult question of how to deal with the fact that the performance of the human eye changes depending on the level of illumination to which it is exposed. The photopic curve applies only at 'high' light levels (daylight, lit interiors etc.), where the rods are less active and cones dominate our vision, and colour discrimination and the ability to resolve detail in the visual field are both good. At 'low' levels (e.g. moonlight), only the rods are active, visual acuity is poor, and it is not possible to distinguish colours; in this condition, the scotopic spectral luminous efficiency curve, $V'(\lambda)$, applies. The intermediate region, the so-called mesopic, has proved an almost intractable problem so far. Here the eye's sensitivity changes rapidly depending on the characteristics (level and spectral distribution) of the lighting used, shifting towards the blue as the level decreases.

This is not a purely academic question, but has potentially far reaching consequences for the specification and measurement of lighting in a range of critical situations, such as road lighting, road and rail signalling, and lighting of emergency escape routes. Under the current system of photometry, lamps which emit a large proportion of their power around the peak of the $V(\lambda)$ curve (such as high pressure sodium lamps) are rated as having a high luminous efficacy and are thus the lamp of choice in many situations. Under mesopic conditions, however, a lamp with a higher blue content (e.g. metal halide) will have a greater visual effectiveness and may therefore be a better choice. Using $V'(\lambda)$ instead of $V(\lambda)$ to evaluate the output of a high-pressure sodium lamp, for example, will decrease the rated efficacy by more than 30%, whereas for a metal halide it will increase the rated efficacy by more than 70%. The difficulty is that without an agreed system for mesopic photometry, as is currently the situation[9,10], it is not possible to make meaningful comparisons between one lamp type and another, with the result that the optimum lamps are generally not specified.

A major limitation in research to date has been the fact that there are two key response channels in the human visual system. One, the luminance channel, is achromatic and additive; the other, the chromatic channel, provides colour information and is non-additive. The relative contribution from each channel depends on the light level and the task being undertaken. Flicker photometry, for example, is dominated by the luminance channel and is the basis for the $V(\lambda)$ function. Heterochromatic brightness matching, on the other hand, is dominated by the chromatic channel and is not well-described by $V(\lambda)$, even in the photopic range. As a result, researchers have developed many different models by which to describe the performance of the eye in the mesopic, the characteristics of which have varied significantly depending on the experimental conditions under which they were developed.

Despite these problems, there have been indications over the past 10 years that a consensus is gradually being reached, with most researchers agreeing that foveal vision in the mesopic is well represented by the $V(\lambda)$ function, and that where wider fields are involved the visual response is likely to depend on the task being undertaken[8].

The most recent research has therefore shifted towards a new approach to this problem. Instead of trying to describe the detailed performance of the eye under a given set of conditions, the emphasis has been on developing a system which can be readily implemented in practice, but which may not provide a precise description of visual performance. This places two important constraints on the model:

- It must be additive.
- It must tend to $V(\lambda)$ at the upper end of the mesopic region and to $V'(\lambda)$ at the lower end.

The results of this research were presented at the recent CIE Expert Symposium, ‘Vision and Lighting in Mesopic Conditions 2005’ [11]. At the discussion session following the symposium, a clear distinction was drawn between the two approaches to mesopic photometry and it was proposed that two systems should be developed. The first, the so-called ‘luminance system’, should focus on an additive system to provide a bridge between the $V(\lambda)$ and $V'(\lambda)$ functions and would be used for specification of lighting installations etc. in the mesopic range. Although this system would not provide a precise prediction of the performance of any particular visual task, in this respect it would be no worse a representation of the eye’s true behaviour than is the present photometric system in the photopic. The second, the so-called ‘brightness system’, should incorporate the influence of the chromatic channel and would link with work on brightness matching in the photopic region.

The work presented at the symposium, and elsewhere, is now sufficiently advanced to form a basis for the luminance system. Research carried out independently by two separate groups, using two different approaches, has resulted in a model of the form $x\ V(\lambda)+(1-x)\ V'(\lambda)$, with x being a function of the level of illumination[12,13]. It was agreed during the discussion that those involved in the development of the luminance system should, over the next year or two, refine the model based on existing experimental data, with the aim of having a trial system ready during 2007 or 2008 for field-testing by the road lighting and road safety industries in particular.

Thus the CIE is acting as a focus for international debate on mesopic photometry (via TC1-58 in particular, coupled with TC1-37 and TC1-46 which are working to develop a system for brightness evaluations) and appears to be fulfilling this role very effectively. It is inconceivable that any model of mesopic photometry will gain widespread acceptance without the endorsement of the CIE.

Even when a system has been recommended by the CIE, it will still be necessary to convince manufacturers, specifiers, regulatory bodies and users in general that the new system represents a significant improvement compared with the existing system. There are a number of arguments that can be made in favour of using a mesopic system of photometry, such as energy savings as a result of using lamps with optimum mesopic efficacy and improved safety for road users and pedestrians at night, but studies to demonstrate that these potential advantages are realised in practice are also necessary. Indeed several such studies have already been undertaken (for example[14,15]), which have demonstrated benefits in specific instances, but more are still needed

4.2.4 Large Field and Off-Axis Measurements

As indicated above, the present photometric measurement system is based on spectral luminous efficiency functions for a 2° field and central fixation. However in a ‘real’ environment, the visual field is usually much larger than 2° and objects are often located in the periphery of the field of view, rather than on-axis. Although a set of colour matching functions has been defined for the standard 10° colorimetric observer[16], and a function for a 10° photopic photometric observer has also recently been defined[17], measurements over all field sizes (and at all positions in the visual field) are currently still made using the $V(\lambda)$ function, even though this may give results which differ from the actual visual sensation. It seems there is currently no real enthusiasm for a change to the present system of photometry, particularly since investigations by visual research scientists appear to give inconsistent results[18]. It is likely that there will be some resistance to be overcome if the 10° function is to be introduced into general lighting design practice, where appropriate, and case studies may be necessary to demonstrate any benefits in terms of improved task performance and/or increased energy efficiency.

4.2.5 Brightness

As described in Section 4.2.2, the photometric measurement system is based on the principle of additivity. In practice, however, several different channels exist in the visual system, each activated by a different aspect of vision, and not all of these channels behave in a linear fashion. Many tasks involve the interaction of several channels, and it is not surprising, therefore, that the present system of photometry does not adequately represent these. The implications of this are most acute in cases where it is required to predict the brightness of a heterochromatic surface; a luminance measurement, which is based on the $V(\lambda)$ function, may depart seriously from the actual visual sensation. Much research has already been carried out on this subject, and more is underway[8,19]. The question of brightness matching is very closely related to the need for a colorimetric system which more closely represents the visual sensation. Research efforts in this area are being coordinated through CIE TC1-26, TC1-36 and TC1-37.

It is important to note that there is often much confusion between the terms ‘luminance’ and ‘brightness’ and that these are often, incorrectly, used interchangeably. Luminance is a purely physical quantity based on the use of the $V(\lambda)$ function; it is measured either directly, by use of a meter whose spectral responsivity has been matched closely to $V(\lambda)$, or indirectly by mathematical integration of the spectral radiance of the source multiplied by $V(\lambda)$:

$$L_v = K_m \int L_{e,\lambda} \cdot V(\lambda) \cdot d\lambda$$

Brightness, on the other hand, describes a perceived phenomenon and does not obey Abney’s law i.e. it is non-linear. Considerable research effort has been devoted to developing a system to transform luminance values to values that are more consistent with the perception of brightness. Some interim recommendations have been made for use with small fields in the photopic region[20] and further recommendations are being investigated under CIE TC1-37.

It is also important to note that confusion often arises between the needs for research into a system of photometry for predicting brightness matches and the need for research into mesopic photometry. This has been fuelled in part by the fact that much of the research into visual performance in the mesopic range has been based on methods using heterochromatic brightness matching. However it is important to keep a distinction between these two avenues of research and their potential implications for lighting practice. Luminance and brightness are not equivalent at **any** lighting level and any new system that is introduced for ‘brightness’ is likely to be designed to work throughout the photopic and mesopic regions. Its importance will be greatest in the photopic region, however, since it is at these levels that the majority of tasks involving brightness matching are performed (e.g. graphic design, desk-top publishing etc.). Practical systems for mesopic photometry, on the other hand, are intended to act as a ‘bridge’ between the photopic and scotopic systems, as described in Section 4.2.3. They will not represent the performance of the visual system for brightness matching.

4.2.6 Scales for Flashing Lights

Single-pulsed or repetitively flashing lights are used in many applications, particularly in transportation signalling. In the past, the temporal profile (i.e. the variation in intensity with time) for these sources was smooth and the various methods which were developed to determine the visibility or effective intensity of the light from measurements of the peak intensity and pulse width etc. all gave similar results, in good agreement with experimental results. Thus existing specification standards for areas such as marine signalling and roadway warning lights use relatively simple approaches, such as Blondel-Rey and/or Form Factor methods, to calculate effective intensity. However many modern light sources, such as xenon lamps and pulse-width modulated LEDs, have very complex temporal profiles, often with a single visible pulse actually being comprised of a train of closely-spaced (visually-indistinguishable) pulses. Existing standards have been shown to give conflicting results when applied to these sources; differences of several hundred percent can occur between the methods[21]. Research into the visibility and effective intensity of flashing lights is therefore required to support the preparation of improved measurement guidance and better specification standards for signalling in the transportation sectors in particular (road, rail, air and sea). Efforts in this area are being coordinated, as far as possible, by CIE TC2-39.

However visibility or effective intensity is not the only issue for pulsed lights. A key requirement of any sign or signal is that it should be sufficiently conspicuous to attract the attention of the driver, ship's captain, etc. Where it is seen in isolation, or under well-controlled conditions, this can be relatively straightforward to achieve. Often, however, a sign or signal may be observed against a complex background containing a great deal of competing and distracting information. Furthermore, anecdotal reports also indicate that methods currently used to assess the conspicuity of flashing lights under-estimate the conspicuity of LEDs compared with tungsten based sources. These issues are driving an increasing interest in the measurement of conspicuity and research into the relevant parameters, and their relationship with the ability to detect a signal, is needed to support this.

4.2.7 The Colorimetric Measurement System

In much the same way as the photometric system has been developed to provide a basis for measuring the amount of light emitted by a source or falling on a surface, so the colorimetric system has been developed as a basis for measuring the colour of a source or a reflective or transmissive material. As in the case of photometry, the system has been developed on the assumption of additivity, and uses internationally agreed colour matching functions. Two sets of functions have been defined[16]: $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ for a 2° field (the so-called 1931 standard colorimetric observer[22]) and $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$ and $\bar{z}_{10}(\lambda)$ for a 10° field (the 1964 standard colorimetric observer). The $\bar{y}(\lambda)$ function is identical to the $V(\lambda)$ function. In order to 'quantify' the colour of an object, it is necessary to first calculate the tristimulus values of the object and then, from these values, to calculate coordinates for a stated 2-d chromaticity diagram or 3-d colour space. Various chromaticity diagrams and colour spaces have been established and recommendations on their calculation and use are given in the CIE document on Colorimetry[16]. Standard illuminants have also been defined[23], so that the colour of reflecting surfaces can be specified and compared on a consistent basis.

Research into improved colour matching functions, chromaticity diagrams and colour spaces has continued since the adoption of the 1931 and 1964 standard colorimetric observer functions and efforts in this area are now being coordinated by CIE TC1-36, TC1-55 and TC1-56. As in the case of photometry, there is likely to be some industrial resistance to any change in the present system of colorimetry unless significant benefits can be demonstrated.

4.2.8 Colour Appearance

4.2.8.1 Colour of Light Sources

The advent of the fluorescent lamp first highlighted the possible variation in the appearances of coloured surfaces due to different light sources i.e. differences in the 'colour rendering' performance of sources with dissimilar spectral characteristics. In general, it is impractical to assess the colour rendering properties of light sources by direct observations, but two systems of measurement have been investigated. With the data available, both appear to rank different light sources in a similar order of performance. The problem of chromatic adaptation makes it difficult to compare two sources having different colour appearance and it is therefore necessary to select a standard source with a correlated colour temperature as close as possible to that of the test source in order to do a meaningful comparison. At colour temperatures below 3500 K, Planckian radiators are used as these are simulated by incandescent lamps. Above 5000 K the use of the CIE D-illuminants is recommended as being representative of various phases of daylight. For the region in between there are no familiar sources and so the use of Planckian radiators is recommended.

The NPL-Crawford method of assessing the colour rendering depends on comparing the spectral distribution of the test sources with that of the reference. To overcome the problem of interpreting a point-by-point comparison throughout the visible spectrum, Crawford divided the range into six bands, the luminance being integrated over each and expressed as a percentage of the total luminance. A previous system had employed eight bands but the six-band method was found to be superior. In calculating the Crawford index number, the percentage luminance in each band of the test lamp is compared with that of the appropriate reference and the percentage deviation of this ratio from unity obtained. Further calculations are designed to reduce these six numbers to a single index. Generally, the further away the chromaticity of the source is from the black body locus, the higher the value of the index.

The CIE General Colour Rendering Index was devised in 1965 and is based on the change in colour appearance of a surface colour that occurs when the illumination is changed. A correction is included, using the von Kries transformation, to allow for the fact that the chromaticities of the test and reference lamps are usually different. The index is expressed as the scaled mean colour difference for eight test colours and the scaling is designed to give a Warm White fluorescent lamp a value of 50, on a scale that gives 100 to perfect colour rendering. The eight test colours are an approximate constant Munsell chroma and value set with different hues. An additional six colours are used to give additional indices for flesh, saturated red etc. using the Special Colour Rendering Index. During the period 1965 to 1995 there were several improvements made to the calculation of the index.

In 1991 a CIE Technical Committee was formed to review the method of calculating the Colour Rendering Index. This addressed the following issues:

- **Reference illuminant.** It was argued that a choice of a ‘daylight’ illuminant or a ‘tungsten’ illuminant should enable better understanding of the values of the indices for various similar lamps.
- **Chromatic adaptation formula.** It was agreed that the use of the von Kries transform was not optimum, that the desire to use only a small number of reference illuminants required a ‘better’ formula, and that formulae were available that were well supported by experimental data. The CIE had found however, that no formula could be recommended from the several available – a situation that still exists to day.
- **Test colours.** It was suggested that a commercially available chart, for example, the Macbeth ColorChecker could form a more realistic set of test colours.
- **Colour difference formula.** Newer formulae are now recommended by CIE.
- **Averaging technique.** It has long been suggested that a weighted average of the colour difference was more appropriate than the straight arithmetic mean.
- **Scaling.** The use of Warm White was questioned because it is no longer a common, domestic lamp. There are also problems with the present index in that lamps with very poor colour rendering often have negative Colour Rendering Indices.

Many suggestions and combinations were calculated and discussed over a number of years but the final conclusion was that no change be recommended[24]. The main reason was that the representatives of the lamp manufacturers on the Technical Committee were unable to agree that the proposed changes gave them any additional ‘better’ information. Thus the matter was dropped from the CIE agenda. Now that a colour appearance model is recommended by the CIE it may, indeed should, be possible to reformulate the concept of an index in terms of true appearance variables: hue, chroma and lightness, rather than colorimetric variables *X*, *Y*, *Z*[25]. Whether this will be any more acceptable to the light source manufacturers will depend on being able to show added value over the traditional Colour Rendering Index, and this will not be easy; showing that something is more sound scientifically will not be enough. This issue has received renewed attention over the past couple of years due to the introduction of white LEDs, which fare badly using the present colour rendering system as compared with fluorescent lamps, for example. CIE TC1-62 is investigating this issue.

4.2.8.2 Colour Constancy Effects in Lit Environments

The spectral power distribution of the lighting used to illuminate a space has a significant impact on the appearance of that space[26]. Metrics such as correlated colour temperature and colour rendering index are used as ‘shorthand’ means of expressing the spectral power distribution and can be used to give a general impression of how an environment is likely to appear. But these expectations can be confounded by the fact that the eye is extremely good at adapting to the ambient conditions (chromatic adaptation). As a result, there is a tendency for the prevailing illumination in any environment to appear ‘white’ or ‘neutral’ in colour and for the colour appearance of objects to appear somewhat constant under all conditions of illumination. This effect is known as colour constancy. It should be noted that colour constancy effects do not, however, negate the ability of the eye to detect even small differences in colour between materials and objects in a lit environment, especially when a direct comparison can be made.

Current measurement systems for lighting take no account of chromatic adaptation and colour constancy or of the impact these have on the appearance of the lit environment, although some studies have been carried out[27]. Chromatic adaptation is considered in colour appearance models for objects, however (see Section 4.2.8.3 below).

4.2.8.3 Colour Appearance Models for Objects

In practice, an object is rarely viewed in isolation from its surroundings. Thus, although the colorimetric measurement system is invaluable in enabling colours to be reliably reproduced from one location to another (e.g. for production of dyes and pigments) it does not accurately represent the observed appearance of an object in its real environment. As in the case of photometry, problems arise due to the multiplicity of channels involved in the visual process and the non-additivity and inter-dependence of many of these channels. Factors such as the luminance of the object, the background and surround colour and luminance and the degree of adaptation of the observer all affect the appearance of the object and need to be taken into account. There is considerable research activity in the field of colour appearance modelling, which is being successfully coordinated by the CIE. Guidelines for the development and testing of colour appearance models have been drawn up[28,29] and have been used to underpin the development of improved colour appearance models.

In 1998 CIE publication 131 described a colour appearance model, CIECAM97s, that can be used to extend traditional colorimetry (e.g. CIE XYZ and CIELAB) to the prediction of the observed appearance of coloured stimuli under a wide variety of viewing conditions. This is accomplished by taking into consideration the tristimulus values of the stimulus, its background, its surround, and the adapting stimulus; the absolute luminance level, and other factors such as the cognitive effect of discounting the illuminant (the degree of adaptation). The output of colour appearance models includes mathematical correlates for perceptual attributes such as brightness, lightness, colourfulness, chroma, saturation and hue. While the application of such models has not been extensive in the more traditional areas of colour measurement (dye and pigment prediction, graphics arts etc.), it has found many applications in colour management systems for digital imaging.

It must be emphasised that this model is not a relative model. It does not just predict that one coloured sample is redder than another but gives measures of the absolute hue of each sample. Because it also has predictors of brightness, for both neutral and coloured stimuli, it provides a method of comparing the luminance measurement with the brightness prediction of stimuli and could, for example, be used in addition to the visual performance model to give predictors of performance in terms of absolute colour: hue, brightness and colourfulness.

A revised model, CIECAM02, has now been published by the CIE to supersede CIECAM97s[30]. Its advantages include improved agreement with visual data, simplified computation (an issue in digital imaging where the transforms have to be applied to an image pixel by pixel), and reversibility (the ability to input appearance parameters and derive CIE colorimetry).

