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# Visual performance models in road lighting: A historical perspective.

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**Abstract.** *The use of isual performance models in road lighting is an old idea: it was first proposed in the 1930' by Waldram (1938) with the Revealing Power, and by Roper and Howard (1938) who used the notion of visibility distance. The Visibility Level (VL) concept was then proposed by Blackwell (CIE, 1972), and the Relative Visual Performance by Rea and Ouelette (1988). At the turn of the 21th century, some standards have considered using the VL in order to rate lighting installations through the Small Target Visibility concept (IESNA, 2000a). However, the use of visual performance indexes in lighting standards was recently withdrawn, which raises a question: what happened?*

**Keywords:** Visual Performance, Visibility, Target Detection, Road Lighting

## 1 Introduction

This paper describes the birth, rise and possible fall of the visual performance concept in the field of road lighting in the last 100 years. The presentation is both chronologic and thematic, but the main outline is chronologic, for a better understanding of the complex course of the road lighting community evolution. After this historical overview, a discussion is proposed, attempting to draw insights for the future of visual performance in road lighting.

Although this paper is restricted to road lighting, it may be considered by researchers interested in other lighting applications, firstly because some of the main concepts associated to visual performance have first been proposed for interior lighting, and secondly because the main results of this paper address the way lighting engineers build their standards, which obviously apply to all fields.

Of course there are strong differences between outdoor and indoor lighting, in addition to the obvious one that the light sources and typical background luminance are qualitatively different (mesopic vision is relevant in outdoor lighting, not indoor). In outdoor lighting, the performance is associated to the locomotion task, with or without a vehicle, so that the visual task depends on locomotion (Gibson and Crooks, 1938). More specifically, the purpose of road lighting is usually associated to a road safety performance (Box, 1971), which cannot be directly related to indoor performance for usual tasks.

In contrast with previous reviews on outdoor lighting (Waldram, 1950; Fotios and Gibbons, 2018), the present paper focuses on visual performance models, considered as a conceptual tool available for lighting engineers. The starting point is that while vision science and lighting technology have made impressing progress during the last century, the rationale for using visual performance in road lighting evaluation did not tag along.

This is not supposed to be a pessimistic view. I hope this paper may help the lighting community to better understand the current obstacles to a broad use of visual performance models for road lighting design and evaluation. This analysis is needed to overcome these obstacles in the future — or to accept that they will stand here for a while. Therefore, this paper can be seen as a journey in the past for a better understanding of the roots of current problems, rather than a state of the art<sup>1</sup>.

The sources for this review mainly come from the two main lighting engineering journals, *Lighting Research and Technology* and *Leukos*<sup>2</sup>, as well as publications from the CIE Division 4. Some influential papers from vision

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<sup>1</sup>With this in mind, I will not go into the details of computational formulas.

<sup>2</sup>Formerly *Transactions of the IES (London)*, and the *Journal of the IES*.

science are also considered (e.g. Blackwell (1946)), as well as some reports from CIE Divisions 1 and 3 (CIE, 1972, 1981a, 1992a).

Such a review over a very long period of time is highly subjective, in the sense that the list of references says more about the author of the paper than about the history of the field. This is understood, and in this selection, I did not try to consider the best or more influential papers, but those which help best understanding the visual performance concept, its evolution and problems. One side effect is that technical issues about factors which are known to impact the visual performance, such as mesopic vision (Rea et al., 2004; Alferdinck, 2006; Goodman et al., 2007), disability glare (Holladay, 1926; CIE, 2002), gaze allocation (Inditsky et al., 1982) and visual noise (Paulmier et al., 2001) are out of the scope of this paper.

## 1.1 Why focus on visual performance?

Visual performance refers to a human performance for a visual task, such as target detection, object recognition or motion perception. It may be expressed in various units, such as the success rate in the task (in %), or the Reaction Time (RT).

Before going back to the beginning of modern lighting engineering, I need to highlight the differences between the visual performance approach and the usual approach in lighting engineering. The first one has an implicit causal model and aims at predicting the benefits one may expect from an installation, while the second makes correlations.

In most fields of engineering sciences, such as designing a lamp, or a bridge, the causal approach is preferred: from the knowledge of the physics of the system, a model of its functioning can be proposed, as well as figures of merit (if you think of a lamp, the lumen/watt ratio, colour fidelity index, half life duration, and so on). The physics of the system is mostly under control, and the performance can be predicted from the physical characteristics of the system and of the manufacturing process. A physical model not only allows predicting the performance of the lamps that are currently being manufactured, it also allows guessing the performance of new lamps. This kind of predictive model is not perfect (some parameters are not under full

control), but it helps the designer guessing what may happen in new situations. In lighting engineering, a visual performance model is needed in such predictive models.

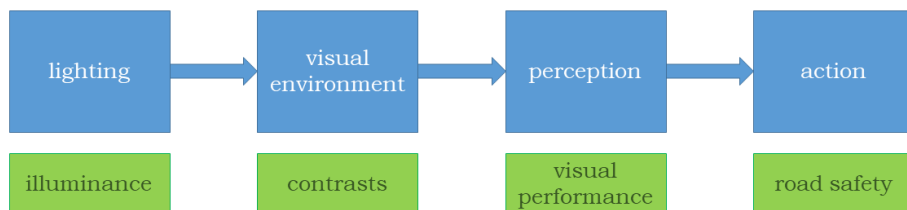


Figure 1: The predictive approach in lighting engineering needs an estimate of the visual performance. A figure of merit of an installation can be related to some level of performance in a task (such as locomotion) through a cascade of predictive models.

This approach is described in the pipeline of Fig. 1. On the road, the lighting installation modifies the visual environment of the driver; his perception of the road depends on this modified visual stimulus. Other physical factors impact the visual environment, such as the materials (e.g. the road surface, the windshield) and the weather conditions (fog, rain). Then, a given visual stimulus may lead to a different level of visual performance depending on the driver’s visual capabilities (contrast sensitivity, acuity, etc.) and behaviour (especially the gaze direction). Finally, the task performance (the driving performance) does not depend on visual performance only, but also on sensori-motor skills, such as the reaction speed. Visual performance is necessary, but it is not enough for a safe travel.

Specifically, in the case of lighting, a reverse model of this causal approach would allow estimating the visual performance from the task performance, the required visual environment from the visual performance, and the lighting design from this visual environment. Then, from a task performance threshold, it would be possible to select an appropriate lighting design to ensure a figure of merit.

Looking at Fig. 1, it is clear that such a model is far from realistic: the real world is closer to the situation depicted in Fig. 2 where additional

factors tend to modify the output of each of the intermediate models. In other words, the complexity of real world situations is difficult to include in a series of boxes that can be studied in controlled situations in the lab.

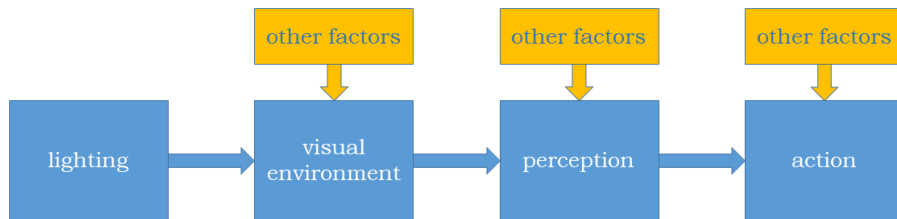


Figure 2: Perturbations of the causal pipeline may result in erroneous predictions.

If we are to take the causal approach seriously in road lighting, the “other factors” of Fig. 2 need to be under control: their impact must be estimated. They can be either included as factors in the model (e.g. the fog density, the age of the driver) or discarded if their impact is considered negligible. In theory, such additional models can be build, but in practice, they may need a lot of data that are not easy to collect. We will see that the lack of control of some of these factors is one of the main reasons for the unsuccessful story, so far, of visual performance in road lighting.

The correlational approach sounds more familiar. Lighting intallations are designed from illuminance and sometimes luminance values which are compared to thresholds provided in standards. This approach does not pretend to predict any level of performance (Fig. 3), as no notion of performance is considered.

Of course, correlation is not causality: whereas the sales of ice creams and sunglasses are highly correlated, it cannot be said that people wear sunglasses *because* they eat ice creams. But correlations take into account most of the “other factors” that the predictive pipeline cannot control. Indeed, any experimental data about task performance (e.g. road safety) can be described with an *ad hoc* model: there is no need here to even understand what factors are at work.



Figure 3: The engineering approach, through correlations.

There is a price to pay: such correlations cannot be generalized without caution to situations that were not considered in the reference data. This is the main problem with this empirical approach, especially to address a changing world, with new technologies, new environments, new behaviours and new needs: correlations are not robust outside the range of the empirical data they are built on. For instance, the predictive model proposed by Newton (the law of universal gravitation) allowed discovering Uranus as a new planet: this might not have happened if astronomy had only been based on correlations.

The causal approach was soon considered in road lighting (Waldram, 1938), and several authors have proposed specific visual performance indexes, with the idea that a lighting installation should guarantee some level of visual performance to the drivers, allowing them to anticipate and make the right decisions in time. The story of these proposals is at the heart of this paper, with the challenge of turning an intuitive idea into an operational tool, easy to measure and useful for lighting quality assessment.

## 1.2 The visual task of night driving

The driving task is an easy one – millions of people do it everyday – but a complex one. It has been described with a varieties of subtasks, and most models organize these subtasks in a hierarchical pyramid with three levels (Allen et al., 1971; Michon, 1985; Ranney, 1994). The first and most critical level refers to micro-performance (the operational, or control level), controlling the vehicle heading and lateral position, with a very short time scale (ms). The second level refers to situational performance (the manoeuvring, or tactical level), such as speed control<sup>3</sup>, overtaking, obstacle avoidance, and other short-term decisions. The time course at this level is in seconds.

<sup>3</sup>Speed control is sometimes included in the first level.

The macro-performance level (the planning, or strategical level) is the highest in the hierarchy and refers to trip planning and way finding; the time scale is longer. In this pyramid, lower levels have priority: when you see a pedestrian crossing the street, you stop looking for direction signs. These three-level models refers to the perception-cognition-action loop from cognitive psychology. They elaborate on the driver's need to anticipate the near future in dynamic situations (Endsley, 1995).

The CIE (1992b) has discussed the *fundamentals of the visual task of night driving*. The visual needs associated to each driving subtask was considered, and the associated visual information needs was described. The report focused on night driving, showing how visual information is modified at night. The purpose of this analysis was to understand how artificial lighting can restore the driver's visual performance and improve road safety.

In addition to the three levels of the driving task, the CIE (1992b) describes the visual task of driving with a sequence of three visual functions: attention, detection and recognition. Visual attention is needed in order to capture the relevant items in the field of view; then, these items need to be detected and recognized, in order to convert a visual signal into an information. This information is then processed, and the cognitive part of the loop may lead to some specific decision, then to an action. As the perception-decision-action loop takes some time, no reaction is instantaneous.

What kind of visual information is needed for each driving subtask? For control subtasks, such as maintaining the heading and staying in one's lane, the first requirement is to have a good estimate of one's position and speed with respect to the road infrastructure. The driver needs a clear view of the road surface and especially of the road markings, in order to anticipate the possible change in road curvature (CIE-PIARC, 1988; COST-331, 1999; Schnell and Zwahlen, 2000). He also uses visual features from the optic flow to estimate his own speed and control the heading (Gibson, 1979). Specific visual cues are needed, such as the vanishing point, the tangent point, or the vehicle ahead (Donges, 1978; Land and Lee, 1994; Lappi, 2014). The vehicle control is described as a continuous sensorimotor loop : the driver does not make critical decisions at some points in time, but continuously compares the planned and the actual heading (regulation from visual feedback).



In terms of visual information, vehicle control uses the optic flow, which takes inputs from the entire visual field. At night, with the headlamps only, a large part of this visual field disappears, which probably weakens the capture of the associated visual features. Things are better under road lighting, but the field of view is still narrower than what it is by day. Unfortunately, it is hazardous to rate this kind of visual performance independently of the locomotion task, because perception and motion are highly intricated, as the optic flow appears only when you move. Thus, the driving performance can hardly be derived from pure psychophysics, and existing studies tend to use driving simulators (Wilkie and Wann, 2002; Kountouriotis et al., 2012; Okafuji et al., 2018).

