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Illuminance Selection Based on Visual Performance - and Other Fairy Stories

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Abstract

The illuminance selection procedure and the illuminances recommended for various applications in the 1993 IESNA Lighting Handbook rest on consensus, as do the illuminance recommendations of every other country. However, relying on consensus does not appear to be a comfortable posture for some in the IESNA. For many years it has persisted in the search for a "scientific" method for recommending illuminances. This paper sets out to explain why such a search is doomed to failure and, as a corollary, why consensus is an inevitable element in any procedure for determining illuminance recommendations. In doing this, it emphasizes the flexibility of the visual system, explains the distinction between task performance and visual performance, considers the divergence between visual performance and visual comfort and proposes an open procedure for obtaining consensus on illuminance recommendations.

Introduction

Once upon a time, there were three illuminating engineers who lived in a small house on Wall Street. They were poor but they were honest. They made their living by providing clear advice on good lighting practice. But they did not sleep well. Their nights were haunted by the knowledge that much of what they recommended was based on accumulated experience and judgment - it was a matter of consensus. In the darkest hours of the night they often thought that one day the wolf of litigation would come to their door and would huff and puff and blow their house down. But with each dawn came new hope. There was a solution. It was to find the magic formula; a formula which accurately described the relationship between lighting conditions and the performance of any task. With such a formula, the illuminating engineers could be objective and abjure consensus. They could simply state what the relationship was between lighting conditions and task performance and leave the users to decide what level of task performance they wanted. Alternatively they could make recommendations based on the formula, explicitly stating the conditions they had used. Either way they would have an defensible basis for their recommendations, a base strong enough to defy the wolf of litigation. Year after year they persisted with their search for the magic formula. After many years and several false dawns the magic formula was found and they all lived happily ever after.

Unfortunately, the above is a fairy story, or rather, the problem is real but the solution is not. This paper explains why a magic formula describing the relationship between lighting conditions and task performance cannot exist in any general form; discusses the difference between visual wants and visual needs and concludes that consensus is an inevitable component in all illuminance recommendations.

Why a magic formula cannot exist

Before discussing the relationship between lighting conditions and task performance it is necessary to define some terms. Specifically, the two terms task performance and visual performance need to be clearly distinguished, because they are sometimes used as synonyms. Task performance is the performance of the complete task. Visual performance is the performance of the visual component of the task. Task performance is what is needed in order to establish cost / benefit ratios comparing the costs of providing a lighting installation with the resulting benefits in terms of better task performance. Visual performance is the only thing that changing the lighting conditions can affect directly.

The underlying reason why a magic formula cannot exit is that no task is purely visual. Most apparently-visual tasks have three components; visual, cognitive and motor. The visual component refers to the process of extracting information relevant to the performance of the task using the sense of sight. The cognitive component is the process by which sensory stimuli are interpreted and the appropriate action determined. The motor component is the process by which the stimuli are manipulated to extract information and/or the actions decided upon are carried out. As an example, consider the task of driving a car along a road. The driver scans the road ahead and its environs to extract information using the sense of sight. This is the visual component. The significance of the information extracted is evaluated by the brain to determine the appropriate action, which may range from doing nothing, to braking sharply, to changing lanes. This is the cognitive component. Actually moving the steering wheel or applying the brake is the motor component. Of course, this is a continuous process where visual, cognitive and motor components interact and overlap. Nonetheless, the only part of the task performance that changing the lighting conditions can influence is the visual component. This implies that the effect of lighting conditions on task performance depends on the role of the visual component in the structure of the task.

The role of the visual component in the structure of a task can vary in at least three ways. First, the *magnitude* of the visual component can vary between tasks. For example, the visual component is greater for data entry from written material than from an audio source. Second, the *significance* of the visual component in the structure of the task can influence the importance of the lighting conditions, and this significance is not necessarily related to the magnitude of the visual component. For example, in the construction of an electronic circuit mounted on a printed circuit board, the visual inspection of the printed circuit board may take only a short time but if a fault is not detected, the consequential costs in terms of time and money may be substantial. Third, the *emphasis* of the visual component can be different for different tasks. For example, reading low contrast, small size print, of the type found on car rental agreements, places greater emphasis on the illuminance provided than the spectral content of that light, while discriminating between textiles of different colors places greater emphasis on the spectral content of the light than the illuminance above the threshold required for color vision.