The science of colour appearance is not complete. The present model does not include modelling of the rod response and is thus not valid to work at very low, scotopic levels of illumination, nor probably through most of the mesopic region. This has been addressed in the literature[31,32] but is not yet recommended by CIE. It does, however, represent an important area of activity, for example, in driving by night or in low-level street lighting, tunnels etc. (mesopic). Thus there is ample scope for further work on modelling to improve the capability to derive measures of performance in terms of readily understood, and easily measured, parameters.

4.3 VISUAL PERFORMANCE AND VISUAL PERFORMANCE MODELS

4.3.1 Introduction

Visibility is the most obvious process that is influenced by light and lighting. The pervasive nature of light and lighting into almost every aspect of our lives means that the physiology, operation and capabilities of the visual system have been the subject of extensive and thorough investigation for more than a century. The long history of research into the human visual system has resulted in a reasonably well-developed understanding of how lighting can affect the ability to perform tasks with a high visual content. It is well established that the visibility of a task is determined by four variables: luminance (and luminance contrast), colour (and colour contrast), visual task size, and the quality of the observer's optical system (which affects retinal image quality and retinal illuminance). A steady reduction in any one of these variables will degrade the ability to perform a visual task, eventually reaching a threshold level where any further reduction will result in inability to perform the task. As the variable is increased from the threshold level, visibility rises rapidly and eventually plateaus, with the precise relationship being dependant on a number of factors, including the adaptation luminance level, task size and reflectance properties of the task. Importantly, relative changes in the individual variable do not produce equal changes in visibility, which means that it is not possible to establish a linear relationship between lighting characteristics and performance; instead various ‘visual performance models’ have been developed to enable predictions of task performance to be made from knowledge of the background luminance, contrast and size of the critical object.

The success, or otherwise, of these models depends on the task being undertaken. In particular, it is important to remember that they are primarily based on research in the area of office lighting, which involves mainly two dimensional tasks and where the lighting conditions are fairly well controlled. There has been relatively little research into lighting for industrial environments, such as factories, where the tasks are typically three-dimensional and where uniformity of lighting, for example, may be more difficult to control.

4.3.2 Factors Affecting Visibility and Task Performance

Any stimulus to the visual system can be described by five parameters: its visual size, luminance contrast, colour difference, retinal image quality and retinal illuminance. These are important in determining whether, and how well, the visual system can detect and identify the stimulus. The colour, spatial distribution, position, intensity etc. of lighting can influence these parameters in the following ways[2]:

- **Visual size –** although lighting can do little to change the visual size of 2d objects, it can be used to enhance shape and form of 3d objects by producing shadows.
- **Luminance contrast** – lighting can change the luminance contrast of a stimulus and hence enhance, or diminish, its visibility. However if the luminance contrast is excessive, disability glare in the eye or veiling reflections from the stimulus can cause a reduction in visual performance.
- **Colour difference –** the use of light sources with different spectral power distributions can alter the colour difference between the object and its background and thus make it more, or less, visible.
- **Retinal image quality** – this is determined by the stimulus itself, the scattering properties of the medium through which light from the stimulus passes and the ability of the eye to focus the image on the retina and is therefore little influenced by the characteristics of the lighting used, although light sources that are rich in short wavelengths produce smaller pupil sizes than sources deficient in short wavelengths (see Section 4.3.2.2); smaller pupil size reduces spherical and chromatic aberrations and gives greater depth of field.
- **Retinal illuminance** - lighting directly affects the retinal illuminance and determines the adaptation state of the eye. Retinal illuminance E_r is related to the luminance of the surface being viewed by $E_r = e_t\ \tau (\cos\theta / k^2)$, where τ is ocular transmittance, θ the angle between the line of sight and the normal to the surface, k is a constant (=15) and e_t is the amount of light in trolands, given by $e_t = L\rho$ where L is the surface luminance and ρ the pupil area in mm^2. Pupil area is determined primarily by the scotopic retinal illuminance.

Four fundamental attributes of an object are maintained constant over a wide range of lighting conditions: lightness, colour, size and shape[2].

- **Lightness** – it is generally possible to perceive a difference between a low-reflectance surface receiving high illuminance and a high-reflectance surface receiving low illuminance, even if the actual luminance of the two surfaces is the same, provided that other visual cues are not deliberately excluded (such visual cues provide additional information that is used to aid this distinction). In other words, luminance is not a precise indicator of brightness or lightness. This makes the use of luminance as the basis of lighting design criteria difficult to justify, although there is no real alternative at present.

- **Colour** – quite large changes in illuminant spectral power distribution can be made without changing the perceived colour of a surface.
- **Size** – the further away an object is, the smaller its image on the retina. The brain uses other clues to estimate distance and hence object size.
- **Shape** – as the orientation in space of an object changes, so the retinal image changes. Other clues allow the brain to determine orientation and hence shape.

4.3.2.1 Illuminance and Luminance

Illuminance will directly affect the luminance of a task and the surround background and therefore affect the contrast ratio of the task and the adaptation state of the eye. If the contrast of a task is too small the detail of the task will not be visible, impacting on the ability to perform the task. Therefore, the factors that influence task contrast are an important consideration for lighting. Not surprisingly, a clear relationship has been established between illuminance and task performance, with performance decreasing as the visibility of a task becomes inadequate[33,34,35,36,37]. However, these studies also highlight a common problem with many illuminance/performance related studies: changes to the illumination system are usually accompanied by other changes to the environment, such as decoration or furnishing. In addition, there are other psychological and social mechanisms that influence our ability to complete a task, which can influence the results of performance studies.

Increasing the illuminance on the task generally produces an increase in visual performance, following a compressive non-linear relationship. That is, although generally task visibility increases as illuminance or luminance increases, even at relatively high levels, the corresponding percentage increase in visibility decreases as the level increases. The illuminance at which visual performance tends to level off is dependent on the visual difficulty of the task, i.e. the smaller the size and the lower the contrast of the task, the higher the illuminance at which performance saturates. Furthermore, although increasing illuminance can increase task performance, it is not possible to bring a difficult visual task to the same level of performance as an easy visual task simply by increasing the illuminance.

In principle, these effects occur for all tasks, although the exact relationship between the illuminance on the task and the visual performance achieved will vary with the nature of the task. Another aspect is the extent to which the visual part of the task determines the overall task performance. Where there is only a small visual component, such as in audio typing, the influence of illuminance on overall task performance is likely to be small, but where the visual component is a major element of the complete task, such as in copy typing, the illuminance provided will have a greater influence.

Research to date indicates that, provided the task luminance is above a threshold minimum level, increasing illuminance has no lasting effects on cognitive work performance[38,39], which suggests there is no benefit to employers in increasing light levels for such tasks. However, there may be benefits in terms of better mental health in cases where the present daily light dose is too low (see Section 6.4). In addition, recent research[40] supports the view that short-term exposure to bright light in the workplace (2500 lx) boosts alertness, concentration and mood, especially during the 'post-lunchtime dip' (see Section 5.3 for more details). In any case, any increase in light levels should be targeted on areas that will be frequently viewed (e.g. desk surface) rather than providing increased illuminance throughout an interior, in order to achieve optimum energy efficiency (i.e. reduce energy wastage).

Despite the difficulties associated with establishing clear relationships between task performance and task illuminance, illuminance recommendations have been established for various situations by bodies such as CIBSE[41] and these have generally served reasonably well. However recent research has shown that when occupants are given the opportunity to set their own preferred illuminance, they often set levels less than those specified[42,43], indicating some revision of levels might be appropriate.

4.3.2.2 Spectral Distribution

There is conflicting evidence regarding the influence of spectral power distribution on task performance. A number of studies have shown that for constant illuminance, the spectral distribution of the light source used has little or no effect on visual performance or acuity in the photopic luminance adaptation range typical of lit interiors (for example[44,45,46]). In other words, the spectral power distribution of the light source generally does not affect performance, providing that the colour rendering properties are acceptably good[47]. However, anecdotal evidence suggests that some arts and craft workers prefer to use incandescent lamps with blue bulbs, instead of bare tungsten lamps, in order to improve visibility, and there is some evidence[48] that lighting with a high blue content leads to a reduction in pupil size, even at adaptation levels where rod-vision is saturated. As reduced pupil size increases depth of field and visual acuity, it has been predicted that ‘scotopically’ enriched light sources (sources with strong emissions around 508 nm) should increase visual performance for certain tasks. Some experimental studies support this theory for tasks involving small, low contrast achromatic targets that are viewed for a short time[49], although such tasks are seldom encountered in a normal working environment. More recent research, however, appears to demonstrate that the visual acuity of school children engaged in a typical reading task can be improved through the use of lamps with high blue content[50], but the case is currently far from proven and this remains an area of heated debate.

The perceived colour of an object of fixed chromaticity is dependant on the properties of the surface of the object and on the spectral distribution of the illuminating light source. If colour is used in a task to increase the contrast of an object from its background, it is the colour contrast that is important and not the actual perceived colour. If a task uses colour to provide some meaning, such as the colour of a warning sign, then this task has a greater cognitive aspect. In both cases, the spectral distribution of the incident illumination can affect task performance, although the level of impact will depend on the task characteristics.

The effect of source spectral distribution on the performance of tasks which are based on colour contrast is limited to low luminance contrast conditions. Ekland[51] examined the ability of people to read an exit sign from a distance when the letters and the background could be varied in colour and in luminance contrast. The results from this work show that when the task and background have the same colour, the ability to distinguish the task from the background declines as luminance contrast falls below about 0.3. When the task and background are of different colour, there is no decline in the ability to read the letters, even when the luminance contrast is zero. This result implies that light spectrum will only matter for the performance of chromatic contrast tasks where luminance contrast is low. In these conditions, a spectral distribution that enhances the colour difference between the task and the background will also enhance task performance.

For tasks where colour discrimination or colour naming is important, the effect of spectral distribution on task performance will depend on the level of discrimination required. Recommendations of the light source to be used for fine colour discrimination, in a number of industries, have been made. If there are no specific recommendations on the type of light to be used, the CIE Colour Rendering Index provides a system to classify the colour rendering properties of light sources (see Section 4.2.8.1).

4.3.2.3 Relationship Between Illuminance, Spectral Distribution and Energy Efficiency

As indicated above, illuminance on the working plane is the key factor determining the acceptability of the lighting in most environments. (Note this is not always true; in cases where the task involves viewing a surface or object which produces specular reflections, for example, other factors such as the position of the light source(s) may be equally important.) Since it is possible to achieve the same illuminance through the use of sources with different spectral power distributions, and hence different efficacies, this raises the possibility for reduced lighting operating costs through the use of high efficacy sources. However there is always some trade off between efficacy and colour rendering, and light sources which have particularly high efficacies will generally distort the colour appearance of surfaces to some extent. This colour distortion may be critical to task performance in cases where colour discrimination is important, such as colour printing and medical diagnosis, and for such tasks, lighting recommendations specify both a minimum illuminance and a minimum CRI. Generally the use of lighting with a high general CRI (i.e. >80) is suitable in terms of task performance and ensures that tasks requiring a fairly high degree of colour discrimination or colour identification can be carried out easily. In cases where colour discrimination is critical, a CRI of greater than 90 is usually recommended.

4.3.3 Task Uniformity and Glare

Most lighting installations serve not only to ensure that the required task can be seen adequately, but also to ensure visual comfort, or at least avoid visual discomfort. Visual discomfort is a rather subjective concept. Thus what is deemed ‘uncomfortable’ or ‘acceptable’ depends on past experience, expectations and attitudes, and also on the context/environment. But in a general sense lighting is intended to enable the visual system to extract information from the visual environment and therefore aspects of the visual environment that make this more difficult can lead to visual discomfort. The key features are visual task difficulty, under or over stimulation of the visual system, visual distraction, and perceptual confusion. These in turn are influenced by, or are dependent on, the light level, light uniformity, glare, veiling reflections, shadows, and flicker.

Too high a degree of uniformity in the visual field is undesirable and can be disturbing (e.g. driving in fog or in a snow storm). But a high degree of non-uniformity, especially across a work surface, is also a source of visual discomfort, even though it may not directly influence task performance[52]. Most lighting installations are therefore designed to provide a uniformity ratio of greater than 0.7, which most people judge as acceptable. Smaller ratios (i.e. greater non-uniformity) are accepted in situations where, for example, light is incident through a window or individuals have desk lights in addition to some form of background lighting. Sudden changes in illuminance can be disturbing and are therefore also undesirable.

Glare is an extreme form of non-uniformity and has been studied extensively. There are four main types that are experienced in ‘normal’ situations: saturation glare (large part of visual field is bright e.g. outdoors on a sunny day), adaptation glare (sudden increase in illumination level e.g. when leaving a cinema during the day), disability glare (due to scattering of light within the eye e.g. when facing an oncoming vehicle at night or when approaching a dark tunnel during the day), and discomfort glare (i.e. a feeling of discomfort in the presence of bright light sources).

4.3.3.1 Disability Glare and Veiling Reflections

The distribution of light on and around the task can affect task performance, either by changing the contrast of the retinal image of the task or by altering the adaptation of the visual system. The contrast of the retinal image can be altered in two ways, by disability glare and by veiling reflections.

Disability glare is most likely to occur when there is an area close to the line of sight that has a much higher luminance than the object of regard. Then, scattering of light in the eye and changes in local adaptation and lateral inhibition can cause a reduction in the contrast of the object. Alternatively, if the source of high luminance is viewed directly, this can cause local dilution of the retinal photo-pigments. As the photo-pigments regenerate, after-images are experienced until chemical equilibrium is restored.

As luminance contrast is a major determinant of visual performance, a change in luminance contrast can affect task performance. Whether it does or not depends on the luminance contrast in the absence of disability glare. Tasks that require extracting information from low contrast details, such as when the visual system is operating close to threshold, will be susceptible to disability glare. Tasks that are characterised by a high luminance contrast will not be so sensitive to disability glare. Disability glare is not common in interiors but can be produced by poorly positioned light sources, unshielded lamps, or by the view of a bright sky or the sun through a window. In the external environment, disability glare is a common feature of driving, particularly at night.

Disability glare has been studied extensively, leading to several different empirical models to predict the amount of disability glare (or ‘equivalent veiling luminance’) produced by a source. Based on these models an equation has been developed to predict equivalent veiling luminance from directly measured variables, and this has since been modified to take account of large angles between the line of sight and the glare source, different age ranges, and eye colour[53]. Thus disability glare is well understood and can be predicted with a good degree of accuracy.

Veiling reflections are specular luminous reflections from surfaces that physically change the contrast of the visual task and therefore change the stimulus presented to the visual system. The two factors that determine the nature and magnitude of veiling reflections are the specularity of the material being viewed and the geometry between the observer, the target and the light source. If the object is a perfect diffuse reflector (i.e. a lambertian reflector) no veiling reflections can occur. If the object has a specular reflection component, veiling reflections can occur. The positions where they occur are those where the incident ray corresponding to the reflected ray that reaches the observer's eye from the target comes from a source of high luminance. This means that the strength and magnitude of veiling reflections can vary dramatically within a single lighting installation[54]. When the specularity is the same across the whole task, for example on the page of a glossy magazine, then the effect of veiling reflections is to decrease the luminance contrast, because the same veiling luminance is added to the luminance of the print and the background. However, when the print and paper differ in specularity, veiling reflections may either increase or decrease the luminance contrast of the print depending on the relative reflectances and specularities of the print and background. Probably the most extreme case is where a combination of specularly reflecting, dark material is used for the print and a diffuse, light material is used for the background. In this case, strong veiling reflections can cause the luminance contrast to reverse, from positive contrast to negative contrast, or vice versa.

The effect of veiling reflections on luminance contrast may be quantified by adding the luminance of the veiling reflection to the appropriate components in the luminance contrast formula.

One aspect of disability glare and veiling reflections that has received much attention is the influence this can have on the readability of VDU screens[55]. As a result of a number of studies, many lighting recommendations for offices now specify the use of luminaires with a defined maximum luminance in particular directions and good surface uniformity. Workplace directives[56] and SLL Guide revisions[57], are aimed at firstly setting lighting criteria and then providing guidance on how to achieve the criteria. This work may still be relevant for the consideration of specular reflecting surfaces, but VDU technology has moved on. With modern, low reflectance, high luminance VDUs, disability glare and veiling reflections are less of a problem and the use of special luminaires is generally not necessary.

4.3.3.2 Discomfort Glare

Discomfort glare has been extensively researched, but is not well understood. The discomfort experienced when some elements of an interior have a much higher luminance than others can be immediate but sometimes may only become evident after prolonged exposure. The degree of discomfort experienced will depend on the luminance and size of the glare source, the luminance of the background against which it is seen and the position of the glare source relative to the line of sight. A high source luminance, large source area, low background luminance and a position close to the line of sight all increase discomfort glare. Unfortunately most of the variables available to the designer alter more than one factor. For example, changing the luminaire to reduce the source luminance may also reduce the background luminance. These factors could counteract each other, resulting in no reduction of discomfort glare. However, as a general rule, discomfort glare can be avoided by the choice of luminaire layout and orientation, and the use of high reflectance surfaces for the ceiling and upper walls.

Many studies into discomfort glare have been undertaken, leading to a large number of systems to predict the degree of discomfort produced in different lighting situations. In all cases increasing the luminance of the glare source, decreasing the luminance of the background, increasing the visual size of the glare source or decreasing the angle between the line of sight and the glare source will lead to an increase in the discomfort glare. The most recent system for predicting discomfort glare is the unified glare rating (UGR) system, which was adopted by the CIE in 1995[58]. However this has not been universally adopted and some other systems are also used in specifications and manufacturers' data sheets, in particular the visual comfort probability (VCP) system which is used in North America. None of the systems is 'perfect', but the UGR values possibly provide the best correlation with subjective ratings[59]. Despite the development of the UGR system, it is still not possible reliably to predict and control discomfort glare. Questions still remain regarding how to determine the luminance and solid angle of glare sources that do not have well-defined edges or a uniform luminance, and how to deal with the effect of the luminance of the immediate surround to the glare source. Problems also arise when applying the formula to very large or very small sources.

4.3.4 Polarisation

The plane of polarisation of the incident light can affect the contrast of reflecting materials. It has therefore sometimes been suggested that the use of polarising media can reduce veiling reflections and hence enhance contrast. Although this can be the case, the effect is generally of limited value and requires careful control of the geometry between the observer, the reflecting surface and the source of polarised light[60].