With respect to situational subtasks, decisions are to be taken, mostly in relation to the traffic, pedestrians and road hazards; the attention-detection-recognition pipeline is required. In the case of hazard detection, attention is particularly needed, because one cannot guess where, nor when, a hazard will occur. In most decision-making subtasks, the whole pipeline needs to be run through before any relevant information can be processed. But in the case of hazard detection, which is maybe the most important in terms of road safety, a reaction may begin as soon as something is detected (and localized), that is, before full recognition of what it is. In all these situations, detection is a key step, which is why road lighting and automotive lighting designers have soon considered target detection as the key index of visual performance that can be restored by artificial lighting at night.

Finally, the visual performance associated to navigational subtasks has been mainly considered in terms of finding and reading direction signs. In this case, there is a continuum between detection and recognition, in such a way that information can be collected sequentially. Indeed, you first detect something on the roadside, then recognize it as a road sign, then extract a first level of information based on the shape and color, and finally – in the case of a direction sign – read a city's name.

A common feature of all descriptions of the driving task is that most information the driver needs is visual (Sivak, 1996). Some part of this visual information disappears or is degraded at night, and artificial light is needed to restore the level of visual performance needed for high-speed locomotion.

It appears from the above description that visual performance cannot be subsumed into a single visual task, such as target detection. Scanning the visual environment, extracting visual features from the optic flow, discriminating and recognizing specific targets, reading, are also important part of the driver's visual task.

However, the only visual performance which was investigated in some depth by the lighting community so far is target detection. As a starting point, this is a good choice: detection is a mandatory step before object recognition and reading, the most important one in hazard detection, and thus a key performance for road safety. Moreover, on the road at night, the quantity of visual information is lower, in such a way that visual search is to some extent made easier than by day.

### 1.3 Overview

Science is cumulative: each generation improves the corpus of common knowledge, in such a way that the History of Science is mainly anecdotal. Indeed, as scientific theories and data continuously improve, one just needs to know the current state of the art.

However, although lighting engineering uses scientific inputs, it cannot be fully described as a science. Scientific knowledge is only one among many criteria that practitioners need to take into account, including technical and economical constraints, in such a way that the standards result from a negotiation between experts (Boyce, 1996). Thus, lighting engineering is not exactly a cumulative field, and looking back into the past may help us grasp current issues. This is why the historical perspective proposed here may contribute to a better understanding of the visual performance concept.

Section 2 of this paper describes how visual performance was introduced in the road lighting community. In the 1930', the causal pipeline was considered (Fig. 1), leading to a series of investigations about the driver's visual performance at night (Dunbar, 1938; Roper and Howard, 1938). The first general model of visual performance for road lighting was proposed by Waldram (1938). The WWII, with the blackout in the UK, was not a good period for road lighting research. With respect to visual performance, it was

up to the 60' a mixed period, with very few studies in road lighting, but important progress in vision science Blackwell (1946); Campbell and Robson (1968). A new interest for visibility is obvious in the 1970', with the first analytical model from the Commission Internationale de l'Eclairage (CIE, 1972) based on Blackwell's work, as well as important field experiments at night (Gallagher and Meguire, 1975; Hills, 1975b).

Section 3 shows that the eighties were, to some extent, the golden age of visual performance in lighting, especially with the diffusion of the Visibility Level (VL) concept in the second CIE model (CIE, 1981a). The VL was introduced to the road lighting community by Adrian (1987, 1989), and was also adopted for road markings (Bry and Colomb, 1988; CIE, 1988). Meanwhile, Rea proposed an alternative model of visual performance, based on reaction time (Rea, 1986; Rea and Ouelette, 1988, 1991).

As the theoretical concepts reached the world of practitioners, new questions emerged (Lecocq, 1991; Ménard and Cariou, 1994; Güler and Onaygil, 2003; Mayeur et al., 2010) about the target, the background and the reference task, in such a way that the 1990' can be seen as the skeptical turn of the century (Section 4).

We show in section 5 how the VL was introduced in several guidelines (CIE, 1995b; AFE, 2002). In the US, the Small Target Visibility (STV) concept (derived from the VL) was proposed as an option in a road lighting standard (IESNA, 1990, 2000a). But visual performance indexes were soon removed from these standards (CIE, 2010; CEN, 2014; IESNA, 2014). This can be seen as a failure of the visual performance approach in road lighting, and maybe of the causal approach of outdoor lighting design. Hopefully, this is not the end of the story, but an opportunity to ask: what went wrong?

It is the normal course of science that apparent failures are questioned in order to improve our understanding, and possibly to open new avenues. Indeed, new and promising approaches of visibility have been proposed since the beginning of this century, not very popular yet, but maybe initiating a renewal of interest for this issue (Section 6). The Revealing Power (RP) concept proposed by Waldram (1938) was coupled to the VL concept by Narisada et al. (2003); Visual performance is now seriously considered in

pedestrian lighting for target detection (Fotios and Cheal, 2013); an image processing computational model of the visibility has been proposed (Joulan et al., 2011a). Also, the prototypes of Imaging Luminance Measurement Devices (ILMD) developed in the 1990' (Rea and Jeffrey, 1990; Brusque and Hubert, 1996) have been replaced by easy-to-use measurement tools (Boucher et al., 2017).

The Discussion (Section 7) makes a balance sheet of what we have learned and what is missing in terms of scientific knowledge and in terms of practical conditions, before visual performance models can be promoted for road lighting design. Some speculations regarding the most probable ways to go there are proposed.

## 2 The Age of Pioneers

The importance of road lighting for road safety was emphasized as soon as 1914 at the Convention of the National Electric Light Association in Philadelphia, but at that time, the focus was on collisions between motor and horse-drawn vehicles. This type of accidents disappeared as the civilization of automobile emerged in the 1920'.

### 2.1 First Steps towards Visual Performance

Cobb and Moss (1927) were among the first to diffuse vision science results to the lighting community<sup>4</sup>. They showed how the visibility of a simple pattern (two vertical bars) depends upon four main factors: size, contrast, background luminance and presentation time. They introduced typical experimental protocols from psychophysics, as well as the notion of a visibility threshold: A target of luminance  $L$  against a background  $L_b$  produces a luminance difference  $\Delta L$ . The target is visible if  $\Delta L$  is greater than the visibility threshold  $\Delta L_{th}$ . Their main result was a substitution principle: the visual performance of observers can be under control if, when some factor is

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<sup>4</sup>Lighting engineering and vision science only have weak links. Among others, Mark Rea suggested that lighting engineers should have a better understanding of vision science concepts (Rea, 1982). His main idea was to use, as a bridge between the two communities, a concept familiar to both: visual performance.

degraded (say the size of details), another one is improved (e.g. the background luminance), and such a substitution can be quantitatively described.

A British Standard (BS) for road lighting was released as soon as 1927. At that time, the main goal of road lighting was to illuminate the road as much as possible, rather than to control the luminance uniformity<sup>5</sup>. Several classes of lighting installations were proposed based on geometric and photometric parameters (luminaire height, inter-distance, etc.). Although this was not in the mind of the authors of the BS, the minimal illuminance on the road surface tended to be considered as a figure of merit of an installation, with obvious drawbacks.

Waldram (1950) has described the main milestones in road lighting between 1920 and 1950<sup>6</sup>. One of these was the test, in 1928, of 52 lighting installations in Sheffield (UK), some in line with the BS, some not. This real life experiment was a playground for a lot of discussions based on facts; it was realized, for instance, how important road surfaces are; it was also realized – it is the focus of this paper – that visibility is a key concept for road lighting.

In the 1930', visibility was considered a figure of merit for road lighting, and especially the visibility of hazards on the road (Halvorson, 1936). The consensus was that hazards are seen in *silhouette* mode, that is, in negative contrast. Thanks to road lighting, hazards are seen earlier by the drivers, which improves anticipation. Without road lighting, the area where the driver can collect visual information is restricted to the headlamp beam.

The visibility of hazards was considered both in road lighting and automotive lighting. Wood (1936), at this time head of the IESNA, argued that road lighting was needed as a countermeasure for road safety at night. He based his claim on quantitative data about daytime vs nighttime accidents<sup>7</sup>, and

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<sup>5</sup>The quantification of glare was already taken into account, thanks to the recent work by Holladay (1926).

<sup>6</sup>The idea of milestones was taken from Wilson (1942).

<sup>7</sup>Wood (1936) explains that during the Great Depression, several road authorities decided to switch off the road lighting on their network to save money. A few years later, it was switched on again, because of night-time accidents.

argued that automotive lightings is mainly designed for urban conditions, where pedestrians are seen in positive contrast, whereas on the road, they appear as dark silhouettes, and their visibility depends on the contrast with the road surface.

Meanwhile, Roper and Howard (1938) proposed that the design of automotive lighting should be tuned to the visibility distance it provides to the driver. They argued that in order to be able to see hazards on the road, two conditions are required: they should be visible at a distance, and the driver should not be distracted by other potential targets. The vehicle's headlamps contribute to both, producing high contrasts on road hazards, and focusing visual attention into the beam. Unfortunately, even if the physics of the scene may be under control, visual attention cannot. Roper and Howard (1938) have proposed an objective measure of visual performance on the road: the visibility distance. They do not mean the distance where obstacles are visible, but the distance where they are seen, that is, when the driver is aware of their presence. They introduced the observer's "consciousness factor" as the ratio of the two. This factor was estimated with a field experiment, where the drivers were not aware that a dummy would appear on the road. In a second lap, they knew it, and the two detection distance could be compared.

The importance of visibility for lighting performance was well understood in the 1930', but there was no general theory, and not many data. Some pioneers investigations have been conducted, such as Wilson's with a wooden cat target (Wilson, 1942). The road surface photometric properties was also investigated, either on the road or in the lab (Cohu, 1936). According to Waldram (1950), the aim of road lighting changed in this period: an installation was no longer considered as a series of lamps each illuminating a specific part of the road, but rather from the perspective of the driver, as a luminance field. There was a shift, from a focus on illuminance to an increasing interest for luminance.

## 2.2 The Revealing Power

In 1937, the British Department of Transport published a standard on road lighting with a focus on road safety. This BS was based both on discussions with experts and on experimentations. Visibility was not considered, but

it was addressed at the same time by Waldram (1938) who proposed the concept of Revealing Power (RP). Although his initial goal was to propose a road visibility index for lighting design, the final result was an index of the ability of the lighting installation to “reveal” a potential hazard.

The Revealing Power of the road is the proportion of objects that a driver will see; the proposed approach is, then, probabilistic. The RP depends on the contrast, and thus on the luminance of both the object and the road surface. These luminances, in turn, depend both on the illuminance from the lighting installation (vertical illuminance for the object, horizontal for the road surface), and on the photometric properties of the materials. The probability distributions of these quantities is needed in order to estimate the RP of an installation.

Another factor is needed: the visual performance of the drivers for a given contrast. A road experiment was conducted by Dunbar (1938) in order to know the contrast threshold required for a safe driving. The participants drove at night under various illumination conditions, and were asked if the visibility was safe enough to drive at 30 mph (48 km/h).

For practical reasons, Waldram (1938) considered a reference situation, with a planar, uniform, lambertian target, and an observer situated at a reference position. From the distribution of vertical illuminance on the road and the reflection coefficient of the target, its luminance could be computed depending on its position on the road, and thus the distribution of the target luminance. The distribution of reflexion factors among real objects was also estimated (Smith, 1938; Moon and Cettei, 1938), which made possible to estimate the luminance of targets encountered on the road. The luminance of the road surface was computed from the horizontal illuminance and the photometric properties of the road, leading to the contrast distribution of potential hazards under a given illumination design. Finally, these contrasts were compared to the contrast threshold relevant for night driving (Dunbar, 1938), and the proportion of visible targets could be computed. The last step would have been to propose RP thresholds for various speeds and various types of roads, but this did not happen.