All this should not be taken to mean that the lighting conditions provided are unimportant for task performance. A simple comparison of the difficulty experienced when driving by day, by night and in dense fog is sufficient to illustrate the importance of the visual component to driving. Rather, what it does mean is that every task is unique in its balance between visual, cognitive and motor components and hence in the effect of lighting conditions on task performance. It is this uniqueness which makes the existence of a magic formula quantifying the precise relationship between lighting conditions and task performance for a wide range of tasks, impossible.

Even if a magic formula was possible, could you use it?

Let us suppose that all the above is false. A magic formula could be found which would quantify the relationship between lighting conditions and task performance, but could it readily be applied? I suggest the answer is negative. The reality of much lighting practice is that a single lighting installation serves to light many different tasks. A look around any office or workshop will demonstrate the truth of this statement. Further, most people do a range of visually-different tasks throughout each day. A consideration of the various materials you look at each day from which you extract visual information, which can range from faces to computer screens, will confirm this assertion. Furthermore, the visual characters of tasks can be expected to change over the life of a lighting installation. To appreciate this, it is only necessary to consider how the nature of office work has changed over the last decade. This inherent variability of the visual demands in many workplaces makes the idea of exactly specifying the characteristics of the lighting to be provided on the basis of optimizing task performance unrealistic. Indeed, it reduces the argument about the exact relationship between lighting conditions and task performance to one of the "how many angels can dance on the head of a pin" variety. True, it would be possible to recommend lighting conditions on a worst case basis, i.e., identify the task which is most visually difficult and recommend lighting conditions such as to ensure it would be performed adequately, but there is no guarantee that this would represent an appropriate trade-off of cost / benefits or that the lighting required for the worst case would also be suitable for easier tasks. Therefore, even if a magic formula did exist, the realities of application require a consensus about the tasks to which it should be applied, for each application.

So what use are visual performance models

If a magic formula quantifying the relationship between lighting conditions and task performance can never be achieved, and if it could, could only be applied through a consensus process, what is the value of the various visual performance models that have been developed? The answer is that even if they do not predict task performance, they do tell us what effects lighting can have on the visual performance of tasks. Such knowledge is valuable because it quantifies the maximum effect a change in lighting conditions can have as well as the relative importance of changing the task stimulus by changing the task materials and by changing the lighting conditions. Indeed, it would be possible to make lighting recommendations based on achieving a minimum level of visual performance. Such recommendations would be justified by the assertion that the business of lighting is to make things visible not to maximize task performance. Maximizing task performance is the business of management. Lighting has a role to play in maximizing task performance but it is one role amongst many and, in many modern production facilities, it is a minor role. However, lighting is a prime mover in making things visible.

Having decided that visual performance models are valuable, it is necessary to consider which model is most useful. The development of visual performance models has an interesting and converging history. Some of the earliest attempts to determine the effects of lighting conditions on task performance occurred in the 1920s (Elton 1920; Weston 1922, Weston and Taylor 1926), among them being some of the famous Hawthorne experiments (Urwick and Brech, 1965). These attempts took the form of field trials seeking a link between the lighting in a factory or part of a factory, and the output achieved. These studies, and the others that have occurred intermittently since (Stenzel 1962), did little more than demonstrate that lighting can improve task performance but the extent to which an improvement occurs, or if it occurs at all, is different for different tasks. It soon became evident that the chances of developing a comprehensive model of visual performance from field studies was remote.