4.3.5 Flicker

Several studies have shown that flicker rates of below ~145Hz, as found with fluorescent lamps operating from conventional (magnetic wire-wound) ballasts, can adversely affect visual performance[61] and creative writing and psychometer performance tasks[62]. Flicker also appears to influence physical comfort and possibly health and be the cause of the eyestrain, headaches and poor vision sometimes reported for tasks performed under fluorescent lighting; a study by Wilkins et al.[63], for example, showed a 50% reduction in rates of eyestrain and headaches when using high frequency ballasts instead of the 100 Hz modulation rates of conventional ballasts. These performance and comfort/health benefits, coupled with increased energy efficiency, provide a strong argument for widespread adoption of electronic ballasts in fluorescent lighting systems.

4.3.6 Visual Performance Models

CIE document 145[64] and Boyce[65] both provide summaries of the outcomes from several analytical studies aimed at determining a relationship between lighting and visual task performance. The general conclusions from such studies are: (a) increasing illuminance in uniform steps from an initially low value at first gives a rapid increase in performance, but the rate of improvement falls off as the illuminance is increased further, eventually reaching a plateau; (b) the point where this saturation occurs depends on the luminance contrast and size detail of the visual task; (c) larger improvements in performance can be obtained by changing the task (e.g. increasing the size detail) than by increasing the illuminance; and (d) it is impossible to reach the same level of performance for a difficult visual task as is achieved for a simple visual task simply by increasing the illuminance.

Various attempts have been made to develop a system for predicting the effect of lighting conditions on visual performance based on the outcomes from these investigations. One of the earliest to find fairly widespread recognition was a comprehensive analytical model developed by the CIE for describing the influence of lighting parameters on visual performance and hence the ability to carry out tasks with significant visual components[66,67]. The model was based on the study and analysis of extensive historical and, what was then, recent research. Two basic approaches to compiling the elements of the model were used:

1. Empirical studies involving the measurement of the speed to carry out and the accuracy of performance of a specific task, conducted under real or simulated conditions.
2. Analytical studies involving the measurement of the operational characteristics of processes believed to be operative in visual work, either singly or in relatively simple combinations.

The model expressed the functional relationship between the overall observer visual task performance and the level of reference luminance or illuminance in terms of two classes of transfer function, operating in series. The first transfer function related the task *visibility level* to the reference luminance or illuminance and the second transfer function related the overall visual task performance efficiency to the task visibility level. Both transfer functions took the form of S-shaped response curves, indicating that there are levels below which, and above which, the relationship between illuminance or luminance, and performance, cease to be linear.

Despite its endorsement by the large number of researchers and consultants involved in the Technical Committee responsible for its preparation, the CIE model was not widely adopted. Research has continued and a number of new models have been proposed. One of the most successful of these is the relative visual performance (RVP) model[68]. A key feature of this model is that over a wide range of task and lighting variables the change in RVP is slight, but at some point it will start to deteriorate rapidly. The model was initially developed using a numerical identification task but was subsequently found to also apply for the reaction time for detection of a square stimulus[69]. The validity of the RVP model has been tested for a number of other tasks and found to fit the measured data well, although not perfectly[70,71,72]. The tasks for which the model is most suited are those where the non-visual component is small, peripheral vision is not important and where the stimuli can be fully characterised by their visual size, luminance contrast and background luminance. It does not cope well with tasks involving visual search (these involve peripheral vision) or colour differences (e.g. an emergency exit sign can be seen even with zero luminance contrast because of the colour difference between the letters and the background). It is definitely not applicable for tasks with a small visual component, since it is linked only to visual performance, not total task performance. It would, however, be possible to use the model to assist with the prediction of task performance in general if a systematic task analysis procedure were developed, to determine the relative impacts of visual and non-visual components on the performance of any task.

Several other models of visual and task performance have also been developed (for example[71,72,73]), but these have proved less successful, either providing a poorer fit to the data for some experiments, or being specific to a particular task, or requiring additional information before they can be used.

Most recently, the CIE[64] has undertaken an extensive review of data from visual performance studies and evaluated the results with respect to the criteria used and to the experimental conditions. The data of the most comprehensive study by Weston in 1945[74] were used as a basis for a new model of visual performance and this model was then compared with the results from other studies (for example[69,75,76,77,78]). The comparison considered the compatibility of the criteria used and also took account of the influence of age on visual performance and the relationship of visual performance to visual acuity. It was found that the new model gave predictions in reasonably good agreement with the results from many of the previous investigations, but there were discrepancies with the results of Rea and Ouellette[69]. This is most likely due to the different criteria used to express visual performance in the two sets of experiments; the studies by Weston comprised visual acuity (a high resolution task) and the time the task required to be performed, whereas Rea and Ouellette used the inverse of the time in which a target, with positive contrast, could be detected (i.e. a visual task that does not require high resolution). High and low resolution tasks are processed by different channels in the human visual system. Detection of a target, as in the studies by Rea et al., requires low spatial frequencies and such information is processed by the magnocellular system. If the resolution of detail is required, such as prevails in reading tasks, the information is in the high spatial frequency range (i.e. involves fine detail) and is processed by the parvocellular system. This then gives an indication of which model to use for given types of task: where fine details need to be resolved the CIE model, based on the work of Weston, may be most appropriate, whereas for tasks involving detection of a target Rea's RVP model may be more applicable. However further research is needed to confirm the applicability of these models before definitive guidance on their applicability can be provided.

The models of visual performance that have been developed so far are all based on activities that are of relatively short duration. When undertaking prolonged work, fatigue and mood changes may also affect performance, and both of these may, in turn, be influenced by the lighting. In particular, lighting conditions that are inadequate for the task are likely to lead to fatigue and hence decreased performance/increased risk taking. But performance when fatigued is also influenced by many other factors; lighting is just one component, and the consequences of inappropriate lighting conditions will depend very much on the nature of the task and the consequences of errors. Lighting conditions such as illuminance and colour temperature have been shown to have an effect on mood[79]; lighting which ensures good task visibility and appears attractive produces positive affect[80] whereas poor lighting which makes the task difficult will generate fatigue and negative affect.

It should also be noted that visual performance models only relate to visual performance efficiency, and this is only one aspect of overall task performance. What is needed is a practical method for relating overall performance efficiency to visual performance efficiency. Nevertheless the models developed so far have three potential uses in lighting applications:

1. To establish differential standards for task luminance or illuminance on the basis of the visibility of the task in the visual scene, the required level of task demand, and the age of the observer.
2. To evaluate the extent to which a given lighting installation provides the visual performance criteria selected for each area of application.
3. To provide measures of overall performance for use in cost-benefit studies of lighting installations.

4.4 IMPAIRED VISUAL SENSORY PERFORMANCE

4.4.1 Lighting for People with Sensory Impairment

People with some form of sensory impairment constitute a significant proportion of the UK population. There are around 2 million visually impaired people (VIP) in the UK who have a vision problem that cannot be rectified by wearing spectacles, and around 8.7 million deaf or hearing-impaired people (DIP). There is also a range of other sensory impairments, including cognitive impairments. Lighting research in the two broad areas of visual and hearing impairment is distinguished by a general lack of an inter-disciplinary and cross-sector approach. There has been very little recent activity in this area, since much of the medical aspects of vision and hearing loss are well established and the main thrust of lighting research has concentrated on the standard observer. In this regard the DIP is generally considered to have standard vision. The compartmentalisation of engineering, science, social science, medical and health sciences research is well known, although it is only through recognising lighting as an intrinsic factor in all these areas that these issues can effectively be addressed.

CIE Technical Report 123-1997[81] provides an extensive reference source for the lighting needs of partially sighted people. No such source exists for DIPs. Those sections concerned with the basic principles of vision and the nature of the effects of low vision in relation to a range of visual functions provide an excellent basis for future research work. Such research is equally valid, in an overall sense, for the lighting needs of older people, since there is a greater incidence of vision and hearing problems with older people. In those countries where there is an ageing population the needs of these user groups are becoming more important. Unfortunately the design guidance and general recommendations in the CIE document are now nearly 20 years old and technology, design methods and design recommendations have moved on.

4.4.2 Medical and Psychological Aspects of Lighting Design for the Sensory Impaired

The medical and psychological aspects of vision and hearing are major academic subject areas in a range of courses. This collective body of academic knowledge and experience has, with few exceptions hitherto, failed to make strong links with the lighting community in the areas of design application and research. This has probably occurred because the research objectives of the ophthalmic, optometric and audiology communities are directed towards detailed medical analysis and the lighting community is concerned with the lighting of the interiors and exteriors of buildings. They may have different primary research objectives, but as emphasis on user needs increases, the psychological and medical aspects of lighting will assume increasing importance. In the psychological academic field there has been a body of work on the perceptual aspects of vision, recognition and comfort and acceptability. CIE is taking this issue forward through the activities of TC3-34 ‘Protocols for describing lighting’, which is setting a potential agenda for the examination and definition of lighting quality indicators.

Building users who are hearing impaired, rank lighting and colour as the two most important environmental aspects of the built environment. DIPs communicate in a variety of ways with the most common being lip-speaking/reading and signing, communication methods that require good lighting. This does not overtly appear in any lighting design guidance for building interiors. Although directional qualities and modelling are mentioned in relation to lighting quality[41] they are not placed within a context that relates to user needs. This, it could be argued, is because there is little research evidence on which to base such guidance; more research would therefore be welcomed.

In a more general sense, the review of light sources for hospital wards[82,83,84] that took place several years ago may need to be revisited with the advent of T5 lamps and the development of other light sources. Recent work by BRE and South Bank University[85] examined general public areas including hospital wards, but not specialist clinical areas.

4.4.3 The Influence of Age on Visual Performance

As the eye ages, changes occur in the ocular media, specifically in the cornea and the crystalline lens. There is an overall decrease in total transmittance of the cornea and the lens, resulting in increased stray light, and this is coupled with a more pronounced decrease in the spectral transmission in the blue part of the spectrum, giving a yellowish tint, particularly in the lens. As a result, a 75 year old eye has approximately 2.5 times more scattered light than that of a 25 year old, for example, and an 80 year old eye has around 21% of the total transmission of a 30 year old. However optical deterioration in the eye cannot fully explain the losses observed in visual acuity (capability to resolve detail) in older eyes, which is mainly caused by the loss of visual cells and ganglion cells that occur over time. A 70 year old person with fully corrected vision, for example, would typically achieve only 66% of the acuity of a 20 year old person. The prevalence of low vision (judged primarily by loss of visual acuity) increases sharply in the elderly, from about 5-6% in the age range 75-79 to over 30% for those aged over 90[86]. As visual acuity is interrelated with visual performance, the latter will also decrease significantly with age. Although this has been allowed for in the CIE performance models, there is nothing to suggest that the requirements of the ageing population have been fully considered in lighting specifications and recommendations in general.

4.5 SUMMARY OF KEY AREAS FOR FUTHER RESEARCH

AREA OF RESEARCH	SPECIFIC ISSUES REQUIRING INVESTIGATION / ACTION	KEY IMPACTS
Scales for mesopic vision	Development of practical systems for mesopic photometry Studies to demonstrate validity and encourage incorporation into lighting specifications and recommendations	Better efficacy for road lighting and resulting energy savings Improved road and rail safety at night More effective emergency escape lighting
Visual scales for large fields of view	Demonstration of better prediction of human visual perception	Improved lighting specifications for better task performance and/or increased energy efficiency
Brightness scales	Development of measurement systems that correlate better with human visual perception	Improved lighting specifications, especially for safety applications
Colour rendering	Improved systems for specifying colour rendering, particularly for LEDs	Reduced barriers to trade for introduction of new (high efficacy) light source technologies such as LEDs
Colour appearance	Improved models for colour appearance, particularly at low light levels	Improved specifications for signage used in low light levels e.g. night-time driving and emergency escape routes
Visual performance	Studies to identify relationship between visual performance and the characteristics of the visual task being performed and the lighting being used (level, spectral and spatial distribution etc.), and development of models to predict outcomes	Improved lighting design Increased energy efficiency in lighting Increased worker productivity Reduced accident rates

Visual Performance	Studies to further examine individual preferences for task illuminance levels and resulting benefits in terms of performance and energy use, and how these might be engineered in practice.	Improved human performance Increased energy efficiency in lighting

5 PSYCHOLOGICAL ASPECTS OF LIGHT AND LIGHTING: PERCEPTION, MOTIVATION, PREFERENCE AND MOOD

5.1 INTRODUCTION

The perceptual system takes over once the retinal image has been processed by the visual system (see Section 4). The simplest output from this perceptual system is a sense of visual discomfort, which can change observer's mood and motivation and hence influence task performance. Lighting also sends a 'message' about a lit environment, which can also influence mood and motivation. There has been limited research into human interactions with, and interpretations of, the visual environment or into the effect of lighting on perception and the influence of this on task performance. The studies conducted so far have been inconclusive at best and frequently give conflicting results[1]. For example, one study[87] found that reduced light levels increased aggression, whereas another[88] found no effects of lighting on mood, either positive or negative. Lighting can certainly be used to draw attention to objects and to modify mood, but it is not known to what extent this can be used to affect task performance, due to the large number of influencing variables involved.

It has been generally assumed that increasing illuminance levels leads to increased arousal (mental and physical activation) and that this will increase task performance, and this led to an increase in recommended illuminance levels through most of the 20th century, until energy usage became a concern. However the evidence for a direct link between illuminance and task performance is weak[39]. Part of the problem is that many other variables also affect task performance, but difficulties in comparing results from different studies also arise due to wide variations in the illuminance levels used. Attempts have been made to combine results from different studies[38] and have shown that changes in the range ~ 70 lx to ~ 500 lx did not produce significant changes in performance, and that people can generally perform well over a broad range. There is clearer evidence that lighting can influence desired behaviour e.g. to increase supermarket sales[89]. But even here it is not clear what aspects are most critical (higher illuminance, better light distribution, 'message' etc.). More research is needed before the mechanisms are fully understood and reliable predictions can be made.

Another factor that may influence performance in an environment lit by electric lighting is the distribution of light within the space. Different light distributions may make the task more or less visible by introducing shadows, glare, or unwanted reflections, in which case the relationship with task performance is obvious and the steps needed to improve performance are clear. But different distributions may also produce different perceptions of the space and this in turn may influence mood and motivation. Studies have been carried out to investigate this potential effect, but these have been of limited scope[72,90] and have not demonstrated any significant effect, provided that the lighting does not adversely affect task visibility or cause visual discomfort.

All studies into the relationship between lighting and the psychological response are complicated by the fact that simple measures of the photometric characteristics of the environment are not sufficient. Unlike investigations into task visibility, it is not enough to measure the illuminance on the working plane, but the impact of all the lighting within the environment needs to be considered. Often the approach taken is to 'map' the luminance distribution within a space using digital imaging methods, but these have several disadvantages:

- Information is provided only in photometric terms or, for the most complex systems, in terms of the R, G, B output of the camera. Full spectral information, which would enable the influence of the spectral characteristics of the sources used to be explored, is not available.
- Even the photometric information cannot be relied on, since it is completely dependent on the 'matching' between the camera response and the $V(\lambda)$ function. Without proper photometric calibration, comparison of results from different studies is impossible.
- The image provides a two-dimensional representation of the space from a single point of view. It does not capture a full, three-dimensional, representation of the space.

New methods for measuring and analysing the lighting within any given environment will be needed before definitive statements regarding the impact of lighting on psychological responses can be made. Research to develop more appropriate measurement systems and techniques is therefore essential.

5.2 LIGHTING PREFERENCE

5.2.1 Spectral Distribution

Even though the spectral characteristics of the lighting may not significantly affect task performance (see Section 4), they do have a strong influence on its acceptability. For example, studies have shown that given a high enough CRI and appropriate illuminance levels, office workers in the UK and USA have a preference for light sources with a lower CCT (~3000 K) as opposed to a high CCT (~6500 K)[91]. Preferences in other cultures (e.g. Japan) where higher CCT lamps have been the norm have not been studied, but may well be different.

One source of light that is consistently highly rated is daylight and many studies have revealed a strong preference for daylight (for example[92]). The reasons for this are thought to be largely due to psychological influences, such as the human need for variety, which can be provided by a window giving a view to the outside and/or incident daylight causing changing patterns of illumination in the working environment; the spectral characteristics are probably not relevant. There is also evidence to suggest that daylight may influence task performance or productivity by affecting mood and motivation, but the results from studies have proved inconclusive (e.g. Hedge[93] found a positive correlation between performance of a clerical task and the presence of daylight, whereas Stone and Irvin[94] did not). One recent study provided evidence of a correlation between daylight and an increase in productivity among office workers[95], and another showed that daylight appeared to enhance the learning performance of children in schools[96]. More research is needed in this area; if a clear relationship could be established, this could impact on design recommendations and offer substantial opportunities to conserve energy by reducing reliance on electric lighting through the greater use of daylight.

5.2.2 Light Level and Uniformity

There is contradictory evidence relating to preferred lighting levels for interiors. Although studies on mood suggested levels of ~ 2000 lx or above should be preferred, investigations on preference have given conflicting results, sometimes supporting the idea that high levels (i.e. greater than 1000 lx[97]) are favoured but sometimes that lower levels (around 500 lux - consistent with current lighting codes and standards) are preferable[98]. Illuminance preferences are probably heavily influenced by the task and by differences between individuals, making it difficult to draw firm conclusions for optimal general lighting recommendations from specific studies. Flexibility in the lighting levels and the ability for individual control of these levels is possibly the best approach.

There is also contradictory evidence regarding the relationship between luminance uniformity and lighting preference. The luminance distribution within a room certainly influences the perception of the space (e.g. perceptions of spaciousness, relaxation, privacy, pleasantness) and anecdotally many people have reported the importance of the lit appearance of a space on human response, comfort and well-being. Judgements appear to be based primarily on dimensions of 'brightness' and 'interest', which in turn relate to the luminance characteristics of the field of view 40° wide in the horizontal plane centred at eye level[99]. Later work indicated that 'brightness', or 'visual lightness', relates to the average luminance of this horizontal 40^0 field and 'visual interest' to the luminance variation in the same field[100]. However, while some studies have found an increase in interest, and increased preference, with the ratio of maximum to minimum luminance[99], others found that installations that are rated as being more uniform are also rated as being more acceptable[101]. These differences may be due to differences in the task/application and/or the environment (including the architecture).

An extreme example of non-uniform illumination in a working environment is the use of desk lights, based on early work in work-place lighting that discovered that people preferred to have a concentration of light on their work area. The recommendation was for the immediate task illuminance to be in the order of two or three times the illuminance in the immediate surround. In some cases this approach has been shown to enhance visual acuity while in others it is claimed to enhance concentration. However, although requests for a desk light are common, this is often denied because it conflicts with the provision of overhead ceiling mounted lighting or it constricts the use of the desk space.

Another factor that can affect the light distribution in a space, regardless of the lighting used, is the room surfaces and furnishings. Dark surfaces will reduce light reaching the eye and may mean additional luminaires are needed (leading to reduced energy efficiency for the installation as a whole). In addition, people generally prefer bright vertical surfaces in a room to dark ones[97,98].