## 2.3 The Dark Age

With the WW II and the blackout in the UK, road lighting design was removed from the priorities of public policies; the 1940' was considered by Waldram (1950) as the retreat milestone – as far as road lighting was concerned. From Beutell (1934)'s proposals however, the British IES worked on a *lighting code*, leading to a proposal by Weston (1943). This approach included a reference visual task<sup>8</sup>. An illuminance level was proposed for any given task, based on a measure of the task difficulty. The key idea, allowing to compare various visual tasks, was the similarity of the relation between illuminance and performance across tasks. The performance improves with illumination, but at some point, a plateau is reached. Thus, the IES recommendation was that the lighting design should allow 90% of the maximal performance.

## 3 The Golden Age

The main theoretical weakness of Waldram's model was the human vision model (Dunbar, 1938). Although it was derived from drivers at night, and thus could claim an ecological validity with respect to the task, it was flawed. Firstly, visual performance were not collected: the model was based on subjective judgments, with the implicit assumption of a correlation with visual performance. Secondly, the data corresponded to cars, roads and lighting systems typical of the 1930' in England.

In the 1970', the status of visual performance changed. The *Commission Internationale de l'Eclairage* (CIE, International Commission on Illumination) promoted the use of psychophysical methods for the estimation of visual performance, avoiding these problems. Meanwhile, a series of road experiment occurred, with the aim of collecting true visual performance of target detection at night. The so-called Ford model can be considered as a part of this collective effort, even if it was focused on automotive lighting (Bhise et al., 1976). After 30 years of lethargy, this period can be described as the “golden age” of visual performance in road lighting, both from a theoretical and experimental points of view.

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<sup>8</sup>The “*simplest imaginable*”, or basic task: any change in the task makes it more difficult.



### 3.1 The CIE visibility models

The common element in the visibility models proposed by Bhise et al. (1976), Dubuisson and Paumier (1987) and Adrian (1989) is the fact that they all elaborate from experimental data on the visibility of uniform disks provided by Blackwell (1946), either directly or from the CIE visibility models (CIE, 1972, 1981a). Even today, Blackwell’s paper is still a reference, because of the quality of the data, and also because of the personal effort that Blackwell himself made towards the lighting community, especially through the CIE. His 1946 paper was the basis of the Visibility Level (VL) concept proposed by the CIE to cope with the variety of visual tasks.

#### 3.1.1 Blackwell’s 1946 paper

More than two billions psychophysical data were collected from 19 trained young women, all with good vision. The training lasted between 6 month and one year until the data was considered stable. In the end, half a million data was used for statistical analysis. At this time, the participants were “veterans”, in the sense that their sensitivity and the repeatability of their data was unusually good.

Several experiments allowed to estimate the contrast threshold  $C_{th}$ , for various values of the target angular size, adaptation luminance and presentation time, usually with a forced choice paradigm ( $C_{th}$  can be derived from  $\Delta L_{th}$ :  $C_{th} = \Delta L_{th}/L_b$ ). The contrast threshold corresponding to 50% chance of target detection was estimated from the data, together with the standard deviation<sup>9</sup>.

The first experimentation addressed the adaptation luminance<sup>10</sup> (between 0 and 343  $cd/m^2$ ) and the target size (between 3.6’ et 121’), in positive contrast. At high background levels, the contrast threshold was found independent of the background luminance (Weber’s law). For small targets, the detection only depends on the target’s angular size (Ricco’s law). The second

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<sup>9</sup>The contrast threshold for 90% or 99% of target detection can be computed from the SD ( $\sigma$ ), which depends on the experimental conditions. Considering that  $\sigma$  is roughly constant, Adrian (1989) computed a constant factor to convert the 50% threshold to a nearly 100% threshold (see Section 3.2).

<sup>10</sup>The adaptation luminance was, in this case, also the background luminance.

experiment was in negative contrast (dark background), with the main result that the threshold is nearly the same in positive and negative contrasts, except for large targets in the dark. In these two experiments, the participants had 6 seconds to decide whether they saw a target; in a third experiment, they were given a longer response delay.

### 3.1.2 CIE report n°19

Report n°19 from the CIE is the first overview of visual performance in relation to lighting parameters (CIE, 1972). Based on Blackwell's data<sup>11</sup>, a visibility model was proposed, and the Visibility Level (VL) concept was first introduced. The goal of this report was to translate the vision science literature, which is hardly useful in practical situations, into something that could help lighting engineers. More specifically, it proposed a predictive model of visual performance, with input parameters easily available from *in situ* measurements. The model could be applied in a variety of reference tasks, both in interior and outdoor lighting scenarios.

With respect to the performance index, Cobb and Moss (1928) only considered the rate of success in a visual task, while Weston (1945) also included the response time. According to the CIE, these two studies led to very similar results, in such a way that it was possible to use the detection rate alone as the index of visual performance<sup>12</sup>.

A theoretical framework was proposed. The main idea is that the experimental conditions contribute to two factors which allow predicting the visual performance: the signal *intensity*  $I$ , and the *sensitivity*  $S$  of the observer. The perception  $P$  of a stimulus only depends on these factors:  $P = I \times S$ . The signal intensity of a target is related to the luminance contrast with the background, while the sensitivity is, of course, the contrast sensitivity<sup>13</sup>. Thus, the main contribution of CIE report n°19 was to sum up a long list of

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<sup>11</sup>H. R. Blackwell was the chairman of the Technical Committees which produced the CIE reports 19 and 19.2.

<sup>12</sup>From the same comparison, Rea focused on response time alone (see Section 3.3).

<sup>13</sup>This model is in line with the main signal processing theory at the time (Shannon, 1948), including the ideas of a signal modulation on the transmitter side, and a modulation sensitivity on the receiver side.

factors<sup>14</sup> into only two.

These two factors allow rating a lighting installation from the visibility of a target under this installation. The target properties contribute to the contrast intensity (leading to the “equivalent contrast”), while a contrast threshold is selected in order to ensure a given level of visual performance<sup>15</sup>.

The contrast threshold depends on the background luminance through a standard curve, the *Relative Contrast Sensitivity* (RCS), which is associated to a standard visual task<sup>16</sup>. The RCS is a normalized version of the inverse of the Contrast Sensitivity ( $C_{th}$ ); it is given as a function of  $L_b$ , with a reference value set to  $L_b = 100cd/m^2$ :

$$\text{RCS}(L_b) = \frac{C_{th}(100)}{C_{th}(L_b)} \quad (1)$$

The nice point is that the RCS is considered independent of the target<sup>17</sup>, which means that it is possible, from this curve, to compute the contrast threshold for any task at any background level from the threshold, for the same task, at another background level.

Visibility depends on the size and shape of the target, on contrast polarity, etc. The Contrast Rendering Factor (CRF) includes all these factors, and modulates the RCS into an *effective* signal intensity. Similarly, when the background luminance is not uniform (typically because of a glaring source), a veiling luminance is computed, leading to the Disability Glare

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<sup>14</sup>Among these factors, Blackwell (1946) intensively explored the “four factors” highlighted by Cobb and Moss (1928) (see Section 2), while Lamar et al. (1947) addressed the target shape. The luminance uniformity around the target was studied by Finch (1959) and Chorlton and Davidson (1959), the coloured contrast by Eastman (1968a). The effect of glare was described by Holladay (1927) and Stiles (1929a,b), while Boynton et al. (1970) addressed transient glare.

<sup>15</sup>Three levels of performance are described: the visibility in the usual sense, which corresponds to optimal viewing conditions; the visibility when visual search is taken into account; and the true visual performance, which also depends on individual factors (training, fatigue, motivation, etc.).

<sup>16</sup>The detection of a disc 4' in diameter, displayed 200 ms in central vision.

<sup>17</sup>In the next CIE report, the dependence of the RCS on the target size and on the observer’s age was considered (CIE, 1981a), see section 3.1.3.

Factor (DGF). Finally, as one cannot keep the gaze on the target, and because the background is not fully homogeneous, a factor is added to take the lack of visual adaptation into account: the Transient Adaptation Factor (TAF). The effective RCS can be computed from the Reference RCS through:

$$\text{RCS}_{eff} = \text{RCS}_{ref} \times \text{CRF} \times \text{DGF} \times \text{TAF} \quad (2)$$

In real situations, the estimation of these factors is difficult, but one can use a visibility-meter. Luckiesh and Moss (1935) were the first to propose such a measurement device, which reduces the target visibility until an observer is at visibility threshold. Other such devices have been proposed since (Simmons and Finch, 1953; Eastman, 1968b; Blackwell, 1970). These tools change the target contrast without changing the background luminance: while a veiling luminance is added (lowering the target contrast but increasing  $L_b$ ), the direct illumination is lowered, in such a way that  $L_b$  is roughly kept constant.

The Visibility Level (VL) is defined in CIE report n°19 as the ratio between the actual contrast and the contrast threshold  $C_{th}$ , that is, the contrast allowing a detection probability of 50%:

$$\text{VL}(C) = C/C_{th} \quad (3)$$

VL can be computed from the RCS, and in practice, it can be directly estimated with a visibility-meter<sup>18</sup>.

The report finally tested its predictive model on available data with good results. This included data from Weston (1945) on Landolt rings, and from Bodmann (1962) and Boynton and Boss (1971) on visual search.

### 3.1.3 CIE report n°19.2

Report n°19 was quickly reconsidered by the CIE, which led to report n°19.2 (CIE, 1981a,b). The same reference task was used, but the VL was emphasized as the “*intensity*” of the visual stimulus, bridging the gap between stimulus characteristics and visual performance.

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<sup>18</sup>It is recommended to estimate a visual performance in two steps, in an integrating sphere: first in the Reference condition, then in the modified conditions (glare, etc.) with a visibility-meter. Only if this two-step approach is not convenient (for instance, on the road) it is proposed to consider the VL in the real task conditions.

The first step of the new model is to estimate the VL. This first applies to the Reference task, then to the actual task (such as reading a text, or a road sign), using modifiers as in Eq. 2. In report n°19, an analytical model was proposed for the RCS. In report n°19.2, it was realized that the RCS is not unique, and parameters have been introduced in the analytical formula in order to take the size of the details and the age of the observers into account.

From the Reference task, the VL for any other task  $T$  can be described as a function of  $C$  with a S-shaped psychophysical curve. The contrast allowing 50% detection in task  $T$  can be considered a measure of the task difficulty.

**Visual performance.** The VL is the input which allows predicting the true factor of interest, the visual performance (VP), which can be described in terms of speed or accuracy (or a mix). How the VP depends on VL is described with log ogives:

$$VP = f(\log(VL)) \quad (4)$$

One important result, looking at the data, is that all these ogives have the same sigmoid shape. Thus, they can be described from their inflexion point's position and slope only. Moreover, it was found that one single parameter is enough, and that this parameter can be understood in terms of the task difficulty (it is thus named  $D$ ).

**Processes.** A step forward, with respect to report n°19, was to take into account oculomotor processes, in addition to the pure visibility process (Bodmann, 1973). The log ogives of Eq. 4 describe the visibility process  $P_1$ , while two oculomotor processes should also be considered:  $P_2$  is associated to the control of visual fixations, while  $P_3$  is involved in saccadic control. Of course, any task also includes some non-visual components, which are merged in a  $P_4$  process. Unfortunately, the relative weight of these processes in the global performance depends on the task, and can only be estimated *a posteriori* from the data. This is what Blackwell actually did; he found that the more difficult the task, the more  $P_2$  and  $P_3$  are involved.

In the final model of report n°19.2, the task is described by three functions which fit into each other. The RCS computes the visibility of the target

( $P_1$ ); the Relative Visual Performance (RVP)<sup>19</sup> computes the visual part of the performance ( $P_1$ ,  $P_2$  and  $P_3$ ); and finally the Relative Task Performance (RTP) gives the full performance, taking the  $P_4$  process into account. With respect to  $P_1$ , in addition to the CRF, DGF and TAF modifiers proposed in the previous version of the report, an Age Factor (AF) is added.

**Experimental data.** The proposed model was tested against 20 datasets available at that time (18 indoor and 2 outdoor<sup>20</sup>). For each task, two parameters needed to be tuned: the task difficulty  $D$  and the weight of non-visual processes. Although the visual tasks and the visual performance indexes were very different across datasets, the CIE model was surprisingly good. In outdoor conditions, it was suggested that a direct measure of VL may be more convenient than a full derivation from the Reference visual task.