An alternative approach, based on modeling the effect of lighting, was proposed by Beutell (1934) and implemented by Weston (1945). Beutell's suggestion was that the visual difficulty of each task could be characterized by the visual size and luminance contrast of the critical detail of the task, any relative movement between the observer and the task and the degree of emphasis to be given to the task in its setting. Weston (1945) took this approach and developed a standard task, the Landolt ring task, in which the observer examines an array of Landolt rings and identifies all those with a specified gap orientation. The Landolt rings forming the array can easily be varied in visual size and luminous contrast. Then the effect of lighting conditions on other tasks can be predicted by measuring the visual size and luminance contrast of the task of interest and using them to identify the matching Landolt ring task. The effect of lighting conditions on the performance of the matching Landolt ring task provides an estimate of their effects on the task of interest. Despite its crude nature, the model that resulted from this approach demonstrated the non-linear nature of the effect of illuminance and the relative importance of visual size, luminance contrast and illuminance.

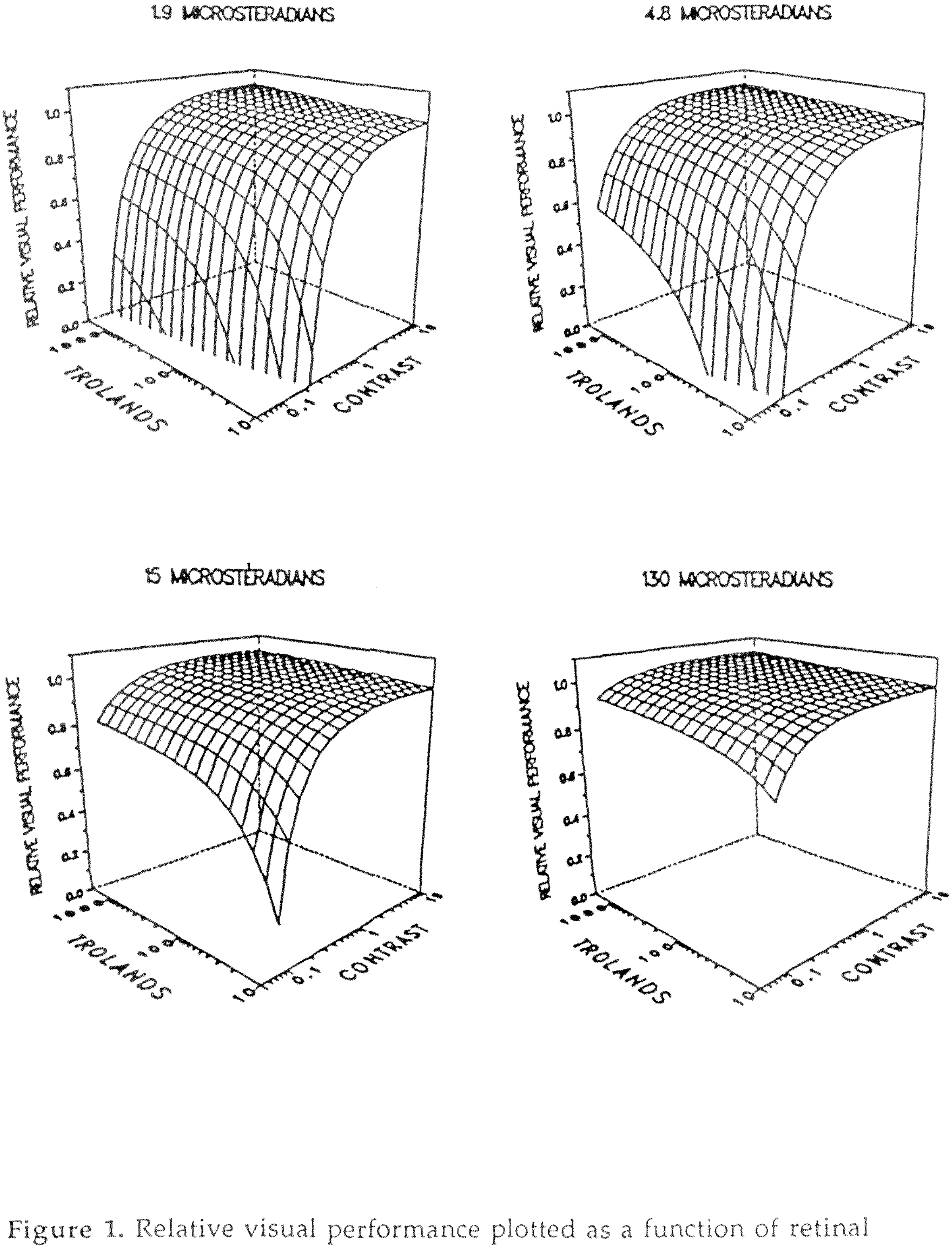
Yet another approach, was developed by Blackwell (CIE 1972). Blackwell's approach was to quantify the visibility of a stimulus in terms of its visibility level. In its simplest form, the visibility level of a stimulus is the ratio of the luminance contrast of the stimulus to the threshold luminance contrast of the same stimulus. The larger is the visibility level, the more visible is the stimulus. This idea is inherently attractive, in that it introduces the human being into the measurement of effect of lighting. Luminance contrast can be measured using a luminance meter but threshold luminance contrast can only be measured by a human being.