Further research is clearly needed before firm recommendations on the relationships between light level / uniformity and preferred working environments can be made. The impact of such recommendations could be significant, but unfortunately this is a topic that currently receives little consideration. It has often been reported that people work better in a visually pleasant and appropriate visual environment and there is certainly evidence to indicate preference for such conditions. Improved lighting design that takes account of this could help alleviate stress and might also increase productivity, both of which bring associated financial benefits.

5.2.3 Lighting Controls

The changes in the technology of lighting control systems over recent years have been significant. These technologies are now generally available and widely used. The desire to reduce energy consumption by switching off electric lighting when it is not essential for task performance has led to a number of studies into lighting control systems (either manual or automatic)[102]. The general conclusions from these studies are:

- Switching on or off of lighting that is controlled manually is most likely to occur at the beginning and end of a period of occupancy
- Manual switching is most likely if the controls are easily understood and readily accessible
- The key determinant of whether lighting is switched on when entering a room is the amount of daylight in the working area; once switched on, the lighting is unlikely to be switched off until the occupant leaves the space, even if daylight levels increase
- The use of time switches can lead to savings in energy consumption in situations where there is a consistent, predictable, pattern of use/requirement for electric lighting
- Systems using photosensors to dim the amount of electric lighting in response to increasing levels of daylight can lead to significant reductions in energy consumption[103,104], although the full potential of these systems is rarely achieved in practice
- Occupancy sensors can lead to substantial energy savings but need to be used with care.

Since controls can operate in the daytime, the need for accurate information concerning the availability of natural light has been a major research activity. The International Daylight Measurement Programme is a milestone event in this regard. The work has continued through activities involving the CIE, such as Satel-lite, SODA and linked activities with the International Energy Agency. New standards are also emerging[105].

5.3 LIGHTING, MOOD AND BEHAVIOUR

5.3.1 The Influence of Lighting on Mood and Behaviour

There is no doubt, based on evidence from both laboratory and field studies, that the visual environment can have an influence on mood and vitality and can thus influence behaviour[79,106,107,108]. This is already exploited in a number of areas, including the arts and commerce. However, the mechanisms involved are complex and research in this area is notoriously difficult. As a result, it is not clear how potent lighting can be in influencing mood, how persistent are its effects, what is the relative importance of changes in spectral distribution, illuminance uniformity, temporal variation in illuminance, etc. More research is needed before any definitive statements or recommendations can be made or before a clear understanding of the underlying physiological and psychological processes involved can be developed, which will make it possible to predict effects in new situations. If successful, however, this research could have significant impact on lighting design practice in many environments, from commerce (retail lighting etc.) to prisons (e.g. lighting specifically intended to reduce feelings of aggression).

Several studies have examined the effect of commonly used fluorescent light sources on mood and performance, but results have proved inconclusive. No consensus on which types of lamp to recommend has been reached. McClouglan, Aspinall and Webb[79] found systematic influences of lighting on mood within the range of lighting conditions found in everyday interior conditions (i.e. the range of illuminances and spectral power distributions typically encountered in lit interiors). In particular they found an increase in anxiety and hostility at high illuminances for cool CCT lamps and a reduction for warm CCT lamps at high illuminances. Such relationships are already being used by some manufacturers to market their products e.g. claims have been made in recent years regarding potential beneficial effects on mood, behaviour and health of so-called ‘full-spectrum’ lamps (i.e. fluorescent lamps with a CCT of >5000 K and a CRI of >90). Studies have found these claims to be unproven, at best[46,109].

Research has not been limited to behaviours that are obviously related to lighting. For instance, some studies have investigated the impact of lighting level on verbal communication and have found a number of different and conflicting behaviours. For example, Veitch and Kaye[110] found conversation was louder at low illuminance levels whereas Gifford[111] found higher illuminance levels led to increased conversation and low illuminances resulted in less conversation. These directly conflicting results can be attributed to the different situations in which the studies took place (in one case evaluating candidates applying for a job; in the other, informal discussions between friends). Clearly, behaviour is not influenced by light level alone, but is heavily influenced by other factors, such as context.

There has been little research so far into ‘dynamic lighting’, but there is some evidence that this is strongly favoured by occupants and has a positive impact on mood[112]. Variability in intensity and distribution of lighting in interiors could be an important psychological factor, especially in situations where people are in a static position for long periods e.g. hospital wards.

If clear relationships between lighting and mood could be established, such that these could be introduced into lighting recommendations for specific situations, the implications could be significant. Anecdotal evidence, for example, suggests that lighting used in prisons can affect the behaviour of prisoners, leading to reduced levels of aggression towards prison staff and other inmates for some lighting installations and increased aggression for others[113]. Studies in this area are complicated by the fact that simple measures of the photometric characteristics of the environment are not sufficient. Measurements are usually restricted to working plane illuminance and, occasionally, luminance distribution. Since human responses to light are governed by the amount and the spatial and spectral distribution of visible radiation within an environment, these measurements provide only very abridged information. The development of new measurement systems capable of determining the absolute spectral radiance distribution within real environments would provide a firmer basis for research into human physiological and psychological responses to lighting.

5.3.2 Seasonal Affective Disorder (SAD)

Reasonably definitive evidence is available that the presence, or absence, of daylight in the working environment may affect people suffering from seasonal affective disorder (SAD), or from a milder form of seasonal mood disturbance, called sub-syndromal SAD, or S-SAD[114,115]. The prevalence of SAD varies with geographic location, being greatest at northerly latitudes. In middle Europe ~ 4%-6% of the population are affected, with as many as 10%-15% suffering from S-SAD. Sufferers typically exhibit symptoms such as emotional depression, social withdrawal, a drop in physical energy, increased need for sleep, increased appetite and weight gain, and often also show reduced immune system activity. It has been shown that exposure to daylight can reduce symptoms and hence increase productivity in sufferers and, since S-SAD is relatively widespread, the impact of daylight on productivity may be high.

Considerable research has been undertaken into the use of light therapy for winter depression and various systems for treatment of SAD have been developed, including light boxes, dawn simulators and LED panels. About 65% of sufferers from SAD have been found to respond successfully to light treatment. The action spectrum for light therapy is not known at present, although indications are that green light is more effective than either blue or red[116]. Other studies have indicated a relationship between circadian regulation, melatonin secretion and SAD[117,118,119,120], which suggests that the action spectrum may be the same as for circadian regulation (see Section 6.2). Despite the lack of knowledge of the action spectrum, a consensus has emerged in favour of 10,000 lx for 30-45 minutes in the early morning as the standard treatment[114].

5.3.3 Other Mood Disorders

Depression places a substantial financial burden on society. A recent study[121] put the cost of depression in England at more than £9 billion a year, almost all due to lost working days (109 million working days lost per year). In addition, WHO puts depressive disorders as the fourth leading cause of ill-health amongst adults worldwide and estimates that by 2020 severe depression will be second only to cardiovascular disease as the largest cause of death and disability[122].

There has been some success associated with the use of light therapy to treat mood disorders other than SAD, such as non-seasonal depression[123], eating disorders[124] and premenstrual dysphasia[125,126]. Research is still underway. It has also been shown to be effective for the treatment of some sleep disorders, such as delayed sleep phase syndrome, where the sufferer cannot sleep until 2-3 am and has difficulty waking in the morning and which can be treated with bright morning light[127]. Light therapy has also been used to benefit elderly people who experience early-waking insomnia, but is not a generic solution for all age-related sleeping disorders[128]. Further research is needed in all these areas.

Buildings that admit direct sunlight are more likely to maintain biological rhythms and emotional stability of the occupants than those that do not, and recent research provides evidence that, for example, depressed patients in sunny hospital wards recover better than those in rooms with no sunlight[129]. Similarly, deaths amongst heart attack patients are lower amongst those in sunlit rooms than those in sunless rooms[130]. These findings could have significant implications for lighting design recommendations, but further research is necessary to support these.

5.4 SUMMARY OF KEY AREAS FOR FUTHER RESEARCH

AREA OF RESEARCH	SPECIFIC ISSUES REQUIRING INVESTIGATION / ACTION	KEY IMPACTS
Measurement equipment and analysis tools	New measurement systems to provide information on spectral and spatial variations within a space and new methods for analysing the results to provide 3-d representation of the space	Measurement methods which take full account of the variability between different light sources and lighting installations, to support research into the relationship between lighting and behavioural response

Relationship between lighting uniformity / spectrum and mood	Studies to investigate and establish relationship between the lighting used within a space and the impact this has on mood and performance	Improved lighting design which takes account of impact on mood Better lighting to enhance mood and increase motivation, performance etc. Better understanding of relationship between lighting and performance, leading to better lighting and less 'wasted' light
Relationship between field uniformity and perception	Studies to investigate and establish relationship between the uniformity of luminance and illuminance within a space and the 'message' this sends	Improved lighting design to maximise visual impact and user satisfaction Improved lighting recommendations to maximise impact of lighting and avoid 'over-lighting'
Relationship between. 'visual lightness' / 'visual interest' and task performance	Studies to investigate the relationship between changes in visual appearance (lightness and interest) of the environment and human performance, and the implications for energy use	Improved user performance and satisfaction Reduced energy use
Relationship between lighting and depression, aggression and mental health	Studies to investigate and establish relationships between lighting and its impact on depression, aggression and mental health, particularly in vulnerable communities or high stress environments	Improved mental health for workers Reduced absenteeism Improved recovery rates in hospitals Improved lighting in prisons, nursing homes, residential care etc. Light therapy for depression
Relationship between daylighting and mood, behaviour and health	Studies to investigate and establish relationship between daylight and mood, behaviour and health	Improved lighting design recommendations which encourage the use of daylight, leading to enhanced user satisfaction and well-being and reduced energy consumption Improved recovery rates in hospitals

6 NON-VISUAL EFFECTS OF LIGHT

6.1 INTRODUCTION

It has been known for some years that there are two distinct neural pathways which are activated by light falling on the retina: the visual pathway, which supports vision and visual reflexes, and the retinohypothalamic track or RHT, which regulates the circadian and neuro-endocrine systems[131,132]. The RHT leads from the retina to the hypothalamus, which is a complex region of the brain that controls many basic functions of the body, such as the sleep/wake cycle, hormonal secretion and core body temperature, as well as higher neural functions, such as memory and emotion. Specific nuclei in the hypothalamic, called the suprachiasmatic nuclei (SCN), form the fundamental parts of the 'biological clock' and act as the body's timekeeper. The SCN relay information to various hormone control centres in the nervous system, including the pineal gland, the pituitary gland and the adrenal gland, to regulate the secretion of almost all hormones (including melatonin, serotonin and cortisol) and to control the concentrations of neurotransmitters such as acetycholine, dopamine and norepinephrine. These in turn regulate sleep/wake cycles, hunger, body temperature etc. Poor regulation affects sleep length and quality, mood, and the immune system. However the amount of light necessary to produce a biological effect is not known at present, nor is it clear whether there is a time-dose relationship or whether a certain minimum exposure level is required to produce a response.

More recent research has identified a new type of photoreceptor in the eye, termed 'intrinsically photosensitive retinal ganglion cells' (ipRGCs), which appear to be responsible for stimulating the RHT. These cells differ from the rods and cones that support vision in several important respects:

- They respond only slowly to light (~10 s exposure is required, compared with only milliseconds for rods and cones).
- They have peak sensitivity between about 440 nm - 480 nm in the blue-green region of the spectrum[133,134]; the photopigment determining this sensitivity appears to be melanopsin[135,136].
- They are large but relatively few in number (a few thousand, compared to millions for rods and cones).

The most widely studied (and probably among the most important) endpoints of ipRGC activity are circadian entrainment, which is important for shift workers and those travelling across time zones for example, and pineal melatonin suppression, which has been implicated as an important factor for a variety of cancers. But there is also evidence for the involvement of ipRGCs in papillary light reflex and other non-image forming responses to light e.g. alertness, mood and performance[137], all of which may be important factors in task performance. These factors are explored in more detail below.

6.2 THE HUMAN CIRCADIAN SYSTEM

All plants and animals exhibit patterns of behavioural changes over an approximately 24-hour cycle that repeat themselves over successive days. These rhythms are called circarhythms. The physiology that controls such circarhythms is called the circadian system, from the Latin, circa, for 'about', and dies, for 'day': about a day. Other cyclic patterns (circannual rhythms) occur over the seasons, such as the seasonal breeding of mammals and seed germination in plants, and are believed to be controlled by gradual change in the light / dark ratio signalled by the circadian system. The basic role of the circadian system is to link the functioning of the human body to the external night/day cycle. It controls daily rhythms such as the sleep/wake cycle, core body temperature, hormone secretion, other physiological parameters including cognitive function, and immune response. It is not just a passive response to external conditions, but a predictor of external conditions to come.

The human circadian system has been the subject of extensive study for only the last two to three decades. Knowledge of the influence of light on the circadian system is therefore much less developed than it is for the visual system and although the outlines of the physiology of the human circadian system are established, there are still many details to be determined. It is known, however, that although social cues such as temperature, sound, caffeine, meal times etc. may affect the circadian system, light is the most potent cue[138,139]. Essentially, the circadian system is driven by an endogenous (internal) 'clock' that is reset or entrained by exposure to light; a messenger hormone (melatonin) carries the 'time' information to all parts of the body. In the absence of external cues (primarily light) the internal clock continues to function but on a period that is not matched to the normal 24-hour cycle. Light is needed to reset the clock to a 24-hour period and also to adjust for the changing seasons. In addition to its influence on the timing of circadian rhythms, light has also been shown to exert a direct effect on a number of physiological variables in humans, such as core body temperature, and on neurobehavioural performance measures such as alertness and reaction times[140,141].

Research has shown that it is not the normal photoreceptors in the eye that influence the circadian system; rather a newly-identified type of photoreceptor in the eye (known as 'intrinsically photosensitive retinal ganglion cells', or ipRGCs) is important (see Section 6.1). The action spectrum of this new photosensory system peaks in the 446 nm - 477 nm region, but its action may be compromised by a possible opponent process for melatonin suppression, suggested by recent research[142] in which the simultaneous presence of long-wavelength radiation might counteract the melatonin-suppressing effect of short-wavelength radiation. The ipRGCs do not maintain any spatial information regarding the stimulus i.e. it is only the level and not the spatial distribution of light that is important. This photosensory system sends signals to the pineal gland to control melatonin production, such that high levels are secreted during the dark phase (night) and low levels during the light phase (day). Melatonin in turn synchronises the activation of many other physiological functions to the times in the 24-hour cycle when they should occur.

Disruption of the normal light/dark cycle can shift the phase of the clock: bright light in the evening or early in the night gives a phase delay; bright light late in the night or in the morning gives a phase advance. This phase shift effect occurs many hours after exposure and the degree of the phase shift depends on the illuminance of the disruptive stimulus. (It should be noted that illuminance is not a good measure in this instance, because the spectral sensitivity of the photosensory system for circadian effects is different to $V(\lambda)$, but nevertheless this is what experimenters use at present.) It is very difficult to determine how much light is actually necessary to influence the circadian system, because it is not possible to measure the actual illuminance at the eye in other than highly controlled situations. (Generally illuminance is measured or specified on a horizontal plane, which does not take account of the fact that people spend large parts of the day looking horizontally; vertical illuminance may be more relevant, although even this does not account for the screening effect of the eyebrows and forehead). It is clear, however, that levels need to be high in order to have a significant effect for lamps of the type typically used in indoor lighting, since the photoreceptor responsible has peak response at short (blue) wavelengths. Current lighting practice may not provide enough stimulation to modify the timing of the circadian system.

6.2.1 Task Performance at Night: Shift Working and Jet Lag

The effects of light on the circadian cycle are important for human performance because the ability to work is reduced during the sleep part of the circadian sleep/wake cycle. If the circadian system is not entrained, or the worker is asked to work during the sleep part of the cycle, as may be the case for people working night shift, task performance is likely to be degraded. Folkhard and Monk reviewed the available information on the diurnal variation of human performance of a wide range of tasks, and showed that night-time performance was significantly worse than the diurnal average in almost all cases[143]. The increasing need to work at night in a '24 hour society' (it is estimated, for example, that ~ 20% of the workers in industrialised countries are shift workers) means that such problems are likely to have an increasingly significant effect, leading to decreased productivity, increased accidents etc.[144]

Good night shift performance is not just dependent on having enough light during the working period to suppress melatonin production. Performance is determined by the level of light exposure and when this occurs over the full 24 hours. Studies have shown properly timed bright light exposure and light avoidance can enhance the adaptation of circadian rhythms to changing shift patterns or to permanent night-time working[145,146]. General guidance has been produced and recommendations should become more precise as knowledge of the relationship between the circadian system and night-time light exposure (duration, intensity, timing and spectral distribution) improves.

Such circadian phase shift techniques have already been successfully applied in some situations e.g. NASA space shuttle flights[147]. More routine applications might not be so successful, because of the difficulty in controlling light exposure for workers throughout 24 hours and not just while they are at work. High light levels during the drive to or from work, for example, may affect the phase shift of the circadian system so that it is not 'reset' to what is needed for night-shift work. Also, a phase shift of 180° takes a number of days, so a rapidly rotating shift system might not give enough time for adaptation to occur. These considerations may have implications for night-shift workers and the methods used to adapt them to changes in shifts.

Melatonin alone does not control sleep, but melatonin suppression during night-time does appear to increase alertness[141,148]. As an alternative (or addition) to the control of light exposure to accelerate circadian re-entrainment, therefore, it might be possible to also use exposure to bright light at night to suppress melatonin and thus improve ability to perform some tasks[140,149,150]. Several studies have found that bright light during overnight work sessions can have immediate effects on complex task performance and can improve performance in comparison with dim light. For example, 3000 lx from white fluorescent lamps produced improved behavioural and mental performance in one study[149] and another[106] showed that constant levels of 2000 lx improved performance of both simple and complex cognitive tasks compared with constant levels of 300 lx. The potential benefits of improved performance and reduced accidents will almost certainly outweigh the costs of providing better lighting, particularly if the increased light levels are targeted so as to reach worker's eyes, rather than being uniformly distributed throughout the working area. However the optimal dose, duration and timing of light exposure for specific tasks remains unknown and further research is needed before recommendations on light levels for night-time working or shift working can be made. In particular, investigations are required into:

- The effect of light exposure on alertness and task performance at different times during the working day. If a clear relationship could be established, this could have a significant impact for new lighting practices to enhance task performance in many areas, and thus improve productivity.
- The use of light exposure at night to improve cognitive task performance. If a clear relationship could be demonstrated this could have a significant impact on lighting practice for night shift workers etc.
- Whether increased alertness following light exposure is followed by greater fatigue when the light is removed. If this is the case, the use of light exposure may be inappropriate or counter-productive.