These two reports, 19 and 19.2, can be considered both as a success and a failure. A success, because a scientific, causal approach is proposed, predicting the visual performance in any visual task, in terms of the lighting parameters (along with parameters specific to the task). The visual performance is mediated by the visibility, which subsums all aspects of the stimulus. It was a nice move, which gave rise to a lot of discussions in the lighting community. On the other hand, some of the model's parameters (such as the task difficulty) cannot be directly estimated. Moreover, the model is uneasy to implement because of the number of parameters. This issue has been addressed by later authors in road lighting through a global *field factor*, which subsums most of these parameters.

## 3.2 Adrian's model

The use of the VL in an outdoor context was promoted by Adrian (1989). But before his influential paper, some authors have considered the VL as an index of visual performance in driving. For instance, Hills (1976) compared it to the Visibility Index (VI)<sup>21</sup>; Dubuisson and Paumier (1987) proposed a modified version of the CIE model for the assessment of tunnel lighting; and

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<sup>19</sup>Be careful that these words also denote Rea's model (Rea, 1986).

<sup>20</sup>The study from Gallagher and Meguire (1975) is reported in Sec. 3.4.1; Another one, with 8 drivers, repeated the same drive with and without optical filters (Economopoulos, 1978).

<sup>21</sup>Cf. section 3.4.2.

in a previous paper, Adrian himself considered using the VL as a figure of merit of road lighting, in relation with Visual Acuity (Adrian, 1987).

### 3.2.1 Acuity and Visibility

He used a critical scenario with a 20-cm square target on the road, 86-m ahead of the driver, which is in the range of a stopping distance<sup>22</sup>. The rationale was that the driver needs to detect a hazard early enough to stop safely.

Previous data from experiments on target detection (Berek, 1943; Blackwell, 1946; Adrian, 1969) allowed modelizing the impact of background luminance, target size<sup>23</sup>, presentation time and age on the contrast threshold. Adrian estimated the contrast threshold for 99% detection from the threshold for 50% detection, which is not an easy problem<sup>24</sup> because the answer depends on the task.

The Visual Acuity (VA) is a well known index of visual performance, associated to the vision of small details. Below  $30\text{cd}/\text{m}^2$  (which includes night driving conditions), Adrian remarked a correlation between VA, as measured with Landolt rings, and  $\log \Delta L_{th}$ . Thus, VL and VA, target detection and target discrimination, are correlated<sup>25</sup>. As  $\Delta L_{th}$  depends on  $L_b$ , the ratio VL/VA can be considered as a function of  $L_b$ . Also, a VL threshold can be estimated for a given value of VA<sup>26</sup>. In the abovementioned driving scenario, with  $L_b = 1\text{cd}/\text{m}^2$ , he found  $\text{VL}_{th} \simeq 7$ . In the range of luminance relevant in road lighting,  $\text{VL}_{th}$  was estimated between 15 and 20 in order to reach  $\text{VA}=0.9$ <sup>27</sup>.

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<sup>22</sup>The angular size of the target was  $10'$ , with contrasts between 0.2 and 0.3. Based on oculomotor data collected in driving situations, the observation time was set to 0.2 s (Narisada and Yoshikawa, 1974; Zwahlen, 1985).

<sup>23</sup>Above some critical angle  $\alpha_c$ , Weber's law applies and the detection threshold  $\Delta L_{th}$  does not depend on the target size; for smaller targets,  $\alpha^2 \Delta L_{th}$  is constant (Ricco's law).

<sup>24</sup>This issue was first raised by Hills (1976).

<sup>25</sup>VL can be written either as  $\Delta L/\Delta L_{th}$  or as  $C/C_{th}$ .

<sup>26</sup>For instance, a minimal VA is required for a driving licence.

<sup>27</sup>This value is consistent with Gallagher and Meguire (1975): above  $\text{VL}=15$ , the drivers had no collision with the obstacles (see section 3.4.1).

### 3.2.2 Adrian’s 1989 model

In Adrian’s classical model,  $\Delta L_{th}$  is also estimated from psychophysical data (Adrian, 1989). The output of the model is the  $\Delta L_{th}$  allowing a 99.93% probability of contrast detection, for a uniform target on a uniform background, in the lab.

As this model was based on data collected with long stimulus durations, a term was added to take into account shorter observation times. Another term ( $F_{CP}$ ) takes the contrast polarity into account: it is set to 1 in positive contrast, with a specific formula in negative contrast (dark target, that is, silhouette mode). This is because the target is more easily seen in negative compared to positive contrast<sup>28</sup>. Finally, an age factor  $AF$  is estimated, leading to:

$$\Delta L_{th}(\alpha, L_b) = 2,6 \times AF \times F_{CP} \left[ 1 + \frac{a(\alpha, L_b)}{\Delta t} \right] \times \left[ \sqrt{\Delta L_{\infty}(L_b)} + \frac{\sqrt{\phi(\alpha, L_b)}}{\alpha} \right]^2 \quad (5)$$

where  $\phi$  represents the visual performance under Ricco’s law, and  $\Delta L_{\infty}$  under Weber’s law ( $\alpha$  is the target size)<sup>29</sup>.

## 3.3 The Relative Visual Performance

During the same period, an alternative model was proposed by Rea to predict the visual performance of industrial workers from lighting parameters (Rea, 1986). Although it was not meant for outdoor lighting, it is worth mentioning here because it involves a very general approach of visual performance, especially the second version of the model (Rea and Ouelette, 1988, 1991): it is arguably more suited for road lighting than for indoor lighting (CIE, 1992a).

The visual task representative of an office work was first to compare two lists of numbers: the participants had to detect the differences. The success rate and the task duration were recorded as two aspects of the performance.

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<sup>28</sup>In previous studies, the contrast polarity was considered negligible (Blackwell, 1946; Herrick, 1956; Judd and Eastman, 1971; Hills, 1976).

<sup>29</sup>Three formulas are proposed for  $\Delta L_{\infty}$  and  $\phi$ , depending on the range of  $L_b$ .



For a given background luminance, the visual performance depends on the contrast, following a S-shaped curve; this stands whatever the definition of visual performance, success rate or the inverse of the task duration. This led Rea to consider the task duration as a better proxy for visual performance: it is more accurate than the error rate<sup>30</sup>.

The S-shaped curve was understood by Rea as a supra-threshold sensory compression, because performance reaches a plateau at some level (Weston, 1943). When the stimulus is below this level, the performance is dramatically degraded: down the escarpment, it falls near zero. This curve was described with a Naka-Rushton equation<sup>31</sup>:

$$\text{VP} = \frac{1}{T} = \frac{1}{T_{min}} \frac{(L - L_{th})^n}{(L - L_{th})^n + k^n} \quad (6)$$

$T_{min}$ ,  $n$  and  $k$  are estimated from the data (they depend on  $L_b$ ). Rea then proposed a Relative Visual Performance (RVP), the ratio of this VP over an optimal VP value (taken in optimal background conditions, for a contrast equal to 1).

A later version of this model used a target detection task instead of a reading task (Rea and Ouelette, 1988). The performance still is a RVP, that is, a ratio of reaction times<sup>32</sup>, and the data is still described with a Naka-Rushton curve, with  $n = 1$ . The two versions of the RVP have been compared (Rea and Ouelette, 1991), showing that the two basic tasks are equivalent for the measure of visual performance, at least with respect to reaction time. One interesting feature of this model is that it includes very few free parameters, and no correction factor.

### 3.3.1 Visibility as a spatial filter

Hills (1975a, 1976) used a spatial filter to compute the visibility of a target on the road (see also Section 3.4.2). He used a vision science model (Fry,

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<sup>30</sup>This is true for tasks with very few errors.

<sup>31</sup>From the classical Naka-Rushton curve, which describes the response of a biological system as a function of the stimulation (Naka and Rushton, 1966).

<sup>32</sup>It was also realized that the motor response time is uncompressible, leading to a minor modification of the formula.

1965) where the visual performance results from the spatial convolution of the visual input (the target) with a function of the form:

$$f(r) = f(0) \left( \frac{r_m}{r + r_m} \right)^3 \quad (7)$$

where  $r$  is the target radius, and  $r_m$  a critical radius which depends on the experimental conditions<sup>33</sup>. The target is detected if integral  $I$  reaches some threshold<sup>34</sup>:

$$I = \iint_{r,\theta} f(r) r dr d\theta \quad (8)$$

From the literature under road lighting (Dunbar, 1938; de Boer et al., 1951) and on unlit roads (Roper and Howard, 1938; Moore, 1952) and from his own data (Hills, 1975b), he could estimate the  $f$  function (Eq. 7)<sup>35</sup>. Ogives are given for  $\Delta L_{th}$  as a function of the target area, for various  $L_b$  values.

This model, built on experimental data in driving situations, was compared to psychophysical models (Stiles and Crawford, 1933; Blackwell, 1946; Herrick, 1956). When  $L_b < 3cd/m^2$ , laboratory models were found to underestimate the visual performance, and Hills speculated that this might be due to a better use of peripheral vision in night driving situations<sup>36</sup>.

### 3.4 Closed Road Tests

In the 70', while analytical models of visual performance were derived from psychophysical data, several road experiments tried to understand the relation between these theoretical models and driving performance.

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<sup>33</sup>The Contrast Sensitivity Function (CSF) was considered too complex, and Hills preferred this “single-channel” model (see section 6.2). Other such models were available at that time: Blackwell and Smith (1958) used corrective factors, while Fry (1947) proposed to use sensitivity data from rectangles rather than disc targets. Beurle et al. (1968) proposed a two-step model: the first one has a central symmetry, while the second uses a line detector.

<sup>34</sup>The absolute threshold ( $L_b = 0$ ) was first modelled (Nolan, 1957; Fry, 1965); Beurle et al. (1968) extended the formula to  $L_b > 0$ .

<sup>35</sup>The dependence of the critical angle  $r_m$  on  $L_b$  is taken from psychophysical data (Blackwell, 1946; Beurle et al., 1968).

<sup>36</sup>Although Hill’s model was published in *Lighting Research and Technology*, it was relatively unnoticed by lighting practitioners, or even by the CIE and the IESNA.

### 3.4.1 Streets of Philadelphia

Gallagher and Meguire (1975) conducted an important experiment on a closed road in Philadelphia, collecting visibility data at night under street lighting. The participants had to detect a dark grey cone without hitting it; the distance to the cone at the moment of detection (time-to-contact, TTC) was measured and compared to various visibility indexes, for various lighting conditions and target positions. The authors proposed a Visibility Index (VI), based on the RCS promoted by the CIE (1972):

$$VI = C \times \frac{RCS \times DGF}{5.74} \quad (9)$$

This index was compared, among others, to the contrast  $C$  alone, and to the effective visibility  $VL_{eff}$  (CIE, 1972).

The best correlation between the TTC and a visibility index was with the contrast, which may be surprizing at first sight. Contrast may be good for a correlation, with a single target, but cannot be a predictive index of the driving performance<sup>37</sup>, which is what lighting engineers needs. This is why the authors recommended the use of the VI as a predictor of the TTC, taken as a road safety index (the correlation was better with VI compared to  $VL_{eff}$ )<sup>38</sup>.

Finally, Gallagher and Meguire (1975) proposed that a lighting installation should be tuned in such a way that 85% of the population can see the target in due time.

### 3.4.2 Australian trilogy

In a serie of three papers, Hills proposed an alternative visibility model (Hills, 1975a,b, 1976). The visibility of a variety of targets has been assessed in a driving situation at night, and various visibility indexes have been considered. The study included three steps: in a first paper, psychophysical models were discussed and a formula was proposed (Hills, 1975a); then, a

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<sup>37</sup>It is well known, for instance, that the target size impacts the detection distance.

<sup>38</sup>Due to the inter-individual variability, all correlations were weak. The higher value for  $R^2$  was 0.3.

driving experiment was conducted on a closed road (Hills, 1975b) and a general model of the visibility for night driving was proposed (Hills, 1976). One of the key issues was the choice of the “field factor” between the visibility threshold in laboratory conditions and in driving situations.

Hills’ model uses a spatial convolution of the visual stimulus with a spatial filter; it is described in details in Section 3.3.1. In the closed road experiment, Hills (1975b) estimated the filter’s parameters, as well as the field factor for targets relevant in driving scenarios (uniform discs and pedestrian dummies). Participants were on the passenger seat<sup>39</sup>; they had to say when the target was *just visible*, then when it was *just obvious*. The targets size and luminance were manipulated, as well as the speed and the presence of road lighting. The data roughly followed Ricco’s law, and – more important to him – his own model had a good fit with the data (Hills, 1976).