Having developed equipment for measuring the visibility level of any stationary stimulus, Blackwell then attempted to use this metric as a means of predicting task performance, the principle being that visibility level would act as a unifying variable to combine the effects of illuminance, visual size and luminance contrast. His first attempt (CIE 1972) appeared to work with some tasks but not with others. He revised his model (CIE 1980) but by this time it was collapsing under the exponential growth in the number of modifying factors that had to be introduced to make the model fit the experimental results. Such growth is to be expected if, as discussed earlier, each task has a different structure.

The next significant figure on the scene was Rea. Fundamentally disagreeing with the threshold basis of visibility level used by Blackwell, he returned to what is essentially Weston's approach. Smith and Rea (1979) developed their own standard task, the numerical verification task, in which observers compare two columns of twenty, five-digit numbers for discrepancies between the two columns. Using this task, a model of visual performance, the Relative Visual Performance (RVP) model, was developed for a range of adaptation luminances and luminance contrasts (Rea, 1986), based on the speed with which people could carry out the task. Clear and Berman (1990) later provided an alternative, visibility level model to fit both the speed and accuracy data obtained on the numerical verification task.

While attempts were made to minimize the motor and cognitive components of the numerical verification task, there remained a lingering doubt that the resulting RVP model would not apply to other tasks. To overcome this doubt, other experiments were undertaken using simple reaction time to the detection of a stimulus as the dependent variable (Rea, Boyce and Ouellette, 1987; Rea and Ouellette, 1988). The advantage of using reaction time for the detection of a stimulus as the dependent variable is that the cognitive and motor components of the task can be minimized, the visual component maximized and the question of the trade-off between speed and accuracy rendered moot. The results of these experiments confirmed the RVP model as a comprehensive model of visual performance. Bailey, Clear and Berman (1993) have produced a competing model using reading speed data and based on visual size rather than luminance contrast. They have confirmed the general form of the contrast-based RVP model but claim their size-based model is more accurate.

Despite the inevitable conflict between these more recent, competing models, their similarities are more striking than their differences. Both show a compressive relationship between some measure of the stimulus to the visual system and the performance of the task. As an example of such a compressive relationship, Figure 1 shows the form of the relative visual performance (RVP) surface for four different visual size tasks, each surface being for a range of contrasts and retinal illuminances (Rea and Ouellette, 1991). The overall shape of the relative visual performance surface has been described as a plateau and an escarpment (Boyce and Rea 1987). In essence what it shows is that the visual system is capable of a high level of visual performance over a wide range of visual sizes, luminance contrasts and retinal illuminations (the plateau) but at some point either visual size, or luminance contrast or retinal illumination will become insufficient and visual performance will rapidly collapse (the escarpment). It can be argued that the first duty of all illuminating engineers is to provide lighting which ensures that all tasks are being performed at the plateau level and not close to the escarpment. The existence of a plateau of visual performance, or rather a near plateau because there is really a slight improvement in visual performance across the plateau, implies that for a wide range of visual conditions, visual performance changes very little with changes in the lighting conditions. To put it bluntly, what this means is that for many visual