Furthermore, any potentially negative impacts on the long-term health of workers due to light exposure at night will also have to be considered (e.g. potential increased rates of some cancers, see Section 6.3). More research is needed to enable guidelines for nightshift workers to be prepared, which will cover not just lighting at the workplace but also provide advice on minimising light exposure during their sleep period etc.

Jet lag is a significant problem for travellers crossing several time zones and can lead to symptoms such as sleep disruption, gastro-intestinal problems, irritability, depression and confusion. Several studies have shown that properly timed exposure to bright light, and bright light avoidance, can reduce symptoms (for example[151]). There are no set recommendations, but generally bright light exposure in the morning following eastbound travel or in the afternoon following westward travel can be beneficial[128]. Even if it is possible to accelerate re-entrainment at the beginning or end of a period of night-shift work or after a long flight, this still leaves a number of days when it is necessary to perform tasks during ‘circadian night’. This can affect ability to perform all types of task, not just visual tasks, since the circadian system affects all parts of the brain and body. Bright light exposure during the circadian sleep phase, as described earlier, may be beneficial in such cases.

6.2.2 Sleep Disorders and the Circadian System

People with Alzheimer’s Disease and some other dementias often show circadian phase delays and the use of light treatment to improve night-time sleep and reduce confusion and agitation in the early evening has been shown to be successful in several trials[152,153,154]. Debate continues regarding the mechanism of the therapeutic effect and its generalised applicability, but there is a general consensus that it is a promising, non-pharmacological treatment for behavioural and sleep-wake disturbances in sufferers of dementia[128]. Research is needed to establish guidelines for appropriate light intensities, durations and timings.

The characteristics of the human eye change with age: the lens thickens and becomes more opaque and its transmittance in the shorter wavelength region is particularly reduced (yellowing effect). This means the amount of light available to stimulate the circadian photoreceptors is significantly reduced in elderly people and may explain reductions in the amplitude of circadian rhythms, sleep disorders etc. A recent study[155] demonstrated the efficacy of carefully timed light exposure for improving the sleep patterns for elderly patients in residential care.

Consideration of sleep disorders, and the role of light in addressing these, is not restricted to the elderly, however. At the other end of the age scale, premature babies have been found to have difficulty in adjusting to hospital environments during the early stages of care and to exhibit problems with establishing regular sleep-wake cycles when they are taken home, both of which might be due to constant exposure to relatively high light levels. Infants presented with cycled light during their final few weeks in hospital show, among other improvements, better weight gain and faster adjustments to home life[156,157.]

6.2.3 Summary and Implications

The effects of light exposure at night can be divided into effects on immediate physiology and effects on more remote performance. Compared to the visual system, the circadian system has a much higher threshold to light intensity, a peak sensitivity at much shorter wavelengths, is non-image forming, requires longer light exposures for activation and is differentially sensitive to light depending on the time of day. Bright light at the 'right' wavelengths (i.e. the blue region, between 446 nm - 477 nm) can certainly shift the phase of the circadian system and rapidly suppress melatonin production. This can be used to correct misalignment of the circadian clock and the light-dark cycle, or to increase alertness at night without necessarily shifting the phase of the circadian clock by suppressing melatonin. However there is evidence that the simultaneous presence of long-wavelength radiation might counteract the melatonin-suppressing effect of short-wavelength radiation[158] and this could have important implications for the future development of recommendations for lighting for circadian phase regulation.

Until the human circadian system is more fully understood it would be inadvisable to introduce changes in working practices or other applications based on manipulating the circadian system with light. It is possible that there could be long-term side effects that are not yet appreciated or understood (e.g. suppressing melatonin might lead to increased oestrogen levels and higher incidence of breast cancer[159]). More research is also needed in order to know how best to manipulate the circadian system (light level needed, duration etc.). Finally, the relationship between circadian rhythms and task performance is currently not known, and will probably depend on the task, so the effect of changes needs to be carefully assessed.

6.3 MELATONIN AND HEALTH

Research has shown that misalignment between the internal circadian clock and the external environment may contribute to a variety of health problems such as cardiovascular disease, diabetes, sleep disorders, gastrointestinal disorders and even cancer[160,161]. Melatonin is thought to play an important role in all these health disorders.

There is strong evidence that melatonin plays an important role in controlling cell proliferation, survival, differentiation and loss and metastasis[162,163] and is therefore an important factor for a variety of cancers, particularly breast cancer[164,165]. Melatonin has been shown to inhibit cancer growth, whereas melatonin suppression by exposure to bright light stimulates tumour development and growth[163,166]. Although breast cancer is possibly the most extensively researched area to date, the role of melatonin in the growth of other cancers has also been demonstrated. For example, there is evidence that nocturnal melatonin concentrations may inhibit the growth of melanoma cells[167]. There is also concern that the ubiquitous use of electric lighting in the evenings in industrialised cultures may result in systemic reductions of the quantity or cyclic amplitude of melatonin secretions and lead to increased rates of cancer in Western societies in particular. Furthermore, studies have shown that shift workers can suffer from a range of health problems that may be linked to disruptions to their circadian rhythms, such as a higher incidence of cardiovascular disease and gastrointestinal problems, cognitive and psychological problems and potentially increased risk of breast and colon cancer[168,169].

Melatonin is also known to influence the activity of several components of the immune system and may therefore influence a very wide range of disease processes. The mechanisms by which melatonin mediates immune response are poorly understood at present but it is known that the immune system shows a circadian rhythm[170] with the ability to fight initial exposure to a pathogen being greatest when the organism is active (i.e. during the day for diurnal animals) and infection-fighting mechanisms being more active when the organism is at rest. A yearly cycle is also apparent. As knowledge about these rhythms expands, and the role of melatonin and light exposure becomes clearer, possibilities to optimise the effectiveness of drugs and other medical treatments, by linking these to the rhythms of the immune system, may be established. Much more research is needed.

Recent research indicates that even low intensity light exposure at night can have an effect e.g. work by Brainard[171] indicates that levels of as little as 1 lux of short wave (blue) light may be sufficient to suppress melatonin production when administered in the middle of the night. This is supported by other research, which suggests there is a dose-related suppression of melatonin levels with a concomitant dose-related stimulation of tumour growth[172]. This indicates that if night lighting is needed (e.g. in hospitals, nursing homes, dormitories etc.), low levels of amber light may be preferable to white light in terms of health. However, although some research has already been undertaken, much remains unknown regarding the intensity, spectral characteristics and timing of light exposures that might lead to adverse health effects such as higher incidences of breast and other cancers in humans – more research is needed.

In addition, since circadian rhythms exist in many physiological systems, the timing of administration of medication and other treatments in relation to the circadian cycle can influence its effectiveness[127]. Optimal treatment times may be at night (e.g. cancer treatments[173]) or during the day (e.g. beta-blockers to treat hypertension[127]). It is therefore possible that light therapy might have a role to play in synchronising circadian rhythms to ensure that treatments are given at the optimal phase in the cycle. Much more research is required before such recommendations could be prepared. In addition, it has been pointed out that most research into the effectiveness and safety of drugs has been carried out using the nocturnally active rat, although these studies are aimed at demonstrating their use for day-time active human, i.e. the drugs were given during the rat's night, but our day. The implications for the efficacy and safety of current medical practice are unknown.

6.4 REQUIREMENT FOR A DAILY 'LIGHT DOSE'

Research has shown[174] that exposure to light at the level and spectral power distribution typically found in offices, schools, homes etc. is insufficient for effective circadian regulation and that the daily 'light dose' received by people in Western countries might therefore be too low[175]. As a result, unless people are exposed to some other source of bright light during the morning in particular, they may experience circadian disruption and consequent problems such as depression, poor sleep quality or even more serious effects, such as increased cancer risk or reduced immune function[169,176,177]. This means that providing light simply for visual performance may not be sufficient, particularly during the winter months, when people often travel to and from work in the dark and do not go out of doors during the day.

Recommendations for achieving a required daily light dose may be necessary.

It is not only the daily light dose that is important, however. Periods of darkness are required in addition to periods of light in order to maintain circadian rhythms and take full advantage of the powerful effects of light on physiology and psychology[145,177]. Sleep deprivation definitely disrupts neuroendocrine function but it is also possible that low light levels overnight (while sleeping) might disrupt melatonin rhythms[178]. Recommendations for a daily 'dark dose' may therefore also be important.

Furthermore, for most latitudes the length of day/night varies with the seasons and this regulates seasonal changes in behaviour. Consistent use of artificial light in the evening in modern urban environments at temperate latitudes removes seasonal variations in the duration of melatonin secretion[179] but the potential impact of this on health is not known. Seasonal changes in any recommended 'light' and 'dark' dose may need to be considered.

6.4.1 The Role of Daylight

The greatest health benefits will be obtained by increasing exposure to light in the blue-green region of the spectrum rather than by increasing light levels overall (assuming that existing light levels are appropriate for the task being carried out). This will also avoid unnecessary increases in energy consumption. Daylight, if properly used (i.e. by limiting glare and avoiding solar heat gain) is an energy-efficient way of providing light in any situation. But its relatively high levels of radiation in the blue-green spectral region mean it may be particularly effective at providing health benefits when compared with electric light. Indeed there is already evidence to support such enhanced health benefits e.g. Wirz-Justice et al.[180] found that subjects with SAD were treated more successfully by taking a one-hour walk each morning (illuminance ~ 1000 lx) than by 30-minute exposure to bright electric light (illuminance ~ 2800 lx) – see also Section 5.3.2.

Greater use of daylight in building design (e.g. by enabling light to penetrate deeper into the working space and by giving more workers increased access to windows and daylight) is an attractive option for increasing workers' daily light dose, particularly since it uses no energy, but it must be controlled if it is to be used effectively. Simply providing windows is not enough: these can produce glare and reduce task visibility, and workers often use blinds to block direct sunlight. Careful design of daylight control systems is necessary and research into new window systems (including new glazing materials) and blinds/sunshields is required to support this.

Other changes in current working practices could also bring health benefits without increasing energy consumption. For example, simply encouraging workers to take a morning walk outdoors could increase daily light dose without any increase in lighting levels.

6.5 IMPLICATIONS FOR LIGHTING RECOMMENDATIONS

Good quality lighting should take account of non-visual (health) effects as well as the provision of adequate/appropriate light for task performance[181]. Existing lighting recommendations (e.g. SLL, IESNA) concentrate on luminance and illuminance levels for various situations and tasks and may need to be revised as knowledge of non-visual effects increases. For example, they may need to provide for access to light brighter than that needed for visual performance for at least a minimum duration in the morning. Furthermore, there are many situations where building occupants are seldom exposed to outdoor lighting levels:

hospitals, workers in factories and industrial plants, nursing homes, prisons etc. Biologically therapeutic lighting may be particularly beneficial in these situations, to ensure that occupants get their required daily light dose, but this is not considered in current guidelines.

Clearly many factors will need to be considered when preparing improved lighting recommendations, and further research will be needed to support all of these:

- At present, there is no agreement about the optimal daily light exposure, the optimal spectral distribution and the best timing for light exposure in relation to the circadian rhythm. These must all be investigated before the results can be incorporated into lighting recommendations. This will include consideration of the need for a daily 'light' and 'dark' dose and of the role of daylight in maintaining a healthy circadian system.
- The timing of light exposure influences its effects[182,183]. In other words, recommendations for practical applications need to be specific to the time of day and/or take account of the pattern of exposure with time.
- The relationship between light and shift working needs special consideration, to take account of both the positive effects (e.g. the use of appropriately timed bright light to increase alertness or to assist with adjusting to a change from daytime to night-time working) and possible adverse effects (e.g. potential increases in cancer risks).
- Because the non-image forming receptors appear to be concentrated in the lower portion of the retina, and the eye's optics invert the image, spreading light targeted on these cells (i.e. blue-rich light) on the ceiling and upper wall surfaces of a room may be more effective than delivering it on the floor or desktop. It may therefore be appropriate to emphasise vertical illuminance and irradiance in lighting recommendations, instead of horizontal illuminance.
- Electric light is currently designed to maximise the conversion of electric power into visible radiation. The proportion of light in the blue region of the spectrum is consequently relatively low, since this is relatively poor in terms of visual efficacy. Lighting recommendations may need to consider not only the lumen (visible) output of lighting products but also the biological effectiveness.

6.6 OTHER PHOTOBIOLOGICAL EFFECTS OF OPTICAL RADIATION

6.6.1 Photobiological Safety Standards

If exposure levels are high enough, optical radiation can cause damage to both the eye and skin, through thermal and photochemical mechanisms. UV radiation can cause photokeratitis of the eye, erythema of the skin[184], lens cataract, skin ageing and even skin cancer. Visible radiation can cause photoretinitis of the retina. IR radiation can cause thermal damage to the retina, cataract and burns to the skin. Maximum 'safe' exposure limits have been defined by ACGIH[185] and these have been used as the basis for recommendations on the photobiological safety of lamps[186].

The ACGIH photobiological hazard functions and exposure limit values (ELVs) are based on research carried out at various institutions over a number of years and are recognised internationally, with some slight modifications, through the International Committee on Non-Ionising Radiation Protection (ICNIRP). The functions and ELVs are not questioned, but the way in which measurements should be performed in order to evaluate the photobiological hazard for particular types of source, particularly LEDs, is an area of lively debate. In particular, there is some conflict between the measurement recommendations in the photobiological safety standards which have been produced by CIE[186] and IEC[187] and this is currently being addressed by both bodies in order to achieve a greater degree of harmonisation and to give clearer guidance to manufacturers and users of LEDs. This is becoming an increasingly urgent priority as the radiant power of LEDs continues to increase. Currently CIE TC6-47 is preparing recommendations on the measurement of the optical radiation output of LEDs for safety evaluation purposes and IEC TC76 is considering issues related to the safety of LEDs used for communications purposes.

The hazardous effects of optical radiation can be greater for certain individuals than those for the general population. Babies, particularly premature babies, are susceptible to retinal damage from exposure to UV radiation, as are patients who have had one or both lenses removed due to cataract. Some medical conditions can enhance photosensitivity, as can some pharmaceuticals, and in these cases there is increased risk of skin damage from exposure to UV radiation. Special precautions are needed in all these cases.

6.6.2 UV Radiation: Dangers and Benefits

The dangers of overexposing skin to UV radiation have been well-publicised and campaigns to reduce sun exposure have had considerable success. There is no doubt that too much exposure to UV radiation is damaging to the skin, leading to premature skin ageing and potentially also to serious conditions such as skin cancers. These harmful effects should not be ignored and efforts to restrict over-exposure, and particularly to minimise the growing trend towards the use of sunbeds, will continue to be a high priority for health campaigners.

Whether commonly used electric light sources produce enough UV radiation to cause skin cancer is not certain. An unfiltered quartz-halogen tungsten lamp can produce enough UV radiation to induce erythema[188] and quartz-halogen luminaires often include a glass filter to reduce UV emission. The CIE has concluded that there is insufficient evidence to support the hypothesis that common fluorescent lamps can cause malignant melanoma[189]. Adherence to lamp safety recommendations, such as those from the CIE[186], should be sufficient to avoid undue exposure from most lamps and the forthcoming EU Physical Agents Directive will place increased requirements on employers to ensure their workers are not exposed to unsafe levels of optical radiation.

It is less well-known, however, that some exposure to UV radiation is necessary to maintain adequate levels of vitamin D in the body. Vitamin D deficiency leads to rickets in children and osteomalacia in adults, and a number of research studies have provided strong evidence that vitamin D is an important risk reduction factor for diseases such as multiple sclerosis, diabetes, tuberculosis, high blood pressure and heart disease as well as many forms of internal cancers, including breast, colon, ovarian and prostate cancer[190,191,192,193,194]. The majority of vitamin D in the body is provided by exposure to solar UVB radiation, being synthesised from sterols in the skin; little comes from dietary sources. Typical Western lifestyles, in which people spend most of the daylight hours behind glass, provide insufficient exposure to UV radiation to maintain healthy levels of vitamin D. In Australia, for example, where the anti-sun campaign has been particularly successful, vitamin D deficiency now affects nearly 25% of women[195]. One recent study[196] suggests that more than 45,000 people in the USA die prematurely each year from cancer due to insufficient vitamin D (and therefore insufficient UVB exposure). Further research is needed in order to provide recommendations for a safe balance between achieving sufficient UVB for vitamin D synthesis and avoiding serious skin conditions such as malignant melanoma. Public health campaigns will also need to be adjusted to take account of these recommendations and to ensure that misinformation regarding vitamin D deficiency does not result in a backlash against avoidance of sunburn etc.

6.6.3 Germicidal Effects of UV

UV radiation can destroy many types of virus, bacteria, yeasts and moulds through the absorption of the radiation by the DNA molecule. This causes mutation or cell death, and has an advantage over many other routes of disease control (such as antibiotics) in that the target organism cannot develop resistance. As a result, the use of UV radiation for the purification and sterilisation of air, liquids (particularly water) and granular materials is of increasing interest, particularly with the emergence of drug-resistant strains of some diseases such as tuberculosis[197].

These bactericidal effects have been known for many years. A study in 1877[198], for example, showed that sunlight has a bactericidal effect even when it has passed through glass. Until the advent of antibiotics, hospitals and sanatoria were built with large south-facing windows to admit direct sunlight and help prevent the spread of disease. Nowadays, the germicidal effects of sunlight are not considered when planning buildings – this is an area in which a change to existing recommendations could be considered. An even more effective way of utilising UV radiation, however, is through intense UV sterilisation systems. These use low pressure, high power, mercury discharge lamps, with special envelopes which transmit radiation at 254 nm. In sealed systems, such as those used for water sterilisation, radiation at 185 nm is also used (these lamps cannot be used for air sterilisation since radiation below 200 nm is strongly absorbed by oxygen in the air to produce ozone). Such sterilisation systems are now finding their way into hospital air-conditioning plants and their impact could be significant: in 1997, for example, it was estimated that at least 5000 patients in the UK die each year as a direct result of hospital infections and that such infections were a contributory factor in a further 15,000 deaths.

Research and development in this area is focussed primarily on the design of improved systems for use in air conditioning networks, for example. Measurement is also of interest (e.g. for monitoring of lamp output for maintenance purposes and for on-site checks to ensure people are not being exposed to these extremely hazardous UV radiations) and some research is underway to develop detection and monitoring systems that are less susceptible to degradation. This would reduce maintenance costs and encourage greater take up of UV-based sterilisation systems.