### 3.4.3 Surround lighting

A field experiment has been conducted at night in low beams by Van Bommel and Tekelenburg (1986) with true pedestrians as the targets – a rare feat. The driving task was to drive between cones, and two factors were manipulated: the road lighting intensity and the surround lighting. The results were clear: increasing the road surface luminance improves the visibility distance, but only with a surround lighting. Road lighting focusing on the road surface does not help seeing the pedestrians on the roadside.

## 4 The devil is in the detail

It became clear in the 80’ that the CIE visibility model could be relevant as a figure of merit for road lighting, and might be included in standards. The main attempt in this direction was the Small Target Visibility (STV) concept. Meanwhile, lighting engineers raised a series of questions about the relevance of the VL in practical situations, showing that the way from a theoretical model to practice is not an easy one.

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<sup>39</sup>The experimenter drove at constant speed.

## 4.1 The STV

The STV was an attempt to convert the VL into a figure of merit for a lighting installation. Keck proposed that an installation could be assessed with the mean value of the VL, using a reference target situated at various positions on a regular grid between two luminaires.

The idea was tested by Ménard and Cariou (1994) in two ways: first with respect to the VL, then to the STV. The relevance of the VL to rate the visibility of targets under road lighting was tested with square targets of 20 cm in height, with a 20% reflectance, positioned on a special track where the luminaires could be manipulated in height and inter-distance. They were placed at one of 21 positions on the grid. Participants were 83 meters away from the targets, following Keck's design; they had to rate the target's visibility on a 5-points scale<sup>40</sup>.

The correlation between the computed VL and the visibility rating was good, but the authors lacked enthusiasm for the STV concept, because it is a mean value. Therefore, a contrast inversion on the road surface, leading to a bad lighting and to nearly invisible targets, may be rated with a good mean VL (and a good STV value), whereas it should be rejected in terms of lighting quality. Ménard and Cariou (1994) proposed that the STV should not be employed alone, but with an index of the VL uniformity.

This issue was also investigated by Güler and Onaygil (2003) in a simulation, where the VL of simulated targets was computed on the STV grid for various lighting configurations. The computation followed report 115 of the CIE (1995b), and the VL threshold was set to 7 (Adrian, 1987, 1993; Adrian and Gibbons, 1995; Lecocq, 1997). The simulations included various types of road lighting; the height and inter-distance of the luminaires was also varied, leading to more than 1000 simulated installations.

Report CIE n°115 proposes either to rate an installation in terms of luminance, or with the STV (CIE, 1995b). Güler and Onaygil (2003) systematically compared the two criteria, and noted when a given installation

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<sup>40</sup>Ménard and Cariou (1994) collected subjective estimates of the visibility, just like Dunbar (1938).

was accepted by one criterion and not by the other<sup>41</sup>. They found that installations rejected by the luminance criterion are not always rejected by the STV. A lot of such situations were found with VL values  $< 1$  (invisible targets), leading the authors to follow Ménard and Cariou (1994) and to propose adding a luminance uniformity and a VL uniformity criterion to the STV concept.

## 4.2 Limits of the Visibility Level

### 4.2.1 Eccentricity

In terms of vision science, the VL also raised specific problems. CIE report n°95 followed the reports n°19 and 19.2 mentioned above and made an overview of vision science concepts, discussing their possible use in a more general model of visibility (CIE, 1992a). Specifically, the limitations of the CIE model in terms of target eccentricity were discussed.

According to report 95, the probability of target detection directly depends on the VL (CIE, 1992a). It is given by frequency of seeing curves:

$$p(\text{VL}) = 1 - 2^{-\text{VL}^a} \quad (10)$$

Unfortunately, this only happens in foveal vision; for a target eccentricity  $\theta$ , the detection probability  $p(\text{VL}, \theta)$  cannot be derived from VL and  $\theta$  only, it also depends on the target shape, texture, etc., in such a way that no general formula can be proposed, which is a bad point for the usefulness of the VL concept.

Can the target eccentricity be included in a visual performance model? Inditsky et al. (1982) considered the target detection probability during one fixation as a function of the target eccentricity, and named it the “visibility lobe”. It can be measured for any task, and CIE report n°95 describes the visual performance from these visibility lobes rather than from the VL, because the VL is restricted to central vision. A “visibility angle”  $\omega_e$  is defined, and can be compared across illumination situations:

$$\omega_e = 2\pi \int_{\theta} p(\text{VL}, \theta) \sin \theta d\theta \quad (11)$$

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<sup>41</sup>In CIE report n°115, using the luminance criterion, a longitudinal uniformity  $U_l = 0.7$  is needed, while using the STV,  $U_l = 0.2$  is considered enough.

### 4.2.2 3D shape of the target

Adrian's model uses planar uniform targets, because most psychophysical data (including Blackwell's ones) use planar uniform targets. But hazards on the road are seldom flat. Lecocq (1991) proposed using a 3D target shape, a sphere, which he suggested is more relevant for driving applications.

He started from a paradox raised by the STV concept. He first thought that the minimum VL on a grid would be a better index of the lighting quality, compared to the mean VL. Indeed, dangerous installations tend to create areas where some targets become invisible. But he realized that for a given installation, the lighter the (flat) target, the smaller the mean VL, until some contrasts become positive. The paradox is that the figure of merit (the STV) is degraded, while it is common sense that under road lighting, light targets are easier to see than dark ones. The next step was to notice that on the road, the light targets are seen because of their 3D shape, which creates local contrasts (shading).

Lecocq then considered a simple 3D target, a sphere. For visibility computations, he did not use psychophysical data on sphere detection, but the usual planar model on uniform small parts of the sphere. To do that, the sphere was approximated with a polyhedron with 50 faces. The luminance of each face was computed from the lighting design characteristics and from the orientation of the face.

How can we estimate the visibility of a polyhedron from the visibility of each face? There is no theoretical solution available to address this general problem<sup>42</sup>, and Lecocq proposed to split the faces into two subsets: the dark and the light ones (with respect to the background luminance). If a target is not visible when considered planar (using Adrian's model), the visibility of each of the two sub-targets is computed. If none of these is visible, the internal visibility (light vs dark sub-targets) is computed. Finally, the target visibility is the higher of four estimates: the global visibility, the visibility of the sub-targets with respect to the road surface, and the internal visibility

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<sup>42</sup>Kokoschka (1985) considered the visibility of a heterogeneous target (CIE, 1992a). He derived a formula to compute its visibility from the CIE model in one specific case, with homogeneous sub-targets of equal areas.

(auto-visibility). This approach allows considering visible some targets that would have been considered invisible by Adrian’s model. A few years later, this model was refined with the additionnal constraint that each face has the same apparent area, as viewed from the driver (Lecocq, 1999).

These ideas have been tested by Bacelar et al. (1999). A panel of observers were asked to rate the visibility of spherical targets (as in Ménard and Cariou (1994)), and this rating was compared to the visibility computed with Lecocq’s formula, under various lighting designs<sup>43</sup>. The results were similar to those in 1994 with planar targets, meaning that Lecocq’s formula makes sense. Moreover, the spherical targets with low visibility were more visible than the corresponding flat targets, meaning that the two types of targets are not equivalent to assess the merit of a lighting installation<sup>44</sup>.

#### 4.2.3 2D shape of the target

The disc itself raises some questions. Does the visibility of a target only depend on its apparent surface? If so, the psychophysical data of disc detection is enough to estimate the visibility of targets of any shape. This issue was first addressed by Lamar et al. (1947, 1948) in vision science, but the road engineers community began to tackle the problem in the 1980’, when road markings visibility became a key issue. For instance, the CIE-PIARC (1988) proposed a formula to convert a road marking into an “equivalent disc”, allowing to use the CIE (1981a) visibility model.

Going one step further, Schnell and Zwahlen (1999) proposed a visibility model computed from psychovisual data on rectangular targets. In their formula, an additionnal parameter is added, the ratio of the width and length of the rectangle. More recently, Crescenzo et al. (2019) collected psychophysical data on squares, and compared the relative merit of the different models in the range relevant for road markings at night.

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<sup>43</sup>The luminance values on the sphere were computed, not measured, because measurements on a sphere is not easy.

<sup>44</sup>Lecocq (2000) also tested his idea on the reduced scale (1:15) model of a 225-m road section with road lighting; the small luminaires could be tuned in various configurations.



#### 4.2.4 Background uniformity

In previous lab experiments, the targets are presented on a uniform background. On the road however, the luminance background is not uniform. Its heterogeneity depends on the road surface and on the lighting design, to the point that luminance uniformity is considered a quality index in several standards.

Brémond et al. (2011) have estimated the quantitative bias of this approximation in driving conditions. They used data from a road experiment (Mayeur et al., 2010), where participants had to drive under road lighting. The target detection distances were recorded, while photometric measurements were made on the road surface around each target (and on the targets), from the driver’s point of view.

From four measurement points around each square target, three estimates of  $L_b$  were computed: the mean of the four luminance values, the luminance below the target, and the luminance which results in the higher contrast with the target<sup>45</sup>. The computed VL was compared to the target detection distance: a good correlation would mean that the VL is a good index of the visual performance. The best fit was when  $L_b$  was computed from the highest of the four contrasts. It was also possible to compute the VL at the moment of target detection, and again, this method had the best ratings.

#### 4.2.5 Field factor

The purpose of the field factor is to bridge the gap between the visual performance in the lab, with the task of target detection only, and the visual performance on the road. It is a black box which includes all factors that are not considered in the lab; the discussions mentioned above have entered the black box with respect to the driver’s gaze (Sec. 4.2.1), the target (Sec. 4.2.2 and 4.2.3) and the road surface (Sec. 4.2.4).

Buyyukinaci et al. (2017) have considered the relevance of the VL, exploring other dimensions: the colour temperature and the target reflectance, as well as the VL ability to discriminate the classes of road lighting installations

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<sup>45</sup>With a uniform background, these three estimates are equal.

in the European Standard EN 13-201. Also, their study contributed to the literature about the field factor for road lighting, which is generally estimated between 7 and 15 (de Boer et al., 1951; Janoff, 1992; Lecocq, 1997; Adrian and Gibbons, 1995). Various lighting designs were implemented on an experimental road, and luminance maps were taken with a photo-luminancemeter. A laboratory experiment was then conducted, where various stimuli were displayed against these luminance maps on a calibrated screen, and the participant's contrast thresholds were collected<sup>46</sup>. When  $VL > 7$ , all participants detected all targets (whatever their color and reflectance), and this result was consistent across lighting designs.  $VL = 7$  was thus confirmed as a threshold for road lighting.

A different line of research was conducted by Mayeur, focusing on the discrepancies between the target detection task in the lab and when driving. Her investigations involved several experiments, each one focusing on one or two specific differences between the lab and the driving conditions. These experiments went from laboratory studies close to the reference psycho-visual task to a true driving task, step by step, getting closer and closer to the driving task. The first lab experiment investigated the effect of the target eccentricity, and more importantly of the task complexity, on the detection performance (Mayeur et al., 2008). The visual performance was compared when target detection was the only task, and when the participants also needed to perform a sensori-motor task, namely directing a point along a circuit in a videogame<sup>47</sup>. A second lab experiment showed the effect of the optic flow and of the scene semantics on the target detection performance (Mayeur et al., 2009). In a third experiment, on a test road, the participants had to detect a "small target" on the road surface (Mayeur et al., 2010). They repeated the task as a driver and as a passenger, which allowed understanding the effect of the driving activity alone. An additional static condition showed that the visual performance was better in the static than in the passenger condition, and better in the passenger than in the driver condition, even in this low demanding driving task (no traffic, no curve, and under road lighting).

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<sup>46</sup>This experimental design is similar to Lecocq's (Lecocq, 2000).

<sup>47</sup>This task was selected because it was considered close to driving in terms of the perceptive and cognitive processes involved.

More recently, Chen et al. (2018) conducted a driving simulation experiment, where the performance of target detection was compared in static and dynamic conditions<sup>48</sup>, in relation with the computed VL; the effect of the mental workload on the field factor was confirmed.