1.9 MICROSTERADIANS

4.8 MICROSTERADIANS

15 MICROSTERADIANS

130 MICROSTERADIANS

Figure 1. Relative visual performance plotted as a function of retinal illumination (trolands) and luminance contrast, for a fixed size of target, as measured by the solid angle subtended at the eye (microsteradians). A solid angle of 4.8 microsteradians represents the size of the digits used in the numerical verification task.(From Rea and Ouellette, 1991)

tasks, lighting is unimportant to visual performance, the visual system being flexible enough to cope equally well with a wide variety of visual stimuli.

So what use are visual performance models? The answer is that they give us a clear understanding of and a method for calculating the impact of specific lighting conditions on the visual performance of many tasks. Such calculations give us a means of knowing when we are close to the escarpment but, as explained above, this does not give us an understanding of how the same lighting conditions influence task performance. Visual performance models are valuable but they are not the magic formulae. The IESNA RQQ committee recognized this in 1991, when it published a draft report (IESNA 1991) setting out a method for selecting task illuminance. What this report suggested is a selection procedure in which the level of relative visual performance is selected by consensus and then the RVP model is used to derive the illuminance required to achieve the specified level of relative visual performance. Unfortunately, this innovative approach to making illuminance recommendations appears to have disappeared into limbo.

If a magic formula did exist, would you want to use it

A devotee of the conspiracy theory of history might suggest that one reason why the recommendations of the RQQ committee may have disappeared into limbo is that it is difficult to believe that the RVP model could be used to justify many of the illuminances recommended in the IESNA Lighting Handbook 1993. The easiest example to demonstrate this point is reading. Table 1 shows the illuminance required to achieve a RVP of 0.98, for print sizes ranging from 6 point to 10 point, for print of contrast of 0.7 on paper of reflectance 0.7, seen by people of 20 or 60 years of age, at a distance of 40.5 cm. Table 1 also shows the illuminances recommended by the IESNA Lighting Handbook (1993) for reading 6 point, 8 point and 10 point type. Given that most reading materials present in offices today are in 10 point type or larger and are printed in high contrast on white paper, these results suggest it would be difficult to justify any illuminance for commercial office buildings above 100 lx, if the recommendation were to be made on the basis of visual performance alone.

The true basis of illuminance recommendations

It would be a brave illuminating engineer who specified a lighting installation for a commercial office building which only produced 100 lx. Several studies have shown that such an illuminance would be considered too dim, uncomfortable and hence unacceptable (Van Ierland 1967, Saunders 1969, Boyce and Rea, 1994). Yet in 1917, such an illuminance would have been

Table 1: Illuminances required for a Relative Visual Performance of 0.98 for 20 year olds and 60 year olds reading 6, 8 and 10 point print of luminance contrast = 0.7, compared with the illuminance recommendations of the IES.

Print size	Print contrast	Illuminance (lx)		IES Recommended Illuminance (lx)
		20 yrs	60 yrs	
6 point	0.7	79	302	500 - 750 - 1000
8 point	0.7	38	148	200 - 300 - 500
10 point	0.7	27	101	200 - 300 - 500

regarded as excessive (Audel, 1917). Twenty years ago the average illuminance recommended for offices was 1000 lx. Today it is 500 lx. How can this be? Why should the illuminance requirements for office work change so much over the years? The true basis of illuminance recommendations can be found by considering the possible answers to this question. One possible answer is that peoples' inherent visual performance capabilities have changed over the last century but this seems unlikely given that the human visual system evolved over a much longer time period. It could be argued that the difficulty of visual tasks has increased greatly, thereby requiring higher illuminances. Again, this seems unlikely. The introduction of modern office technology has, if anything, increased the quality of printed materials. The day of the fifth-carbon copy is over. The most likely answer is that illuminance recommendations are not determined by visual performance alone but rather are subject to many other forces. These forces are both practical and political. The practical forces are matters of technology. There is no point in making illuminance recommendations which cannot be readily achieved in existing buildings with existing technology. The political forces are both financial and emotional. The financial force is the cost of providing a given illuminance relative to the benefits obtained. The emotional force is the extent to which the lighting is designed to make people comfortable and to meet their expectations. The illuminance recommendations made at any specific time and in any specific country will vary with the balance between these forces. Table 2 shows the illuminance recommended by the IESNA for general offices in each edition of the IES Handbook, the dominant lighting technology used in offices at the time and the economic/political state of the USA. Obviously this is a crude picture, especially because the IES has frequently changed its descriptions of office tasks, but the pattern of change in illuminance recommendations with the technical/economic/political balance of forces is suggestive of their importance.