6.6.4 Optical Radiation in Medicine

There are many applications of optical radiation in medicine. Research is actively being pursued in all these areas but is outside the scope of this report. For completeness, however, the principal areas are summarised below:

- Although the use of UV radiation in phototherapy for skin diseases such as psoriasis, eczema and atopic dermatitis is well-established, research is still needed to improve measurement and treatment protocols, to improve its effectiveness and minimise potential long-term effects such as skin carcinogenesis.
- Research is also underway in the newly-emerging area of photodynamic therapy (PDT), where a photosensitiser and a visible light source are used for targeted treatment of cancers, both of the skin and inside the body. PDT has been found to be particularly successful for the treatment of precancerous and cancerous skin conditions such as

actinic keratosis, Bower's disease, superficial squamous cell carcinoma and basal cell carcinoma, but further research is required as new types of treatment source, e.g. LEDs, become available.

- Intense pulsed light sources (IPLs) are being introduced into phototherapy, for a variety of applications such as hair removal, reduction of the appearance of port wine stains, and treatment of skin problems such as eczema. However the dosimetry of these sources is not well-established at present and research is underway to improve this.

Various forms of optical radiation are also used in medical diagnosis, such as optical coherence tomography (OCT), minimum erythemal dose (MED) studies for various skin conditions, Raman spectroscopy and Fourier transform IR spectroscopy. Research to improve these, and to introduce new diagnostic methods, is underway.

6.7 SUMMARY OF KEY AREAS FOR FUTHER RESEARCH

AREA OF RESEARCH	SPECIFIC ISSUES REQUIRING INVESTIGATION / ACTION	KEY IMPACTS
Spectral sensitivity of new photoreceptors	Determination of spectral sensitivity of ipRGCs	Ability to specify and design new lighting systems targeted at delivering 'healthy light' Development of measurement instrumentation for studies into 'healthy light'
Circadian system	Studies to identify details of relationship between light (dose, timing and duration), melatonin levels and circadian phase / alertness / task performance	Ability to manipulate circadian rhythms to take account of adapting to shift working, jet lag etc. Improved performance and reduced accidents for shift workers Lighting recommendations for treating sleep disorders
Melatonin (and other hormones) and health	Studies to identify the role of light in the control of melatonin (and other hormones) and its impact in diseases such as cancer, diabetes, cardiovascular disease etc.	Recommendations for 'healthy lighting' Lighting strategies to reduce risk of serious illness for shift workers Improved lighting for situations where illumination at night is essential (hospitals, prisons etc) Improved public health
Daily light dose	Studies to determine daily 'light dose' and 'dark dose' required to maintain healthy circadian rhythms and to support recommendations for how these should be measured / specified	Improved lighting practice for health Improved public health – minimisation of problems such as depression, poor sleep quality, increased cancer risk or reduced immune function
Impact of daylight on health	Studies to determine effectiveness of daylight compared with electric light in maintaining healthy circadian rhythms and other hormonal effects	Lighting recommendations to encourage greater use of daylight Reduced energy consumption Improved public health

UV and health	Studies to support improved recommendations for UV exposure	Reduced vitamin D deficiency and reduced incidence of consequent health problems Improved public health campaigns for sun exposure
Phototherapy	Development and testing of new phototherapy techniques e.g. PDT	New and improved treatment for skin cancers and other conditions
Dosimetry	Development of instrumentation and/or guidelines for the correct dosimetry of new medical light sources e.g. IPLs	Correct measurement of new medical light sources, ensuring safe and effective treatment
Photosterilisation	Development and testing of UV germicidal systems	New methods to reduce transmission of tuberculosis and other infections Improved design of hospital lighting and sterilisation systems
Medical imaging	Research to improve existing medical imaging methods / support new diagnosis methods	Better diagnosis using medical imaging systems Earlier detection of life-threatening diseases e.g. cancers

7 MAJOR APPLICATION AREAS FOR LIGHTING RESEARCH

7.1 LIGHTING AND THE AGEING POPULATION

7.1.1 Background

The population of the United Kingdom and the rest of the World is both increasing and ageing. Currently approximately one tenth of the World's population is over 60 years old and it is estimated that by 2100 the proportion will have risen to one-third. As indicated previously (see section 4.4.3), visual performance degrades significantly with age, so this increase in the older population is also expected to lead to an increase in the numbers of visually impaired people. Indeed of the 148,680 people registered partially sighted in England as of 31 March 2000, 102,710 were 75 or over. This age category was also responsible for a large percentage of the new cases registered that year, accounting for 12,140 of the 17,490 new cases.

As the visual system ages, its performance degrades:

- The ability to focus at close distances is impaired, due to increasing rigidity of the lens.
- The amount of light that reaches the retina is reduced, due to changes in the ability of the pupil to open widely and loss of ocular transparency.
- More light is scattered as it passes through the lens and other components of the eye, which degrades the image on the retina.
- The spectrum of the light reaching the retina is changed, due to yellowing of the lens.
- The amount of stray light within the eye is increased, due particularly to increased lens fluorescence, resulting in a 'haze' effect over the whole of the visual scene.

The incidence of pathological changes in the eye also increases with age. Diseases such as glaucoma, cataract, macula degeneration and diabetic retinopathy all become more common, resulting in an increasing prevalence of cases of low (or impaired) vision or even blindness, particularly for those aged about 70 and over.

As would be expected, these changes in visual performance can have a severe impact on the ability of the elderly to carry out many everyday tasks. Tasks such as seeing in dim light, distinguishing certain colours, reading small print and driving at night are all more difficult when vision is impaired.

The impact of impaired vision coupled with inappropriate lighting can be significant. For example, studies have indicated that poor lighting is associated with falls among the elderly[199] and the Consumers Affairs Directorate in 1999 reported that 1,110 people aged over 75 died as a result of a fall in the home and 231,000 people in the same age range attended A&E as a result of a fall in the home. Less severe effects can include fatigue, headaches and eyestrain. As the retirement age increases, and people need to continue to work into their late 60s or beyond, this will place ever greater demands on lighting in the workplace as well as at home.

It is important to note that the solution to effective lighting for the elderly is not simply the provision of higher lighting levels – in some cases this can actually be counterproductive and lead to increased problems. It is possible to divide older people into two categories: those whose vision is affected by pre-retinal scatter and thus have reduced image contrast; and those who are limited by some form of retinal dysfunction and thus have acuity and contrast sensitivity reductions. For the first category too much light would be a problem, as more light would be scattered. For the second category higher levels of light would be of benefit.

The following characteristics of lighting are therefore important:

- The amount of light. Increasing the illuminance generally results in better visual performance, although the degree of improvement depends on the cause of low vision.
- The spectral power distribution. Lamps with high colour rendering generally result in better ability to distinguish colours, but sources with high emission below about 450 nm are best avoided, since these can lead to increased lens fluorescence.
- The spatial distribution. Visual performance for those with low vision is improved if light is uniformly distributed across the relevant surfaces and through the avoidance of areas of shadow. It is important to avoid sources of glare, since increased light scatter in the eye means elderly people tend to experience greater disability glare than the young.

Specific advice on lighting for different activities for the elderly or those with low vision is given in various international and national recommendations (e.g. CIE[81]) and by welfare organisations. Following this guidance should result in improved visual performance for the elderly or those with low vision without adversely affecting those with normal vision. The most important priority at present would seem to be to make sure that existing recommendations are properly implemented in national and international standards and guidelines.

Despite the relatively good availability of lighting guidance for improved task performance for the elderly or visually impaired, however, there are still some areas that would seem to warrant further research:

- To explore the concept of the ‘elderly lumen’. Current photometric values for lamps and lighting are specified only using the $V(\lambda)$ function, but in a context where the average age of the world’s population is steadily rising, this concept of a universal lumen is increasingly difficult to substantiate. Supplementary measures should be considered, which would assist with the accurate representation, in design guidance, of the way that older people see and would enable the light output characteristics of different light sources to be compared in a more visually-meaningful way, allowing sensible choices to be made by designers.
- To measure the adaptation times of older people and those with visual impairment. There is a universal need for the eye to adjust to different light levels, but for older people and those with visual impairment, adaptation times are generally extended as compared with younger people. Experimental studies are needed to provide improved lighting design guidance that takes account of this fact. The very real problem that older people have when either leaving or entering a building, under either daytime or night-time conditions, is of particular concern.

It must also be remembered that it is not only the visual aspects of lighting that are important. Many older persons can suffer from the effects of too little light to effectively entrain their circadian system and maintain correct circadian rhythms, leading to sleep disorders and depression, for example. Research suggests a level of 2500 lux or more delivered to the eye is necessary[200]. Infirmity means that many older persons have little exposure to natural light out-of-doors, and their exposure to daylight will therefore often be only through windows and skylights. Since the visible light transmittance of glazing materials (particularly if double glazed or coated with reflective films) is typically only around 30% to 65%, and since many of the materials used have low transmittance for the photobiologically-active wavelengths around 459 nm to 484 nm, it can be very difficult for people to be exposed to sufficiently high light-levels even when sitting close to normal sized windows.

Too much light exposure at inappropriate times can also lead to impaired circadian entrainment for the elderly, especially for those in care homes or hospital environments. The need for care personnel to be able to move around safely and to check on patients and residents during the night, or for residents themselves to be able to get to the bathroom safely at night, means that a low light level is maintained throughout the night. Simple measures, such as using an amber light rather than white light to provide for safe movement at night without suppressing melatonin production, can be very effective[155]. In addition to the direct benefit of such measures to the elderly residents of care homes, through better sleep quality etc., indirect benefits can be found for the care workers themselves, through reduced aggressive behaviour from patients with Alzheimer's, for example, as a result of their better sleep patterns.

7.1.2 Key Areas for Research

AREA OF RESEARCH / ACTION	SPECIFIC ISSUES REQUIRING INVESTIGATION / ACTION	KEY IMPACTS
Visual needs of the elderly	Improved lighting standards to incorporate the known lighting requirements for enhanced visual performance for the elderly	Reduced accidents (falls etc.) for elderly persons Better quality of life for elderly persons
The concept of the 'elderly lumen'	Establishment of the agreed spectral sensitivity function(s) for the elderly	Visually-meaningful measures of the light output characteristics of light sources for the elderly, leading to improved lighting design and more effective lighting
Adaptation times of older people	Investigation of adaptation times for changes in light level for the elderly	Improved lighting for older people e.g. when leaving or entering a building, leading to reduced accident rates (falls etc.)
Circadian entrainment for the elderly	Studies to investigate 'light dose' and 'dark dose' for residents in care homes etc. to determine more effective lighting systems for circadian entrainment, taking account of improved knowledge of the circadian system	Better quality of life for elderly persons: better sleep quality and reduced sleep disorders, reduced depression Safer working environments for care workers

7.2 LIGHTING FOR THE WORKING ENVIRONMENT

7.2.1 Offices

Increasingly the office environment is where people spend their working lives, and offices and related establishments therefore form a substantial part of the UK economy. It is estimated that they account for around 110 million m^2 of floor area and employ around 8 million people, or about 30% of the UK working population. Optimum efficiency for office workers is therefore desirable, not just for individual organisations, but for the productivity of the nation as a whole. The productivity of an office is very dependent on human performance, which will, to a significant extent, depend on the quality of the working environment, particularly the way it is lit. Furthermore, energy consumption for electric lighting in offices in the UK is around 5500 GWh per annum and although this represents only a small part of the total office operating costs, it is not insignificant in energy terms or in its contribution to global warming. The goal of good office lighting, therefore, is to enhance both human productivity and energy efficiency.

Most recommendations for office lighting are based around the provision of adequate lighting levels for desk-top-task performance and the avoidance of adverse effects such as glare, as described in Section 4.3 on visual performance. Thus all specifications for office lighting contain recommended horizontal illuminance levels, although the levels specified have varied over the years and can be significantly different between countries. The general tendency over the years has been towards the provision of higher levels of illuminance on the working plane. As demands for energy savings grow, however, it becomes ever more important to consider whether the recommendations are appropriate.

Over the past 20 years there has been a trend away from paper-based offices, where the primary viewing surface was horizontal, towards computer-based offices, where the primary surface is vertical and increasing the illumination on the surface makes the task less visible. Modern offices need to be able to cope with the use of computers as well as paperwork and office lighting recommendations therefore also consider the lighting distribution of the luminaires, to take account of the influence this can have on the readability of VDU screens. As a result of a number of studies, many lighting recommendations for offices now specify the use of luminaires with a defined maximum luminance and good luminance uniformity, to avoid glare. With modern, low reflectance, high luminance VDUs, however, this is less of a problem and the use of special luminaires is generally not necessary. Recommendations may need to be revised as a result.

One area in which current office lighting recommendations are extremely limited is that they take little, if any, account of other aspects of lighting, such as lighting preference and the effects on mood, motivation and behaviour (see Section 5). This is arguably the area in which research efforts should now be focussed. A more flexible and user friendly approach to office lighting, that takes account of, for example, user preferences for task lighting and stimulating visual environments could provide human benefits and energy efficiency improvements. The ‘optimum’ office environment could be envisioned as follows. A permanent installation of building lighting would be required, which provides background lighting that contributes to the appearance lighting and allows for basic movement around the space, for safety and security. It would be linked to the daylighting, so that electric lighting was not used when not required. This would be complemented by task lighting for each individual workstation, to provide task illumination to an appropriate level of illuminance, without direct or reflected glare or masking shadows. The task lighting unit would be dimmer controlled, to enable choice by the users, and to minimise waste it would be linked to an occupancy control to switch the light off, after a suitable delay, when the user leaves the workstation. This approach has been shown to be preferable by users and uses less energy for lighting; a reduction of up to 50% is considered likely[98]. However it is likely that an installation of this type would have a higher capital cost and without evidence that it would enhance worker efficiency it will be difficult to persuade clients to change. Conventional short-term research is unlikely to provide a convincing answer, but the set-up of a trial installation, which can demonstrate the approach and which can be monitored in terms of user satisfaction, performance and energy use over a reasonable time span is more likely to provide answers. Ideally the results would need to be compared with those of a similar office with conventional ceiling mounted lighting to ascertain the benefits, or otherwise. Also, if the approach is successful then it provides a demonstration installation by which to convince others. A few such systems have been installed but none have been monitored to check their performance.

7.2.2 Other Working Environments

In terms of lighting, offices are the most intensively studied of all working environments. Office working involves mainly two-dimensional tasks and lighting conditions that are fairly well controlled, and research has led to the development of various visual performance models, as described in Section 4.3. However, these models are difficult to apply in practice in other working environments, because:

- Industrial environments, such as factories, typically involve tasks that are three-dimensional and where uniformity of lighting, for example, may be more difficult to control; models based on two-dimensional tasks may not be relevant and research into three-dimensional tasks is therefore needed.
- Existing visibility/visual performance models have been developed from research involving foveal vision only. But many tasks (e.g. identification of damaged components on a production line) involve peripheral as well as on-axis vision. Research is needed to support models for tasks involving off-axis vision.
- Visibility is only one of many factors that can affect the performance of any given task. In order for the models to be used effectively to improve task performance, and thus increase productivity, it is necessary to develop a classification system or analysis method that allows tasks with an important/significant visual component to be identified. Improved understanding of tasks most sensitive to lighting conditions would help lighting installations to be more effectively designed, so as to improve productivity or to reduce energy consumption without adversely affecting productivity.

One area that has been explored in some detail, however, is retail sales, due to the potentially-significant commercial implications. Studies have shown that lighting can be used to draw attention to an object and can also change the perception of that object, depending on the way in which form, texture and colour etc. are affected by changes in the lighting. But the impact of lighting on retail sales is less clear, and studies have not shown any consistent or predictable effect. Other factors come into play and, as in other applications, the balance between these and the impact of lighting on behaviour will depend on the specific situation. More research is needed, but if it were possible to predict effects this could lead to increased sales and/or the reduction of energy consumption in retail environments.

7.2.3 Key Areas for Research

AREA OF RESEARCH / ACTION	SPECIFIC ISSUES REQUIRING INVESTIGATION / ACTION	KEY IMPACTS
Lighting appearance / preference	Studies to investigate the impact of the lit appearance of the working environment on mood, behaviour and performance	Better lighting to encourage increased productivity, reduce stress etc. Better worker satisfaction; reduced absenteeism
Task performance for 3-d and peripheral tasks	Studies to investigate the impact of lighting on the performance of 3-d tasks and tasks involving peripheral vision	Visual performance models for a wider range of tasks, to support better lighting for working environments Increased productivity Lower energy consumption
Task classification systems	Development of classification systems or analysis methods to allow identification of tasks with significant visual component	More effective lighting systems for critical tasks Improved productivity Reduced energy consumption
Trial/demonstration installation studies	Studies to: (a) investigate / demonstrate innovative office lighting techniques incorporating an holistic approach to design and (b) to monitor their performance	Greater take-up of improved lighting schemes Improved productivity for UK plc Reduced energy consumption in office environments

7.3 THE EFFECT OF LIGHTING ON SAFETY, SECURITY AND CRIME

7.3.1 Background

The use of lighting as a means to reduce street crime has a long history, dating back as far as the 15th century when householders in London and Paris were required to hang a lantern outside their homes during the winter evenings. Systematic research into the impact of lighting on crime has a much shorter history, however, being largely restricted to the past thirty or forty years. The results of these studies have been rather mixed[201,202,203,204]. Nearly all studies have shown that fear of crime is reduced following the introduction of improved street lighting, particularly among women and the elderly. But the impact on the incidence of crime is less clear-cut, with most studies showing some reduction with improved lighting, but others showing no effect and some even showing an increase in some types of crime.

There are many ways in which lighting may influence crime or the fear of crime. The most obvious is by affecting how well people can see i.e. visibility. Good lighting will improve visibility and thus increase the distance at which suspicious behaviour can be seen giving more time and opportunity for escape from a threatening situation, for example. However it may also make it easier for a criminal to pick out a suitable, vulnerable target. The balance between these two extremes will depend on the exact circumstances and on the perception of the level of risk in the mind of the criminal.

Another way in which lighting may influence rates of crime is by changing the behaviour and confidence of the community at large. Fear of crime is increased in situations where people cannot see clearly and decreased when visibility is good. As a result, more people tend to venture out when the lighting is good, giving less opportunity for criminal behaviour to go unnoticed. Crime rates may fall as a result.

A third factor is even more indirect: good lighting engenders a feeling that the community is ‘cared for’ and increases the desire of inhabitants to protect one another through neighbourhood watch schemes etc. This can also lead crime rates to fall.

Crime, and fear of crime, is high on the political agenda and is a major cause of concern for large sectors of the community. If lighting can be improved so as to reduce crime rates or to increase confidence within the general community, then this of itself is to be welcomed, let alone any financial benefits that may result[205]. In general this will mean greater use of lighting in external environments, so it is important that this is used as effectively as possible, in order to minimise energy consumption. Fortunately, despite the inconclusive and sometimes conflicting findings from the research studies carried out so far, and the complicated interplay between the various factors that influence the relationship between lighting and crime, there is a reasonable degree of consensus regarding what constitutes good community lighting. The important factors are the illuminance level on both horizontal and vertical surfaces, illuminance uniformity (avoidance of areas of darkness), the control of glare, and good colour rendering. The optimum source spectral power distribution is still a matter for debate. Street lighting levels at night fall in the mesopic range, so a source with high output in the blue spectral region may be more effective than one with lower blue output. Some research is underway to investigate this[206] but more is still needed.