#### 4.2.6 Visibility distance

One claim of the visibility approach to lighting design is that the VL is a proxy for visual performance. Brémond et al. (2013) have challenged this proposal, comparing the computed VL in a simulated driving situation with a more intuitive index of visual performance, the detection distance. When a driver approaches a target, the VL of the target changes (because its angular size increases, and because it enters the headlamps beam). Considering the VL at the moment of target detection ( $VL_d$ ), they argued that if the VL is a proxy for the visual performance,  $VL_d$  should be roughly constant whatever the target and the driving scenario. Moreover, the mean  $VL_d$  would be an estimate of the field factor.

An experiment was conducted in a driving simulator, with various targets<sup>49</sup>. The participants drove on a highway at night, with simulated headlamps. The detection distance was recorded, and the target visibility was computed from a calibrated image of the scene at the moment of target detection. The mean  $VL_d$  was compared to the mean detection distance, showing that the detection occurred near the same VL value, whatever the target. The field factor was close to 7, which strengthens the previous literature on this topic.

### 4.3 Discussions on the RVP

In the CIE model, the visual performance is not precisely defined: it can be a success rate (accuracy), a reaction time, or a mix. The RVP model uses the reaction time alone, and does not consider the accuracy data (Rea and Ouelette, 1988). Clear and Berman (1990) noticed that speed and accuracy are correlated, and that this correlation can be modeled, leading to a better performance prediction. They have considered the time needed to reach a

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<sup>48</sup>In the dynamic condition, the vehicle speed was fixed.

<sup>49</sup>Cars, pedestrians, road signs, and a STV “small target”; some were coloured and textured, some were grey and uniform.

given accuracy level, as a function of the visibility. With this in mind, they have reconsidered Rea's data about the numerical verification task (Rea, 1986). Their predictions were better than those from the original paper, with fewer free parameters.

Another line of discussion came from the CIE. The CIE visibility model was updated in 1981, and Rea's RVP concept was proposed in 1986 (CIE, 1981a; Rea, 1986). Given that the RVP was grounded on a completely different rationale, the CIE decided to consider the RVP, which resulted in CIE report n°145 (CIE, 2002). The main purpose of this report was to rate the merit of Rea's model for interior lighting<sup>50</sup>.

The reference data – and the reference performance model – in the CIE report n°145 was taken from Weston (1945), who measured the visual acuity with Landolt rings in various experimental conditions. He proposed an index  $P$  of the visual performance which includes the reaction time  $T$  and the success rate  $R$ :  $P = R/T$ . A formula computes  $P$  as a function of the target contrast, detail size, background luminance and observer's age.

The CIE compared Weston's model to several psychophysical models of visual performance (Simonson and Brozek, 1948; Muck and Bodmann, 1961; McNelis, 1973; Loe and Waters, 1973; Smith and Rea, 1978), including those from Rea and Ouelette (1988, 1991). It was found that the RVP is not suited for visual tasks where visual acuity is involved, and thus, for interior lighting assessment.

Unexpectedly, the CIE models were not considered in this report. Yet, the reference task in reports 19 and 19.2 is close to Rea's task of simple reaction time. Considering road lighting, where the usual reference visual task is hazard detection, Rea's model may be more relevant than Weston's to rate the merit of an installation<sup>51</sup>.

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<sup>50</sup>Remember that the first version of the RVP used a typical interior lighting task as the reference task (the numerical verification task).

<sup>51</sup>CIE report n°145 describes two types of visual tasks, needing two types of visual performance models, because the visual pathways and the underlying physiological mechanisms are different. In an acuity task, and each time the vision of details is involved, the signal processing follows the parvo-cellular visual pathway of the brain; in simple detection tasks, the magno-cellular pathway is more involved. This may be the physiological

This was understood by Rea et al. (2010), who proposed a software for the computation of visibility on the road in various conditions of illumination. As an example of the potential benefits of their approach, an intersection was simulated with various scenarios; the visual performance was computed using the standard STV target.

## 5 The Rise and Fall of visual performance?

As visual performance indexes became an opportunity for lighting engineers, they have been more and more discussed. It is not enough to have a scientific rationale, there is a need that, as a figure of merit, these indexes are correlated with what experts use to rate as good lighting installations. In the end of last century, the STV was considered an option in some lighting standards, but this situation did not last long, and the illuminance soon came back as the main criterion.

**Visual performance in road lighting standards.** The CIE published a number of recommendations for road lighting. The visibility first appeared in report n°115 (CIE, 1995b). This report is cautious about visual performance. Adrian’s model is presented and discussed, together with the STV methodology, but the CIE does not recommend using the STV as a figure of merit, because of the lack of consensus on the target, and on the concept itself<sup>52</sup>.

In previous reports, the recommendations used illuminance and luminance thresholds (CIE, 1965, 1977), while in the next edition of report n°115, the visibility concept almost disappeared (CIE, 2010). It was no longer part of the recommendations, even if several visual performance concepts (VL, STV, Revealing Power) were mentioned in passing, with a reference to the CIE TC<sup>53</sup> 4-36<sup>54</sup>.

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mechanism explaining that the performance models are not the same with stimuli of high and low spatial frequencies.

<sup>52</sup>The mean VL value on a grid was not broadly accepted, see above Sec. 4.1.

<sup>53</sup>TC: Technical Committee.

<sup>54</sup>This TC on *Visibility Design for Roadway Lighting* did not publish any report so far.

Meanwhile, the IESNA proposed, as an option, to use the STV concept in road lighting as early as 1990, with a threshold on the mean VL (IESNA, 1990); this proposal was validated in the final document (IESNA, 2000a), but removed in the next version (IESNA, 2014).

In short, some attempts were made at the turn of the century to use visual performance models in road lighting standards, but this time is over. Considering the conclusions of CIE report n°145, where Rea’s approach of visual performance was also discarded (CIE, 2002), one may feel that visual performance is slowly disappearing from the agenda.

**Back to Illuminance?** A recent review emphasizes the lack of interest of the lighting community for visual performance concepts. Fotios and Gibbons (2018) have highlighted some of the limitations of current standards in outdoor lighting (road lighting and lighting for pedestrians) in terms of scientific foundations, leading them to ask for a revision of these standards, which should be more evidence-based.

However, their rationale does not consider the “causal approach” of science as a goal. They advocate, instead, the engineering approach described in Fig. 3, looking for correlations between illuminance and various quality indexes of outdoor lighting. The claim that lighting engineering should be more scientific does not include a claim for a causal model of the system under study.

## 6 Alternative avenues

In contrast with this pessimistic view, original approaches have emerged to obviate the problems of previous visual performance models.

### 6.1 The Revealing Power 2.0

The Revealing Power uses, as input, the probability distribution of the reflectance factors of the potential hazards (see Sec. 2.2). When Waldram (1938) proposed this concept, he used statistical data about british textiles (Smith, 1938), and an empirical model of visual performance on the road (Dunbar, 1938)

The concept was reconsidered by Narisada and Karasawa (2001), both in terms of the distribution of reflection factors, and in terms of the vision model. With respect to reflection factors, a measurements campaign was conducted with objects taken on the road, in Japan. Surprisingly enough, the distribution was quite close to Smith’s data. The innovative proposal (which deserves the “2.0” label) concerns the vision model. Whereas Dunbar (1938) based his model on the judgments of people driving under road lighting, Narisada and Karasawa (2001) and Narisada et al. (2003) used the VL as proposed by the CIE (1981a).

As a result, it was possible to draw iso-visibility lines on the road surface in specific lighting scenarios, that is, lines of equal VL for a standard target. The proportion of the road surface which is above a given level of VL can then be estimated: it is the Revealing Power of the installation.

Unfortunately, in these papers, the probabilistic aspect of the RP concept is lost, because the distribution of the target reflectance is not directly considered as an input. But the main point is that this revival of the RP suggests a new avenue of researches for a full probabilistic approach of the visual performance, based on a psychophysical vision model.

## **6.2 Contrast sensitivity**

Up to now, the visibility models presented in this review were grounded on a reference task: the detection of a uniform target on a uniform background (Blackwell, 1946; CIE, 1972, 1981a; Adrian, 1989; Rea and Ouelette, 1991). Some of the discussions raised by the visibility concept were associated to these reference experimental conditions (e.g. Sec. 4.2.2 and 4.2.4). Using gratings as the target is an alternative approach<sup>55</sup>.

### **6.2.1 The Contrast Sensitivity Function**

In the 1960’, evidence was given from physiology and from experimental psychology that the visual system is similar to an image processing device,

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<sup>55</sup>Remember that Cobb and Moss (1928) already used gratings as their reference stimuli. But at that time, their benefits were not fully understood.

extracting local features at various spatial scales. More specifically, the contrast sensitivity with respect to any target can be derived from the contrast sensitivity to gratings (Enroth-Cugell and Robson, 1966; Campbell and Robson, 1968). Indeed, the detection threshold for any object can be derived from the Contrast Sensitivity Function (CSF) of the human eye, which includes the detection threshold for gratings at all spatial frequencies. This can be understood as a decomposition of the visual signal in Fourier components, followed by a variable threshold on each of these components (Watanabe et al., 1968; Kelly and Magnuski, 1975; Barten, 1999).

In short, it should be possible to predict the visibility of a target on any background from the CSF of the human eye. This is not possible from contrast sensitivity data collected on uniform targets: the visibility of a complex target cannot be derived from the visibility of simple uniform targets.

### 6.2.2 Edge visibility

The report n°95 from the CIE (1992a) introduced the CSF to the lighting community. It suggested to ground visibility computations on vision science knowledge about the optics of the image forming on the retina, on the Modulation Transfert Function (MTF) of the eye (van Nes and Bouman, 1967), and on the photo-receptors sensitivity. The visual signal is processed in the retina in such a way that the eye can be compared to an optical filter feeding a parallel computer.

The idea that visibility is due to the contrasts on the edges of a target, not to the target itself, explains that edge detection is the core of image processing models for target detection (Marr and Hildreth, 1980; Marr, 1982), where contrast sensitivity is described with linear spatial filters<sup>56</sup>. But this intuitive idea is not much considered in lighting engineering.

It has been suggested that the visual system resembles a bandpass filter (Sekuler, 1975; de Valois and de Valois, 1988), and there was a debate about whether it can be described as a single filter (as in Hills' model, see section

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<sup>56</sup>The good point with linear filters is that one can use the linear systems theory (Wandell, 1995).



3.3.1), or as a filter bank with various spatial scales (Campbell and Robson, 1968)<sup>57</sup>. In the multi-channel hypothesis (several filters), how are these channels combined? According to Koenderink and van Doorn (1984), if the signal exceeds some threshold on any of the channels, the edge is detected, which can be described with a **Max** operator.

In a target visibility model based on the detection of gratings, the reference data is the CSF. A number of authors have proposed experimental data and analytical models of the CSF in various experimental conditions, beginning with Berek (1943). According to the CIE report n°95, the most important contributions are those from Overington (1982) (Oracle model), Zuidema et al. (1983) (quantum concept), Koenderink and van Doorn (1984) (multi-channel model) and Ginsburg (1986). Ginsburg's model takes into account many aspects of the visual task: the target characteristics (size, shape, contrast), background properties (luminance, noise), display device, observer (position, VA, accommodation) and task (presentation time, task difficulty). Some of these factors are shared with the CIE models, but the theoretical backgrounds are different.

The Oracle model belongs to the signal detection theory: the detection threshold depends on the Signal-to-Noise Ratio (SNR) with respect to the information sent to the receiver (the perceptive system). In this model, the performance threshold (for a given task) is associated to a specific SNR level. A model of the SNR is needed, as well as a SNR threshold associated to various visual tasks (the SNR level is associated to the task difficulty)<sup>58</sup>.

What is the difference between different visual tasks, such as detection, recognition and discrimination? One of the first answer was in terms of spatial frequency: Johnson (1958) proposed specific thresholds of the spatial resolution in order to achieve each of these specific visual tasks. Ginsburg (1986) was in line with this idea and suggested that task complexity is asso-

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<sup>57</sup>The number of spatial scales is estimated between 4 and 6 (Wilson and Bergen, 1979; Wilson et al., 1983).