Table 2: Illuminance recommendations for reading in every edition of the IES Lighting Handbook, the dominant lamp technology used in office lighting and the economic / political state of the U.S.

IES Handbook	Visual task: Reading	Illuminance (lx)	Lamp type	Economic / Political State
1947	Regular Difficult	300 500	Incandescent	Moderate growth
1954	Regular Difficult	300 500	Incandescent /Fluorescent	Strong growth
1959	Regular Difficult	1000 2000	Fluorescent	Strong growth
1966	Regular Difficult	1000 1500	Fluorescent	Strong growth
1972	Regular Difficult	1000 1500	Fluorescent	Growth
1981	Regular Difficult	200-300-500 500-750-1000	Fluorescent	Post energy crisis
1987	Regular Difficult	200-300-500 500-750-1000	Fluorescent	Post energy crisis
1993	Regular Difficult	200-300-500 500-750-1000	Fluorescent	Environment concerns

The influence of technology and economics is widely recognized in many fields, but the difference between the visual performance and visual comfort is less familiar. Figure 2 shows some results taken from a study which measured the performance of a task requiring the subjects to find a two digit number among 99 such numbers randomly distributed over a table, for different illuminances on the table (Muck and Bodmann 1961). The speed of performance increases monotonically as the illuminance increases, but the percentage of subjects considering the lighting comfortable shows a clear optimum. What Figure 2 demonstrates is that visual comfort and visual performance are not synonymous. It is possible to have an illuminance which allows a high level of visual performance but which is uncomfortable. This, in turn, suggests that visual performance and visual comfort represent two successive constraints on illuminance recommendations. The successive