One criticism of many of the previous research investigations is the lack of detailed photometric survey data on the lighting installations being studied, possibly because many of these investigations have been performed by those who are not lighting experts. The result of this lack of detail means that although it can be demonstrated that lighting can reduce the level of or fear of crime, it is not clear what are the important aspects of the lighting installation in achieving this effect. Future research should take care to address this criticism if it is to be of maximum benefit and utility. Levels of illumination, as well as crime rates, should be measured before and after changes to the lighting, and ideally investigations should include experimental control areas, both adjacent and non-adjacent to the test area, in order to test hypotheses about displacement and diffusion of benefits. Attempts should also be made to investigate how the effects of improved lighting vary according to characteristics of areas and how far there are different effects on different kinds of crime.

Another aspect of lighting and crime is the use of CCTV. In this case specialised lighting can be used to enhance the performance of CCTV systems. The amount and spectral characteristics of the source will depend on the characteristics of the CCTV camera, and the intensity distribution also needs to be controlled, to avoid areas of shadow or large changes in luminance across the field of view. Developments here are driven by the camera systems, rather than the lighting, and there therefore seems little need for lighting research in this area.

7.3.2 Key Areas for Research

AREA OF RESEARCH / ACTION	SPECIFIC ISSUES REQUIRING INVESTIGATION / ACTION	KEY IMPACTS
Influence of lighting on crime or fear of crime	Systematic studies to investigate how lighting affects crime rates and fear of crime, including good photometric data and effectively defined control sites	More effective lighting Reduced crime Reduced fear of crime, particularly for women and the elderly Enhanced quality of life within whole communities
Scales for mesopic vision	Studies to demonstrate utility of mesopic scales in predicting reduced crime or fear of crime and to encourage incorporation into lighting specifications and recommendations	More effective lighting for streets and other communal environments Energy savings Reduced crime rates or fear of crime

7.4 LIGHTING FOR TRAVEL AND TRANSPORTATION

7.4.1 Background

Lighting forms an essential element of all modern transportation, whether it be to provide information to the driver of a vehicle (road signs and signals), to control the passage of vehicles, trains etc. (traffic signals, train signals etc.), to provide guidance (lane markers on roads, airport runway markers, marine signalling buoys etc.), to provide warning of potential hazards (wreck marker buoys, lighthouses, pedestrian crossing beacons and the like) or simply to enable obstacles and other potential dangers to be seen (road and vehicle lighting etc.). The ubiquitous nature of lighting in transportation, and the fact that it is essential that signs and signals are both seen and correctly interpreted if people are to travel safely, means that this is an area which is not only strictly regulated, but also one in which potential improvements in the lighting used could bring substantial benefits to the population at large. For example, 3,508 people were killed in road accidents in 2003, 33,707 were seriously injured and 253,392 were slightly injured[207], not only leading to heartache for friends and families, but also placing a significant financial burden on the economy. More than one third (13,934) of the road deaths and serious injuries happened between 7.00 pm and 8.00 am. If even only a small percentage reduction in these accident rates could be achieved through better lighting, the benefits, both personal and financial, would be enormous.

7.4.2 Vehicle Lighting

Vehicle lighting can be divided into two types:

- Signalling and marking lighting (rear lights, side lights, brake lights, direction indicators, emergency flashing lights etc.) – these are usually small in size and of fairly low luminous intensity.
- Forward lighting (headlights, fog lights etc.) – these are usually fairly large in size and of high luminous intensity, and often different aiming positions are available to avoid discomfort glare when two vehicles meet.

Both types of vehicle lighting are closely regulated, with the regulations being based on studies of threshold visibility of targets against a wide range of background luminances[208,209,210]. The regulatory standards for signalling cover minimum luminous intensities that should be provided in different directions, colour (including what colours can be used and where each colour can be used) and, where flashing lights are used, the frequency of the flash. For headlights, the regulations represent a compromise between forward visibility and minimising glare to approaching vehicles. For this reason, headlights have two luminous intensity distributions: high and low beam, and regulations specify both maximum and minimum luminous intensity values, for both high and low beams, for a number of relevant directions.

Despite this high degree of regulation, and the strict enforcement of these regulations for new vehicles in particular, there are still some areas where further research would be advantageous:

1. To encourage the introduction of new technologies (e.g. LEDs) where appropriate. For example, the very fast rise time of LEDs compared with incandescent lamps may be a useful means for reducing accidents in which a following vehicle collides with the back of the vehicle in front[211].
2. To provide improved guidance in relation to the use and visibility of flashing lights, for emergency vehicles, for example. Two issues are important here:
    a) There is no agreed method for evaluating the visual effectiveness of flashing lights. Most specification standards use the Blondel-Rey or Form Factor methods, but these give widely differing results when applied to modern sources which are being increasingly used in signalling applications, such as pulse-width modulated LEDs[21].
    b) Although flashing lights are undeniably effective in attracting attention to a vehicle, at night they can make it difficult to estimate relative speed, distance, and closure rate[212]. This fact, coupled with the confusion that can be caused by flashing lights on a number of emergency vehicles at the site of a road traffic accident, for example, means that research to support better guidance for the use of flashing lights would be valuable.
3. To support the development and introduction of improved headlights. Much research has been carried out to investigate at what distance objects are visible when driving with headlights[213] and to model the relationship between visibility and luminance contrast[214]. But more research is needed into potential solutions to the problem of maximising visibility while minimising glare e.g. through the use of headlights emitting polarised light or UV radiation[215,216,217].

7.4.3 Road Lighting

Road lighting is provided mainly to enable a driver to see further and better than is possible using the vehicle forward lighting alone. Research has shown that road lighting can be an effective accident countermeasure and it has been estimated that the introduction of road lighting to previously unlit roads could lead to a 65% reduction in fatal accidents at night and a 30% reduction in night-time accidents resulting in damage to property[218].

A large number of factors can contribute to the effectiveness of road lighting in reducing accident rates, some of which may actually act so as to diminish its impact. For example, better lighting can encourage drivers to increase their speed and thus offset some of the advantage gained by increased visibility. Nevertheless, there is little doubt that road lighting is a useful accident countermeasure and that its effectiveness can be closely linked to average road surface luminance[219]. Current road lighting recommendations are therefore based primarily on the amount and distribution of the light on the road surface. In North America additional recommendations relating to the visibility of small targets are included, based on the results of a number of studies[220,221,222] which have shown a link between target visibility, detection/recognition distance, and subjective ratings of visibility.

The CIE has produced recommendations based on average road surface luminance (see CIE Publication 115[223]) that have been widely adopted. However other factors, in addition to road surface luminance, must also be considered:

- Luminance uniformity. Object visibility depends primarily on luminance contrast, which means that objects with the same luminance as the road surface will never be visible unless they are of significantly different colour. Some degree of non-uniformity for the road lighting is therefore desirable, since this means that a wider range of object luminances will be visible at least some of the time. However the non-uniformity must not be large enough to produce large areas of low luminance, since this will make it difficult to detect objects with low reflectance. CIE Publication 115 recommends a minimum to average road surface luminance of at least 0.4 cd m^{-2}.
- Disability glare from the road lighting luminaires. When the angle between the line of sight and the luminaire is small, light from the luminaire can be scattered within the eye and cause a decrease in visibility due to a reduction in the luminance contrasts in the retinal image. CIE Publication 115 includes recommendations to limit these effects.
- Discomfort glare from the road lighting luminaires. This has been the subject of extensive research[224,225,226,227], but no definite conclusion has yet been reached. CIE Publication 115 indicates that compliance with the recommendations for disability glare will lead to road lighting installations that are also acceptable in terms of discomfort glare.

The spectral power distribution (colour) of the road lighting is also important. Night-time road surface luminances fall in the mesopic range (around 0.03 cd m^{-2}), but current recommendations for road lighting take no account of the gradual shift in the eye response characteristics towards the blue in the mesopic. Research in this area has been reviewed elsewhere in this report (see Section 4.2.3). A consensus regarding a practical system for mesopic photometry now appears to be close, but in order for this to gain widespread acceptance and to be adopted by road lighting regulatory authorities around the world, it will be necessary to provide evidence of a good correlation between measurements of light levels made using the new system with reduced accident rates for night-time driving. Field studies are therefore required.

It is interesting to note that, at present, the most widely used source for road lighting in the UK is the high-pressure sodium (HPS) lamp. This has largely replaced the low-pressure sodium lamp, which was once extremely popular due to its high luminous efficacy, but suffered from a complete lack of colour rendering. In terms of mesopic photometry, however, metal halide and fluorescent lamps are more highly rated than HPS, due to the higher proportion of blue light emitted. Nevertheless, widespread adoption of such sources for road lighting may not be the answer. Research has shown that for on-axis tasks $V(\lambda)$ applies to all light levels (see Section 4.2.3), so if the road conditions are such that on-axis tasks dominate (e.g. on a motorway) the advantages of a source with higher blue output may be minimal. If off-axis tasks are significant (e.g. a road with a large number of pedestrians in the vicinity) a blue-rich source could be more beneficial. Secondly, the effect of enhanced blue output on task performance is significant only when the adaptation luminance is below 1 cd m^{-2}, and such conditions may not be encountered in many situations. Studies[228] have shown that the adaptation luminance for a driver using low-beam headlights on an otherwise unlit road is ~1 cd m^{-2}. When road lighting is present, however, the driver tends to fixate over a wider area than that lit just by the headlights, and hence views a wide range of luminances[229]. This means the adaptation luminance is unknown; investigations to determine the state of adaptation for night-time driving under different lighting conditions are needed.

Field studies to validate the use of a proposed system for mesopic photometry for road lighting may also need to be supplemented by further research to investigate in more detail the ability to perform specific critical tasks e.g. detection of movement at the road edge or in the periphery of the visual field, judgement of the relative speeds and directions of other vehicles, identification of road signs and signals, and detection of large objects of non-uniform contrast on the roadway. Investigations will need to consider the fact that, in practice, all these tasks need to be carried out not only under different levels of illumination and with different source spectral power distributions, but also under conditions of non-uniform illumination of the road surface due to the combination of the road lighting and the vehicle lighting. This will support a more comprehensive understanding of the relationship between road and vehicle lighting and the safety of road users and pave the way for recommendations for improved road lighting systems, which will not only take account of the impact of changes in the eye's performance in the mesopic region, but also of the other factors that influence driving performance. Relevant studies could, for example, identify the range of target contrasts typically encountered during night-time driving or investigate which types of task are most important for various types of road.

In general, road lighting is only used at night, but there is one situation where it is used 24 hours each day, namely in tunnels. Tunnel lighting has been the subject of extensive research[230,231,232,233] and as a result recommendations for tunnel lighting are well-established[234,235]; further research seems unnecessary at the present time.

7.4.4 Signalling and Signage

Another aspect of road lighting that is fairly well researched and regulated is signalling and signs. Intensity distribution, luminous intensity or luminance and colour boundary values are all specified in relevant national and international standards, and are based on the results of studies to investigate reaction times to the onset of signals and the number of signals that are not detected under different conditions. The levels specified vary between countries, due to differences in the approaches taken to accommodate the fact that different colours need to have different luminances in order to achieve the same percentage of missed signals, unless luminances are so high that almost no signals are missed.

7.4.5 The Impact of Modern Light Sources and Technologies

In recent years, the use of LEDS in signalling and signage for transportation (road, sea, rail and air) has become increasingly widespread, due not only to their long life and efficacy, but also because colour can be generated without the use of filters. This trend is likely to continue and to gain momentum as efficacy increases further and cost and availability improves. Research into the optimum colour boundaries, intensity profiles etc. for these sources may be needed, to ensure that they are used to their fullest potential.

The introduction of LEDs is also introducing new issues relating to the measurement and specification of the visibility and conspicuity of these signs and signals. Factors such as their relatively narrow spectral bandwidth, small size, high directionality and spatial non-uniformities when used in clusters (as in traffic signals) all need to be considered when undertaking measurements and in specification standards. Several CIE TCs are developing recommendations to deal with such issues (e.g. TC2-45, 2-46 and 2-50). A further complication is that LEDs used in signalling in particular are often pulsed at high frequencies. This gives the appearance of a continuous light source but presents measurement problems which are further exacerbated in situations (e.g. marine signalling) where the intention is to produce a flashing, rather than continuous, light. There is no international agreement at present regarding how to measure the visual effectiveness of a flashing light. Current methods, such as Blondel-Rey or Form Factor approaches, give very different results when applied to flashes which are composed of a train of rapid pulses[21].

The use of ‘adaptive lighting’ on roads and road vehicles (i.e. lighting which automatically adjusts in terms of its luminous output or colour, depending on the ambient conditions) is an attractive proposition in terms of improving its effectiveness and safety, and is becoming a more realistic proposition as the relevant technologies are improved and costs are decreased. Other techniques, such as vision enhancement systems for use in fog, are also being developed. The full benefit of all these developments will only be realised if research into their effectiveness is carried out.

7.4.6 Key Areas for Research

AREA OF RESEARCH / ACTION	SPECIFIC ISSUES REQUIRING INVESTIGATION / ACTION	KEY IMPACTS
New lighting technologies	Studies into the effectiveness of new technologies for transportation lighting (e.g. adaptive lighting, LEDs), including investigation of colour boundaries for signal lights	Optimised lighting for transportation Reduced accident rates Reduced energy consumption
Measurement of pulsed and flashing lights	Establishment of agreed method for evaluating the visual effectiveness of flashing lights	Improved measurement of flashing lights, to correlate with visual effect More effective signalling; enhanced safety in transportation systems
Use of flashing lights	Improved recommendations for the use of flashing lights on emergency vehicles etc.	Less confusion / distraction for drivers and other road users Greater road safety
Improved headlights	R&D for new headlight designs e.g. systems emitting polarised light or UV radiation	Improved headlights to maximise visibility while minimising glare Improved road safety
Mesopic photometry	Case studies to validate new systems for mesopic photometry in road lighting applications	More effective road lighting Improved road safety for drivers and other road users
Driver adaptation	Research into adaptation levels for night-time driving under different lighting conditions	Correct application of new systems for mesopic photometry More effective road lighting Improved road safety for drivers and other road users

Driver task performance	Research into driver performance of critical tasks under different lighting conditions and assessment of relative importance of tasks for different road types	Correct application of new systems for mesopic photometry More effective road lighting Improved road safety for drivers and other road users

7.5 THE EFFECT OF LIGHTING ON HEALTH AND WELL-BEING

7.5.1 Background

As discussed earlier in this report (see Sections 5 and 6) optical radiation has many effects on the human body beyond the straightforward stimulation of a visual response. It can affect mood and behaviour, act as an effective therapy for some forms of depression, and, critically, it governs our circadian system and daily biological rhythms, such as the sleep/wake cycle, core body temperature, hormone secretion, cognitive functions, and immune response.

Understanding the influence of light on mood and behaviour is important if lighting design is to move beyond the provision of lighting for task performance to the provision of visual environments that also stimulate an appropriate psychological or emotional response i.e. 'healthy' lighting environments[181]. As described earlier (Section 5), research in this area is currently at a very early stage but offers the potential, for example, for improved psychological well-being, enhanced worker productivity, reduced absenteeism, better control of behaviours for specific communities, such as prisons, and for lighting that sends the right 'message' for specific environments, such as shops, restaurants and bars. More research is required before a clearer understanding of the underlying physiological and psychological processes involved can be developed, which will make it possible to predict effects in new situations and to introduce new recommendations into lighting design practice.

Understanding of how light exposure affects the human circadian system, on the other hand, has improved dramatically over recent years (see Section 6), although much is still not known. Exposure to light has been shown to not only shift the circadian rhythm, which of itself can affect performance, but also to have an immediate effect on alertness. These effects are important because they can affect performance of all tasks, not just those with a substantial visual component. Light exposure has also been shown to affect health in both positive and negative ways. It is essential for vitamin D synthesis, a deficiency of which leads to bone problems such as rickets and osteomalacia and may also be implicated in diseases such as multiple sclerosis, diabetes, tuberculosis, heart disease and even internal cancers, including breast, colon, ovarian and prostate cancer. Inappropriate or insufficient light exposure leads to circadian disruption and possibly consequent problems such as depression, poor sleep quality, increased cancer risk or reduced immune function.

The comparatively recent discovery of the non-visual pathway that triggers the pineal gland to control the secretion of melatonin has changed the way light is considered with regard to humans. It is conceivable that this is just the beginning of a significant expansion of our understanding of the human response to light and lighting. This could ultimately have major impacts on the way light and lighting is provided, although the range and type of any changes to lighting recommendations are difficult to predict at this early stage. However, it would be useful to explore the subject not just from a physiological aspect, which has been the current focus, but also by observation of human behaviour under different lighting conditions.

Considering these two approaches in parallel might lead more rapidly to a fuller understanding of human responses to light and lighting.

The majority of the research that has been carried out to date in relation to the impact of optical radiation on health and well-being has focused on adults. However life styles for children have changed dramatically in recent years and the short- and long-term implications of these changes are far from understood. For example, many children spend most of their free time indoors, watching television or playing computer games, and receive very little exposure to daylight; the effects on future health and on cognitive development are not known.

Thus the following aspects of the human circadian system and associated health effects require further research:

- Development of a system of circadian photometry, based on improved understanding of the spectral sensitivity of the human circadian system (including any opponent effects) and on the effects of changes in the level, spectral characteristics, duration and timing of the exposure. This will be essential in order to make predictions of the effects of light exposure in any given situation and to design lighting to have positive impacts on the circadian system.
- Development of a better understanding of the role of melatonin excretion/suppression, vitamin D synthesis and other human physiological responses to optical radiation in medical disorders such as cardiovascular disease, gastrointestinal problems, cognitive and psychological problems, and breast and colon cancer.
- Special attention needs to be given to the impacts on children, so that appropriate guidance can be developed for parents, teachers, etc.