<sup>58</sup>In peripheral vision, the surface of the visual cortex associated to a given solid angle decreases with eccentricity, which can be described with a cortical magnification factor (Cowey and Rolls, 1974). Overington (1982) used this factor to estimate the visual performance outside the fovea.

ciated to the need for higher spatial frequency information<sup>59</sup>. For instance, if the usual CSF is associated to the target detection task, different sensitivity functions may be associated to other, more complex, visual tasks (Ginsburg and Easterly, 1983).

### 6.2.3 Image processing of the visibility

From this vision science and computer vision literature, it was realized that a simple image processing algorithm, simulating the CSF as a filter bank, would be able to rate the visibility of edges in an image. Vision models which use the CSF are particularly suited for an image processing implementation, because the spatial filters at work can be described by Gaussian filters. Joulan et al. (2011b) proposed such an operator, using Differences of Gaussians (DoG) at various spatial scales, in a way which allows simulating any CSF.

For each edge pixel and each spatial channel, a channel-VL is computed as the ratio of the contrast in this channel and the contrast threshold for this channel, taken from the CSF. The highest VL at this pixel (across channels) is selected as the edge visibility at this pixel. That way, from a luminance image, a “visibility map” can be proposed (Joulan et al., 2011b). A threshold on this map produces a map of visible edges, which needs to be associated to prior knowledge about the possible targets localization for a better understanding. The notion of target disappears and is replaced with edges, which is consistent with elementary visual mechanisms (Marr and Hildreth, 1980). This method allows estimating, for instance, road visibility in adverse conditions, such as nighttime (Joulan et al., 2011a) and fog (Tarel et al., 2015).

## 7 Discussion

I have stressed, in section 1.1, the difference between two approaches in engineering sciences: causal and correlational. A visual performance model is needed in the causal pipeline, not in the correlational, and thanks to the development of vision science, such models have been proposed to the lighting

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<sup>59</sup>In other words, a task would be referred to as “complex” if it needs high spatial frequency information.

community and adapted to the specific needs of road lighting. The historical overview presented in sections 2 to 6 shows the progress of these vision models, and – to some extent – of their adaptation to the needs of lighting engineers. However, these efforts did not succeed so far in introducing a fully scientific approach in the design of lighting installations.

## 7.1 What we have learned

The progress over the last 100 years may be considered on the academic and on the engineering sides. From an academic point of view, no doubt that the net result is a scientific progress in psychophysics about visual performance in laboratory conditions, first with uniform targets, then with complex targets and backgrounds. Advances in vision sciences suggest that a bio-mimetic approach of vision is now reachable, through a simulation of some elementary visual processes in the retina and in the visual pathways (Schmitt et al., 1969; Cristóbal et al., 2016).

As concerns lighting engineering, the first step was maybe the main step: Waldram (1938) stated that the goal of road lighting was to allow the driver to detect a hazard on the road with a good probability, early enough to avoid a collision. The main concepts were described: a task (night driving), a scenario (collision with an obstacle), a goal for the lighting installation (ensure some level of visual performance), a performance threshold (“before it’s too late”) and a theoretical framework (probabilities). The next step was to make a quantitative model out of this, and possibly to extend the idea to other situations, such as automotive and pedestrian lighting. This is still an ongoing work.

### 7.1.1 Visual performance

The problem statement was correct, but the quantitative model for each part of the pipeline was weak in the first endeavour. Specifically, the fact that the vision model was based on judgments from drivers under road lighting (Dunbar, 1938) made it uneasy to generalize to other road environments, speeds and lighting systems. This is why, after WWII, lighting engineers turned to psychophysics, using controlled and reproducible vision science data about acuity (Weston, 1945), contrast detection (Blackwell, 1946) and

reaction time (Rea, 1986). This led to a second generation of visual performance models for the design of lighting installations.

This progress led, in the field of lighting research, to useful concepts of visual performance, such as the VL (CIE, 1972) and the RVP (Rea, 1986). There have been attempts to turn these concepts into effective methodologies in lighting standards. Specifically, the STV was designed in order to include the VL as a figure of merit for road lighting (CIE, 1995a; IESNA, 2000b).

Progress was also made in terms of measurement tools, including the availability of portable measurement devices that can be used outdoor on the road, such as the recent ILMD. One intriguing exception is that visibility-meters have disappeared.

### 7.1.2 Visual needs

But a model of visual performance is not enough. Before this approach can reach the day-to-day work of lighting engineers, recommendations are needed in terms of road classification and performance thresholds. Schreuder (1978) was among the first to emphasize that a visual performance model alone cannot help the lighting engineers, because lighting design depends both on visual performance and on visual needs; some rationale is needed to choose the performance thresholds.

**Two options.** Fig. 4 describes the two options which have been proposed so far to estimate the visual needs in a road lighting context: the probabilistic approach and the use-cases approach. No doubt that the probabilistic is the best one, in the sense that it uses all available information to take a rational decision in a probabilistic sense, while using use-cases can be seen as a proxy. But this is a theoretical view; a probabilistic model needs, as input, probability distributions of a number of parameters (e.g. the size, shape and texture of potential targets), and these distributions are not available. Meanwhile, the use-case approach is a reasonable heuristic, even if it is questionable because a consensus among experts is needed in order to choose the use-cases representative of the driving task.

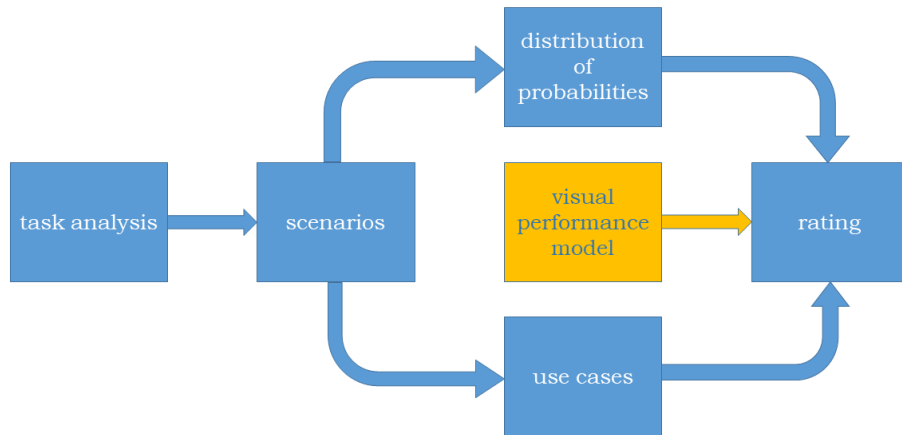


Figure 4: Visual needs come in two flavours. The probabilistic approach dates back to Waldram (1938). The use-case approach needs some consensus among experts; both need a visual performance model.

**Task analysis.** In both options, a task analysis is needed in order to select the critical visual tasks. Whereas reading is the reference visual task for indoor lighting, target detection is more suited for outdoor lighting, where the reference task is locomotion (either with a vehicle or by foot). On the road, the preferred use-case is driving on a straight road and braking or avoiding a target when it is perceived.

This approach dates back to Waldram’s research program. Considering all driving subtasks, beyond hazard detection, would enlarge the focus to other visual needs (Allen et al., 1971). This would allow estimating the specific benefit of road lighting for each of these subtasks (CIE, 1992b), including for instance motion perception (Akashi et al., 2007) and target recognition (Dahlstedt and Svenson, 1977). Schreuder (1978) proposed a general framework where the visual needs are expressed in terms of the space needed for the appropriate maneuver.

A look at other engineering fields gives some insights. In automotive lighting, although visual performance models are not considered any more, the focus is also on target detection (Sivak et al., 2000). The road markings community adopted the CIE (1981a) model to rate the visibility of road markings

(CIE-PIARC, 1988; COST-331, 1999). For pedestrian lighting, the TC 4-52 of the CIE describes the visual needs with respect to four visual functions: hazard detection (pavement obstacles (Fotios and Cheal, 2013; Fotios and Uttley, 2018)), facial recognition (evaluation of other pedestrians (Van Bommel and Caminada, 1982)), reassurance (perceived safety) and pedestrian signaling (being seen by the drivers, that is, visibility of a specific target, the pedestrian). Although it is not the only one, target detection is the main visual task in all these fields.

**Use-cases.** Once a reference visual task is chosen (say the detection of a road hazard), is there a way to select the relevant use-cases? Two approaches have been used. One is to look for the most probable cases, as a proxy for the probabilistic approach mentioned in Fig. 4. Another strategy is to consider that a lighting installation should provide enough visibility in the “worst case” situations.

Whatever the strategy for the selection of the use-cases, the next step is to propose some specifications of the scenario (e.g. for the driver’s age, vehicle speed, target size, etc.)<sup>60</sup>. At this stage, a consensus between experts is needed to decide that some specific scenario may be considered in a standard.

**Performance threshold.** Finally, for a given use-case, a visual performance threshold is needed to rate the merit of an installation. Some proposals have emerged for target detection for road lighting (Gallagher and Meguire, 1975; Hills, 1976; Adrian, 1987, 1989), and have been considered in standards (IESNA, 2000b; AFE, 2002). Beyond road lighting, the COST 331 report made recommendations on the VL threshold for road markings (COST-331, 1999).

## 7.2 Still not working

### 7.2.1 Disappointed hopes

The efforts described in this review have been done in hopes that vision science knowledge could serve in a causal pipeline to predict the visual per-

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<sup>60</sup>This includes some uncontrolled factors, such as the gaze direction, but there is a growing literature about the range of gaze in driving situations (Land and Lee, 1994; Foulsham et al., 2011; Lappi, 2014; Fotios et al., 2015).

formance in driving situations, in a way which would allow the lighting engineers to design their installations from a scientific rationale. This did not succeed so far: visual performance is no longer included in the standards, and the correlational approach is still in use (e.g. with accidentology). This is disappointing, because in spite of important scientific advances, we cannot predict the actual benefit provided by a lighting installation from measurable parameters.

This is not just a theoretical issue, it is a true limitation for current lighting design. If the standards are not based on predictive models, they tend to become outdated when the main uncontrolled factors change (lighting and automobile technology, road surfaces, driver's behaviour and expectations, etc.). New data is always needed, for new correlations.

### **7.2.2 Models and experts**

It may be that the hope for a full rational approach of road lighting is just a dream: Boyce (1996) described the search of a magic formula for lighting design as a "fairy tale": you want to believe it exists, but it doesn't. Even if it was possible to select the optimal lighting design with respect to one task, an installation always makes a trade-off for several visual tasks. And this trade-off cannot be decided by a formula: it is where experts are needed.

It is not to say that visual performance models are useless, only that they are tools in the hands of experts. If quantitative models can predict the visual performance, only experts can decide the appropriate thresholds. Boyce suggested that for a given application, a consensus should select a lighting level allowing the visual performance to stay on a plateau (in the sense of Weston) for all tasks to be carried out under the installation; the quantitative models would then estimate this performance. The appropriate lighting design requires this consensus, because the rationale is not purely scientific, it includes technical, economical and social constraints, and these change over time.

Last but not least, the quality of a lighting installation is not limited to visual performance, it also involves visual comfort. Thus, the two criterions are both important, visual needs and visual wants. Visual wants correspond

to the people's expectations, and change rapidly in our societies, which makes the search for the abovementioned thresholds for visual performance a waste of time, Boyce suggests.

### **7.3 Perspectives**

Despite of the current limitations, progress is expected on the visibility models, on the analysis and assessment of visual needs, and on measurement devices, leaving room for a causal approach of road lighting in the future. Such progress may impact more than road lighting: street lighting, automotive lighting and retro-reflective products may also rely on such visual performance criterions.

#### **7.3.1 What progresses are needed**

The main obstacles have been emphasized throughout this review. Some knowledge is missing, for instance about the distribution of geometric and photometric properties of potential hazards, and about the photometric properties of road surfaces in various conditions. Collecting and sharing these data in open databases would be a useful step for the lighting community.

Rea (1982) suggested that lighting engineers cannot underestimate the potential benefit of understanding vision science, and indeed, another avenue of progress concerns the visibility models, including the definition of visibility through the CSF.