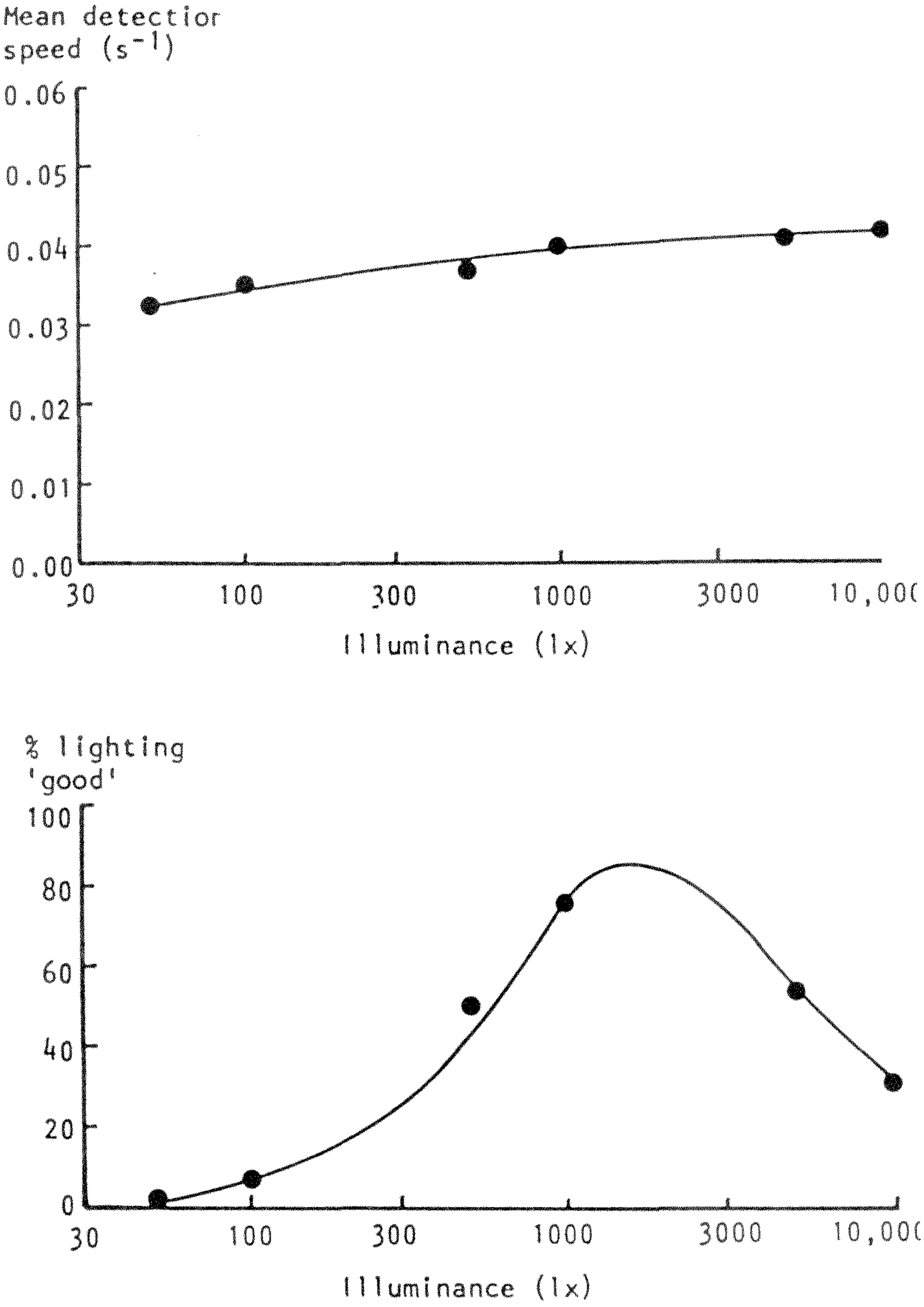


Figure 2. The mean speed taken to detect a given two-digit number from ninety-nine two-digit numbers arranged randomly on a table, plotted against the illuminance on the table. Also shown is the percentage of subjects who considered the lighting of the task "good", plotted against the illuminance or the table (After Muck and Bodmann, 1961)

constraints imposed by visual performance and visual comfort arise from the differences in what they measure. Visual performance measures what *can* be done. Visual comfort measures what is *easy* to do. In modern society, providing lighting is considered to be technically easy so only lighting which makes tasks easy to do is acceptable. Peoples' expectations form another constraint. Expectations are simply what we expect from life. Shifting expectations are a part of life. Expectations as to what constitutes good quality cars, office furniture, computers etc. have all changed over recent years. There is no reason why lighting should be exempt from this process. Put succinctly, illuminances based on visual performance represent visual needs. Illuminances based on expectations represent visual wants.

The effect of the constraints posed by visual performance, visual comfort and expectations can be illustrated by the following list of assertions, given in order of increasing stringency:

- Lighting which limits visual performance will not be comfortable or meet peoples' expectations.

- Lighting which does not limit visual performance will not necessarily be considered comfortable or meet peoples' expectations.

- Lighting which does not limit visual performance and does not cause visual discomfort will not necessarily meet peoples' expectations

- Only lighting which does not limit visual performance, does not cause visual discomfort and meets peoples' expectations will be acceptable to users.

What all this means is that lighting practices, and hence lighting recommendations, are not isolated from the dynamic flux common to most human activities. Hence, the desire to base lighting recommendations on a model of visual performance alone is doomed to failure. Understanding the effect of lighting conditions on visual performance is useful because it allows us to ensure a recommendation will not fail to meet one of the constraints, but anyone writing lighting recommendations also has to consider the other forces acting to determine the acceptability of the recommendations. As many of these forces are psychological rather than biophysical, lighting recommendations are inevitably matters of judgment and hence, in a democratic society, governed by consensus.