7.5.2 Key Areas for Research

AREA OF RESEARCH / ACTION	SPECIFIC ISSUES REQUIRING INVESTIGATION / ACTION	KEY IMPACTS
Influence of light on mood and behaviour	Studies to investigate and establish relationships between lighting and psychological responses (mood, depression, etc.)	Improved lighting for mental and emotional well-being Light therapy for depression
System for circadian photometry	Studies to develop improved understanding of the human circadian system (including any opponent effects) and the effects of changes in the level, spectral characteristics, duration and timing of light exposure	Ability to design lighting for positive effects on circadian system Recommendations for ‘healthy lighting’ Improved public health: minimisation of problems such as depression, poor sleep quality, increased cancer risk or reduced immune function

Physiological responses to optical radiation	Studies into role of melatonin excretion/suppression, vitamin D synthesis and other human physiological responses to optical radiation in medical disorders e.g. rickets, cardiovascular disease, cognitive and psychological problems, and cancer	Recommendations for 'healthy lighting' Lighting strategies to reduce risk of serious illness for shift workers Reduced accident rates Improved public health: minimisation of problems such as depression, poor sleep quality, increased cancer risk or reduced immune function
Effects on children	Studies into the short- and long-term effects of exposure to optical radiation on the health and cognitive well-being of children	Recommendations on light exposure for children for parents and teachers Improved health and well-being for future generations

7.6 LIGHTING AND ENERGY EFFICIENCY

7.6.1 Background

The provision of lighting forms a major element of the UK's energy budget, accounting for about 20% of the total electrical energy consumed each year (i.e. ~58 TWh)[236] and about 30% of the annual electricity consumption for lighting in the service sector[237], and generating around 27 million tons of carbon each year. This energy consumption is split fairly evenly between exterior lighting (road, street, buildings, etc.) and interior applications (homes, offices, shops, schools, hospitals, etc.) Worldwide, estimates of the amount of electricity generated that is used for lighting range from around 5% to 20% for industrialised countries to more than 80% in under-developed countries, with a total global electricity consumption for lighting in excess of 2000 TWh[238]. The environmental impact of lighting is not restricted to the energy consumed, however. The manufacture of lamps and lighting systems consumes precious natural resources such as tungsten and rare earth gases, and pollution can result when lamps and control gear are scrapped, due to the presence of hazardous materials such as mercury, lead and PCBs.

The potential for energy savings and reduced environmental impact from the use of 'better' lighting is clear. In this context, 'better' could mean:

- More energy efficient (new technologies etc.)
- Better designed (so less lighting is needed)
- Better targeted on the application/area requiring illumination (less light wastage)
- Based on less hazardous technologies (reduced hazardous waste)
- Longer lifetime / recyclable (reduced use of natural resources)

7.6.2 Energy Efficient Lighting

Several approaches have been taken to try to reduce energy consumption for lighting. Possibly the most obvious is work by the lighting industry itself in developing new, more energy efficient lighting such as CFLs and in designing more effective luminaires which direct light only where it is needed. Governments have played a role through schemes to subsidise purchase costs for these new technologies in the home in particular and through legislation to improve energy efficiency of new buildings etc. Commerce and industry have been keen to adopt improved lighting with lower energy consumption since this can lead to direct savings on their energy bills. Possibly the area where least progress has been made is in the area of residential lighting, where tungsten lamps are still by far the most commonly used source of electric light.

Research into more energy efficient lighting will certainly continue and must be encouraged. This needs to be coupled with developments to improve the acceptability of new technologies, particularly in the home. Solid state lighting systems (LEDs, OLEDs etc) have an important role to play here. Not only do these sources offer the potential for luminous efficacies which are even better than those of CFLs, for example, but they also present opportunities for completely new lighting designs, such as light bricks and even light emitting ‘wallpaper’. Rapid progress is being made in this area at present, and efficacies to rival fluorescent lamps are already being claimed.

7.6.3 Lighting Controls

Another important area for reduced energy consumption is the development and use of lighting control systems. A recent review[42,43] showed that a combination of manual controls and occupancy sensors can reduce energy consumption by up to 75% as compared with ‘standard’ lighting systems providing a uniform level of ~300 lx throughout the working space. Part of the energy saving comes from the fact that there is a very large variation in the preferred lighting levels between individuals, with only about 25% choosing to work within the 300-500 lx range recommended for offices. Many chose to work at substantially lower illuminances, especially in winter (over 50% worked at below 300 lx in winter and 20% worked at below 100 lx). As well as energy savings, having personal control of lighting levels has also been shown to lead to increased occupant satisfaction and increased productivity. The use of lighting controls, particularly those allowing individual control of lighting levels for individual work areas, adds significantly to the initial costs of a lighting installation and this can prove a significant barrier to their take-up. In addition to the need for further research to determine the optimum configuration for lighting control systems, case studies are also needed to demonstrate their efficacy and the resulting benefits, both for reduced energy consumption and improved worker satisfaction and productivity.

7.6.4 Key Areas for Research

AREA OF RESEARCH / ACTION	SPECIFIC ISSUES REQUIRING INVESTIGATION / ACTION	KEY IMPACTS
Energy efficient lighting	Development of improved lighting and luminaires	Increased energy efficiency Less light wastage Reduced energy consumption
Lighting controls	Case studies to demonstrate benefits of manual and automatic lighting control systems	Increased use of lighting controls leading to reduced energy consumption and increased worker satisfaction and productivity
Demonstration installations and case studies	Studies to investigate and demonstrate the benefits of lighting designed specifically for energy efficiency i.e. combining system design, equipment and the way it is used.	Reduced energy consumption Increased worker satisfaction and productivity

8 SUMMARY OF KEY RESEARCH AREAS

Previous sections of this report have highlighted a large number of areas requiring further research and investigation. The table below summarises the findings by grouping these into themes, but these are cross-referenced with the sections in which they appear so specific issues and research proposals can be identified if required.

Research Area	**Report Sections Giving Details**
Improved visual scales (large FOV, off-axis, brightness, CRI, colour appearance, pulsed sources)	4.2, 4.3, 4.5, 7.2, 7.4
Task classification systems and case studies for improved lighting	4.2, 4.5, 7.2, 7.4, 7.6
Mesopic photometry	4.2, 4.5, 7.3, 7.4
Visual performance systems	4.3, 4.5, 7.2
Lighting and mood / behaviour / perception / motivation	4.3, 5.1, 5.2, 5.3, 5.4, 7.2, 7.5
Energy efficient lighting and lighting controls	5.2, 7.6
Lighting and psychological health	5.3, 5.4, 6.3, 7.5
Circadian system	5.3, 6.1, 6.2, 6.4, 6.6, 7.5
Physiological responses to optical radiation (melatonin etc.)	6.2, 6.3, 6.4, 6.5, 6.6, 7.5
Dosimetry for non-visual effects of light	6.4, 6.5, 6.6, 7.5
UV sterilisation	6.5, 6.6
Visual responses of the elderly	7.1
Effects of light on children	7.5

9 RECOMMENDATIONS FOR THE ORGANISATION OF FUTURE RESEARCH ACTIVITY

As highlighted in the previous sections of this report, there are a large number of areas of lighting recommendations and practice, which might be improved by a better understanding of the relationship between light and lighting and human response, embracing performance, mood, health and well-being, etc. Furthermore, the impact of these improvements could be substantial, not just in purely financial terms (through better utilisation of lighting and therefore reduced energy consumption) but also through improved productivity, reduced absenteeism, better health, and so on. However, the funding available for the required research is severely limited and, if the benefits of this funding are to be maximised, a more coordinated approach is essential.

At present, research into lighting is carried out by diversity of bodies and organisations, including:

- Manufacturers of lamps and light fittings, who generally limit their research to improving product performance and cost effectiveness. They are typically less interested in funding more fundamental research e.g. into human responses studies.
- Universities who conduct research into a range of aspects of lighting but, due to limited resources and the short-term nature of many studentships, the work tends to address isolated topics and often does not reach a definite conclusion. Furthermore, research may be carried out within many different departments, ranging from the human sciences to engineering and architecture etc., but the level of interaction between them and the wider lighting community is often very limited.
- Research institutes (such as the Building Research Establishment and the National Physical Laboratory) who generally carry out lighting research within a fairly narrow remit. For example, research at NPL is focussed on measurement issues. The depth of knowledge and expertise generated within these organisations is not always utilised to best effect by the lighting community in general.

It is therefore important to consider not only what research is required (see previous sections of this report), but also how this should be organised and disseminated in order to derive maximum benefit within the range of specialisms concerned.

9.1 COORDINATING AND FUNDING RESEARCH ACTIVITY

Much of the lighting research carried out in the past two decades has been conducted on a fragmented basis and with a lack of collaboration between the various interested parties. For example, most of the research into light and health or light and mood, etc., is carried out within academic institutions with little involvement from lighting manufacturers or practitioners. As a result, research information is only slowly absorbed into lighting practice. Similarly there is little collaboration between different participants in a single field of application: those involved in road lighting have little interaction with those working on vehicle lighting, for example. Improved collaboration and cooperation is essential if research is to lead successfully to lighting which satisfies both human needs and the needs for improved energy efficiency.

Addressing fundamental questions about the lighting conditions required for optimal human performance and well-being will require collaboration between the disciplines of physiology, psychology, physics and medicine. Answering questions about how to achieve these conditions in practical situations and real spaces will additionally require collaboration with engineering, architecture, lighting design, human factors and ergonomics.

9.1.1 Lighting Foundation

One proposal that received substantial support at the workshop during the CIE Quadrennial Session in 2004 was that for setting up a 'Lighting Foundation'[4]. This would be a charitable body, responsible for generating and distributing funds for lighting research. The Foundation would publicise topics where research should be undertaken and provide funding for this research and dissemination of the outcomes. This would help to achieve a more structured and coordinated approach to lighting research and help to ensure wider take up of the outcomes. However, in order to be successful, its budget would have to be large, possibly incorporating all available funding from other bodies. It is difficult to see how this could be achieved in the short term, particularly across international boundaries.

9.1.2 The Role of the CIE

Another approach would be to establish a mechanism for publicising research proposals, opportunities and results more widely with the intention of achieving better coordination of research through increased dialogue. The CIE would be well-placed to take on this role. The focus would be a database containing proposed research topics, potential project partners, information on funding opportunities, research postings etc and a regularly updated bibliography of the key research papers. Ideally there would also be a research strategy document, prepared/updated on an annual basis by the CIE Divisions. Researchers preparing proposals which fall within the agreed research strategy could be offered letters of support, which could help them to win the necessary funding.

An advantage of the CIE undertaking the role would be the fact that it would be truly international and could therefore help to coordinate research activity throughout the world. The high profile of the CIE would also help ensure wide dissemination of results; indeed it could be possible to publish results in the CIE Collections on a regular basis. Furthermore, National Committees could take a role in coordinating research in their own countries via the CIE database. If such a database is to be effective, however, it would have to be appropriately managed, probably by the CIE Central Bureau, and this would have financial implications for the CIE, and hence also for the National Committees. Additionally it would almost certainly need to be driven forward by assigning responsibility for establishing and maintaining the database to a member of the CIE Board of Administration (e.g. one of the CIE Vice Presidents).

9.1.3 National Initiatives

The International Dark Skies Association has been very successful in recent years in lobbying for reduced light pollution. This serves to highlight how effective a well-focussed campaign of this sort can be, provided it is adequately funded. A similarly well-focussed publicity campaign for lighting quality and design might have similar success in raising awareness of the benefits of improved lighting within the general public and government. Such an initiative would need to involve all those with an interest in lighting research and would require CIE–UK, SLL, ILE, LIF etc. to work together more effectively and to provide an appropriate level of financial support. Most importantly, however, it would need to excite the attention of the media, the public, government and business in some way e.g. by linking it with a high profile government initiative or obtaining celebrity support. A good media relations company could be of assistance with this.

9.1.4 UK Government

Funding for lighting within UK Government (and indeed other governments as well) is currently very limited. The topic of improved lighting is of interest to several different departments (DEFRA, DTI, DETR, MOD) but there is no coordinated policy, nor is lighting seen as a high priority within any of these. Once again, the area of light pollution is leading the way in raising awareness of the importance and impact of lighting and has led, for example, to the recent designation of light pollution as a ‘statutory nuisance’. Campaigners have been greatly helped by the fact that light pollution is visible to all, including the general public.

Increased lobbying and publicity campaigns in the area of lighting quality may have similar impacts. There could also be a role for newer bodies, such as the DTI-funded Displays and Lighting Knowledge Transfer Network, which acts as a focus for knowledge exchange in lighting and displays and holds regular meetings on topics of interest to members, as well as disseminating information about government calls for funding applications etc.

9.2 RESEARCH METHODS

9.2.1 Measurement Protocols

It is clear from the discussions throughout this report that research into the effects of light on human task performance, mood, behaviour and health is far from straightforward. Careful experimental design is therefore essential in order to obtain maximum benefit from any form of human factors research, and to move results from being anecdotal to objective. However analysis and comparison of results from different studies is currently made even more difficult by the variety of measures which are used to quantify the lighting conditions under which the relevant behaviour is studied, and by the inappropriateness of some of the measures for the effects that are being investigated. It is common to see reports of the lamp type and luminaire distribution, for example, without any supporting measurement data of illuminance, luminance, uniformity, spectral power distribution etc.

Greater consideration must be given to the research procedures in order to increase the ability to compare one study with another and to increase confidence in the validity of any conclusions drawn. In particular:

- Researchers need to be encouraged to completely describe the stimulus conditions (light source properties, reflection of room surfaces, luminaire properties etc.) for all investigations. CIE TC3-34 is working on a report ‘Protocols for Describing Lighting’ to deal with this.
- Photopic measurements are used for most investigations, even though these might not be appropriate (especially for investigations into non-visual effects of lighting). It would be preferable for measurements to be made of the absolute spectral irradiance, for example, instead.
- Errors in the spectral correction of photometers are usually ignored. This can mask the effects being investigated – the ‘correct’ dose-response relationship may not be seen.
- It is usually the amount of light reaching the retina that is the most important quantity, but this is very difficult to measure due to head and eye movements. This can explain

differences in the dose-response relationships in different experiments. New measurement instrumentation, which takes account of real human responses and behaviours, will be needed.

- Measuring the illuminance incident on the working surface is not sufficient – it is also necessary to be able to measure easily the light distribution in an environment and to know the reflectance of the working surface and the surrounding surfaces. The development of an imaging system for mapping radiance distributions within an environment would provide an invaluable tool for linking physical measurements and subjective assessments.
- The adaptation luminance is also important, since this determines the diameter of the pupil and hence the amount of light reaching the retina.
- As the eye ages, the amount of short wave radiation reaching the retina decreases (yellowing of the lens). This loss of light occurs in the spectral region that is most significant for non-visual effects of light, so for investigations into these areas it is even more important to make allowances for the age of the subjects etc. when analysing results.
- Placebo effects can occur, where participants in experimental investigations show behaviour which fulfils either their own expectations for the likely effect, or what they believe to be the experimenter's expectations (e.g. the 'Hawthorne effect' in which workers' performance improved regardless of the change in lighting level). Careful experimental design can avoid such effects, e.g. by recording biological effects (hormone levels etc.) as well as subjective impressions.

9.2.2 The Role of the National Measurement System

Many researchers involved in investigations of the effects of light on performance, health and well-being have a background in psychology, medicine, or lighting design, but not measurement. As a result, they may place undue reliance on the 'accuracy' of measurement instrumentation, or make measurements that are inappropriate for the effect being studied (see Section 9.2.1). Improved access to measurement advice and specialist equipment could therefore be of great benefit in ensuring that the conclusions drawn from research studies are based on sound metrology. In the UK (and possibly Europe as well), the National Measurement System Directorate Optical Radiation Measurement Programme could play an effective role in improving the situation by, for example, providing support for experts at the National Physical Laboratory to visit research laboratories to provide guidance or to calibrate reference measurement equipment. It would also be helpful if these organisations could do more to develop new measurement techniques and equipment to enable the lit environment to be described and quantified in more detail.

9.2.3 Study Protocols

Various methods can be used to investigate the relationship between lighting and human performance, health/well-being and comfort. Broadly speaking they can be divided as follows:

- Epidemiological studies – these are used to establish whether two variables are correlated (e.g. night shift working and breast cancer rates) but they cannot be used to demonstrate cause and effect. They are most useful if there are many intervening factors that cannot be controlled or if effects occur only over long periods of time. These studies are very difficult to interpret and often analysing the data in different ways (e.g. by looking for different correlates) can give confusing results.

- Behavioural studies – these involve the observation of behaviour under certain conditions and the interpretation of that behaviour. This approach is valuable where the context in which the behaviour takes place is important (e.g. for studying the impact of lighting on the behaviour of patients in hospital waiting rooms) but has the disadvantage that it cannot explain why the observed effects occur.
- Controlled studies to investigate relationships between specific stimuli and observed responses. In this case the stimulus (e.g. the spectral power distribution of the lighting) is varied in a controlled manner and the change in a given response (e.g. reaction time) is measured. Although such investigations can provide clear relationships between stimulus and response, they are often conducted under very 'artificial' conditions and may be difficult to apply in more realistic environments.

A combination of different approaches may be needed, depending on the behaviour or effect being investigated. Once again, careful coordination of research activities between groups, and correct/appropriate lighting measurement, will be essential if meaning and valid conclusions are to be drawn. Furthermore, it may be necessary to tackle some areas in stages and produce interim changes in recommended design practice, so that some improvements can be made without waiting until a precise and complete understanding of each effect in its entirety is developed.

9.3 DISSEMINATING RESULTS

The ultimate objective of all the areas of research described in this report, and of future research activity in these fields, is to 'improve' the way in which we use light, whether this be to increase its effectiveness (and thus reduce energy consumption or increase productivity), to modify mood or behaviour (e.g. in retail sales) or to improve human health, safety and well-being (e.g. treatment of depression). It is therefore important that research outcomes from the diverse communities involved (lighting manufacturers, psychologists, academics etc.) are effectively monitored and reviewed by the lighting community in general.

The CIE has a key role to play in this respect, since it is possibly the only umbrella organisation under which all of the various research communities come together, and which furthermore has an internationally-recognised standing in the art and science of lighting. Technical reports, recommendations and standards produced by the CIE form the basis for lighting practice throughout the World and are entrenched in legislation in areas such as health and safety, work place lighting, transportation and signalling, trade and measurement. The CIE already has a number of highly effective mechanisms in place which allow it to act as a focus for the dissemination of the outcomes from research into light and lighting, which include:

- CIE Expert Symposia, such as the Light and Health Expert Symposia held in 2004 and 2006, at which latest developments in a given area are presented and discussed.
- Papers and posters at the Quadrennial meeting; these can be particularly valuable in terms of sharing developments between different areas of light and lighting, such as vision research, photobiology, measurement, interior lighting and transportation.
- Establishment of a register of CIE-approved journals in light and lighting, in order to encourage researchers to publish in these high-standing journals and to enable people with an interest in this field to know which journals are most appropriate to read. Currently Leukos (USA), Light and Engineering (Russia) and Lighting Research and Technology (UK) are approved.
- Some CIE Divisions provide a short annual report on key developments and current 'hot

topics' in their individual fields, which can help researchers focus their efforts in the most productive and rewarding areas.

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