What should the IESNA do

Given that illuminance recommendations are subject to many forces; technical, biophysical and psychological, the IESNA has a choice to make about how it determines its illuminance recommendations. I believe the IESNA has four options:

- To maintain the status quo

- To restrict its role to that of a technical engineering society, publish information on how lighting conditions affect visual performance and visual comfort and leave the determination of the lighting actually installed in buildings to market and political forces.

- To accept that the role of lighting is to make things visible and to base its lighting recommendations on visibility alone.

To accept the reality of the many forces acting on lighting recommendations, to work to develop an understanding of how lighting conditions affect visual performance and visual comfort, to set up an open system for obtaining consensus based on data from the field and to publish lighting recommendations based on that consensus.

The first option is a recipe for decline. Any organization which is uncertain about the basis of its most widely used recommendations is in trouble. Further, for the reasons given earlier, I do not believe there is a magic formula which can be used to quantify the relationship between illuminance and task performance so to continue to search for one is a waste of resources. The second option is the safe option but it seems to me to be an abandonment of responsibility. The third option is intellectually defensible but again is a withdrawal from the lighting decision process, a process where the voices of the IESNA membership should be heard. The fourth is the most difficult option but recognizes the IESNA's leadership in knowledge and understanding of lighting. My vote would be for the fourth option, recognizing that it would not be easy. It would not be easy because whereas the effect of lighting conditions on visual performance is, in principle, determined by the capabilities of the visual system which are unlikely to change in the near future, the effect of expectations is much more volatile and is governed by a much wider range of interests. For example, it is arguable that anyone wishing to save the planet could be most effective by working to change expectations about illuminances. If this work lead to a marked reduction in illuminance recommendations, both resource depletion and air pollution would also be reduced. It is equally arguable that moving expectations to higher illuminances would result in sales of more lamps and luminaires. It is the possibility of such attempts to change illuminance recommendations that necessitates the setting up of an open process for determining consensus. The process to be used should itself be the subject of debate. There are a number of models for determining consensus ranging from a "Supreme Court" approach in which a limited number of knowledgeable individuals hear evidence about the costs and benefits of

different illuminances for each application and then issue their recommendations, to the simple application of a time-weighted average of installed illuminances. Whatever the process chosen, there are three aspects that I believe are essential requirements; the collection and analysis of data on current lighting practice and users' opinions of that practice, the evaluation of the data by informed and knowledgeable mediators and the process itself to be open to external scrutiny.

Are we alone?

In case you are thinking that the IESNA is alone in having a consensus basis for its primary recommendations, it is worth pointing out that other professional organizations face the same dilemma. The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) is in a similar position. For many years ASHRAE have published recommendations for a comfort envelope based on a measure of temperature and a measure of relative humidity. These recommendations are clearly based on human thermal comfort and carry with them considerable economic impact. The recommended conditions are much more limited than is needed simply to ensure that task performance is unlimited (McIntyre 1981). The recommended conditions have changed over time as expectations have changed. There is even an argument about the thermal comfort envelope, namely, should it be based on the thermal comfort of people wearing clothes with the same level of thermal insulation or should it be relaxed to allow for the possibility that people can be expected to change their dress according to the thermal conditions (McIntyre 1981). This may seem an arcane argument but in practice considerable sums of money are riding on the answer. The fact is that any professional society making recommendations in an area where people are the consumers of the results of its recommendations is operating in a field subject to psychology as much as biophysics. It is time for the IES to recognize this fact and organize an appropriate process to regularly monitor the consensus on illuminance recommendations.

Postscript

This paper is not the usual conference paper. It does not describe research or application. Some of the statements made are opinion rather than fact. Few are original. My basis for making them rests on nearly thirty years spent in and around lighting research and application. What I have put forward is an argument, written in order to generate an argument, about the nature of illuminance recommendations and the responsibilities of professional organizations. My hope is that these observations will clarify the basis of illuminance recommendations and lead to a more open process of determining what illuminances are recommended.

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