But the main issue is that visual performance does not only depend on the lighting and stimulus characteristics. Uncontrolled factors, mainly human factors, are at work, such as gaze direction and mental workload. These factors cannot be controlled, and a proxy is needed in the reference use cases. The “field factor” is supposed to include all the effects of these factors, but it lacks a consistent theory. Such a theory is not out of reach, however, as various studies have explored some of these factors, and most field data converge regarding the field factor value for night driving on straight roads without traffic.

This leads to the “visual needs”, where a consensus on the relevant use cases is both needed and uneasy to reach. This consensus should be based



on an analysis of the driving task, and of the visual information needs for each of the driving subtasks. The common keyword for road lighting, street lighting, automotive lighting and road markings is probably the anticipation of one's trajectory (Laurent and Thomson, 1991). This idea that the function of lighting is anticipation may possibly serve as a unifying background for outdoor lighting applications.

A visual performance model is a simplified view of the world. All factors are not under full control (see Fig. 2), and we cannot trust a model without field data. This was the aim of various closed road experiments testing visual indexes of target detection (Gallagher and Meguire, 1975; Hills, 1976; Mayeur et al., 2010). But a direct link with accidentology is still missing, which can be considered a weakness of the approach. While correlations have been recorded for half a century (Box, 1971; CIE, 1992c; Elvik, 1995; Wanvik, 2009), very few studies have considered visual performance indexes in relation to road accidents (Bullough et al., 2013; Bhagavathula et al., 2017).

In addition to these directions of research, lighting engineers need cheap and fast devices to check that an installation complies with a standard. Computational models are useful, but they need physical data as input, and unlike most correlational approaches based on illuminance data, the estimation of visual performance needs some knowledge (or hypotheses) about materials properties and visual capacities. Without the appropriate measurement devices, visual performance will not reach the practitioners.

### 7.3.2 A glimpse into the future

**New issues.** Societies change, technologies change. The trend towards autonomous vehicles, for instance, raises many questions regarding the function of road lighting: the figures of merit will probably change, as from a camera sensor point of view, illuminance and luminance are not relevant quantities: their definition is tuned to human vision. Importantly, the variety of onboard sensors makes it a challenge to design road lighting for all vehicular systems. The development of smart (adaptive) lighting also needs new criteria associated with visual adaptation to light and darkness. These emerging issues bring new notions of visual performance, together with new definitions and

new reference scenarios<sup>61</sup>.

Another emerging issues concern the definition of the reference observer and inter-individual differences. As public lighting is provided to all drivers, cyclists and pedestrians, the installations are tuned to a “reference observer”. For urban lighting, this observer may be reconsidered, taking into account people with impaired vision<sup>62</sup>. In the context of an ageing society, this observer may also evolve on the road. Going one step further, for automotive lighting, the need for a reference observer may disappear if headlamps power can be tuned to each driver’s visual abilities. All these options open the way to new criteria of visual performance.

**New approaches.** New measurement tools have appeared, including ILMD<sup>63</sup>, which makes image processing approaches of lighting assessment much easier. Specifically, the photometric databases needed in the probabilistic approaches could possibly be fed with data collected using ILMDs embedded in vehicles, which would be much easier than current practice.

Virtual reality is also an emerging tool which can help lighting design in comparing visual performance in the lab and on the road, or comparing installations — if the display photometry is under control in the range of outdoor lighting.

Coming back to the competition between the correlational and causal approaches, the main event in the last 10 years was the development of machine learning techniques coupled to “big data” analyses, to a point that the so-called “artificial intelligences” are now almost everywhere (LeCun et al., 2015). To date, engineering standards are AI-free, but that may change in the future. The main purpose of deep learning is to “learn” a relation between a large series of input data and some output classification (e.g. the performance level of a lighting installation). That is exactly the purpose of

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<sup>61</sup>Apart from visual performance, there is a growing concern about the unwanted effects of lighting. In addition to disability glare, this includes discomfort glare, blue light hazard, circadian rhythm and the protection of biodiversity.

<sup>62</sup>Remember that the observers in Blackwell’s studies all had a very good vision.

<sup>63</sup>The CIE has recently highlighted the 10 main topics of a Research Strategy for the coming years, among which: *Metrology for Advanced Photometric and Radiometric Devices*.

correlations in the current approach. Machine learning techniques make predictions for data close to those in the learning dataset, just like traditional correlations. But unlike traditional correlations, they can use huge datasets with thousands of free parameters. And unlike the causal approach, this is done without modeling the relation between input and output: the neural network is a black box.

The “big data” may soon become an option to build lighting standards on. To this end, the first step would be machine-learning the performance of lighting installations all over the world, providing a general model based on all available parameters (including the weather, the country, the traffic, the luminaires model, the road surface photometry, the nature of the road markings, etc.); the second step would be the selection of a simplified model, based on photometric values available for lighting engineers.

Both the predictive and the correlational approaches are changing. The correlational approach is strongly renewed by the big data, while the predictive approach (especially the probabilistic one) may be renewed by the deployment of ILMDs and by bio-inspired models of vision.

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## References

- Adrian, W. (1969). Die Unterschiedsempfindlichkeit des Auges und die Möglichkeit ihrer Berechnung [Calculating the contrast sensitivity of the eye]. *Lichttechnik*, 21(1):2A–71.
- Adrian, W. (1987). Visibility levels under night-time driving conditions. *Journal of the Illuminating Engineering Society*, 16:3–12.
- Adrian, W. (1989). Visibility of targets: model for calculation. *Lighting Research & Technology*, 21(4):181–188.
- Adrian, W. (1993). Visibility levels in street lighting: an analysis of different experiments. *Journal of the IES*, 22:49–52.
- Adrian, W. and Gibbons, R. (1995). Fields of visibility of the nighttime driver. *Lighting Engineering*, 3:1–12.
- AFE (2002). *Recommandations relatives à l'éclairage des voies publiques*. Association Française de l'Eclairage, Paris.
- Akashi, Y., Rea, M. S., and Bullough, J. D. (2007). Driver decision making in response to peripheral moving targets under mesopic light levels. *Lighting Research and Technology*, 39(1):53–67.
- Alferdinck, J. W. A. (2006). Target detection and driver behaviour measurements in a driving simulator at mesopic light levels. *Ophthalmic and Physiological Optics*, 26:264–280.
- Allen, T. M., Lunenfeld, H., and Alexander, J. G. (1971). Driver information needs. *Transportation Research Board*, 366:102–115.
- Bacelar, A., Cariou, J., and Hamard, M. (1999). Computational visibility model for road lighting installations. *Lighting Research and Technology*, 31(4):177–180.
- Barten, G. J. (1999). *Contrast sensitivity of the human eye and its effects on image quality*. SPIE Optical Engineering Press.
- Berek, M. (1943). Zeitschrift. *Instrumenten-kunde*, 63:297.

- Beurle, R. L., Daniels, M. V., and Hills, B. L. (1968). Visual pattern detection. In *Proc. IEE Conference on Pattern Recognition*, volume 42, pages 86–94, Teddington, UK.
- Beutell, A. W. (1934). An analytical basis for a lighting code. *Illuminating Engineering*, 27:5–11.
- Bhagavathula, R., Gibbons, R. B., and Nussbaum, M. A. (2017). Effects of intersection lighting design on nighttime visual performance of drivers. *Leukos*, 14(1):25–43.
- Bhise, V. D., Farber, E. I., and Mc Mahan, P. B. (1976). Predicting target detection distance with headlights. *Transportation Research Records*, 611:1–11.
- Blackwell, H. R. (1946). The contrast thresholds of the human eye. *Journal of the Optical Society of America*, 36(11):624–643.
- Blackwell, H. R. (1970). Development of procedures and instruments for visual task evaluations. *Illuminating Engineering*, 65(4):267–291.
- Blackwell, H. R. and Smith, S. W. (1958). The effect of target size and shape on visual detection. Technical Report 2144-346-T, University of Michigan, MI.
- Bodmann, H. W. (1962). Illumination levels and visual performance. *International Lighting Review*, 13:41–47.
- Bodmann, H. W. (1973). Visibility assessment in lighting engineering. *Journal of the Illuminating Engineering Society*, 2(4):437–443.
- Boucher, V., Greffier, F., Fournela, F., and Dronneau, R. (2017). High dynamic range imaging luminance measuring device (hdr-ilmd) and applications in motion. In *Proc. of the CIE midterm session*, page 301.
- Box, P. C. (1971). Relationship between illumination and freeway accidents. *Illuminating Engineering*, 66(5):365–393.
- Boyce, P. R. (1996). Illuminance selection based on visual performance — and other fairy stories. *Journal of the Illuminating Engineering Society*, 25(2):41–49.

- Boynton, R. M. and Boss, D. E. (1971). The effect of background luminance and contrast upon visual search performance. *Illuminating Engineering*, 66:173–186.
- Boynton, R. M., Corwin, T. R., and Sternheim, C. (1970). Visibility losses produced by flash adaptation. *Illuminating Engineering*, 65:259–266.
- Brémond, R., Bodard, V., Dumont, E., and Nouailles-Mayeur, A. (2013). Target visibility level and detection distance on a driving simulator. *Lighting Research and Technology*, 45(1):76–89.
- Brémond, R., Dumont, E., Ledoux, V., and Mayeur, A. (2011). Photometric measurements for visibility level computations. *Lighting Research and Technology*, 43(1):119–128.
- Brusque, C. and Hubert, R. (1996). La métrologie de la luminance par caméra CCD: étalonnage et qualification du système Mélusine. *Bulletin des Laboratoires des Ponts et Chaussées*, 205:39–47.
- Bry, M. and Colomb, M. (1988). Visibilité de la signalisation: les besoins des usagers et les technologies disponibles. *Revue Générale des Routes et des Aérodrômes*, 658:1–7.
- Bullough, J. D., Donnell, E. T., and Rea, M. S. (2013). To illuminate or not to illuminate: Roadway lighting as it affects traffic safety at intersections. *Accident Analysis & Prevention*, 53:65–77.
- Buyyukinaci, B., Onagyl, S., Guler, O., and Yurtseven, M. B. (2017). Determining minimum visibility levels in different road lighting scenarios. *Lighting Research and Technology*, page (available online).
- Campbell, F. W. and Robson, J. G. (1968). Application of Fourier analysis to the visibility of gratings. *Journal of Physiology*, 197(3):551–566.
- CEN (2014). *Road Lighting standards: EN 13201*. European Committee for Standardization, Brussels (Belgium).
- Chen, Z., Tu, Y., Wang, Z., Liu, L., Wang, L., Lou, D., Zhu, X., and Teunissen, K. (2018). Target visibility under mesopic vision using a driving simulator. *Lighting Research & Technology*, (available online).

- Chorlton, J. M. and Davidson, H. F. (1959). The effect of specular reflection on visibility. Part II: Field measurements of loss of contrast. *Illuminating Engineering*, 54:482–488.
- CIE (1965). International recommendations for the lighting of public thoroughfares. Technical Report 12, Commission Internationale de l'Éclairage, Vienna.
- CIE (1972). An unified framework of methods for evaluating visual performance aspects of lighting. Technical Report 19, Commission Internationale de l'Éclairage, Vienna.
- CIE (1977). Recommendations for the lighting of roads for motorized traffic. Technical Report 12-2, Commission Internationale de l'Éclairage, Paris.
- CIE (1981a). An analytical model for describing the influence of lighting parameters upon visual performance. Volume 1: Technical foundations. Technical Report 19/2.1, Commission Internationale de l'Éclairage, Vienna.
- CIE (1981b). An analytical model for describing the influence of lighting parameters upon visual performance. Volume 2: Summary and application guidelines. Technical Report 19/2.2, Commission Internationale de l'Éclairage, Vienna.
- CIE (1988). Brightness-luminance relations: Classified bibliography. Technical Report 78, Commission Internationale de l'Éclairage, Vienna.
- CIE (1992a). Contrast and visibility. Technical Report 95, Commission Internationale de l'Éclairage, Vienna.
- CIE (1992b). Fundamentals of the visual task of night driving. Technical Report 100, Commission Internationale de l'Éclairage, Vienna.
- CIE (1992c). Road lighting as an accident countermeasure. Technical Report 93, Commission Internationale de l'Éclairage, Vienna.
- CIE (1995a). Discomfort glare in interior lighting. Technical Report 117, Commission Internationale de l'Éclairage, Vienna.

- CIE (1995b). Recommendations for the lighting of roads for motor and pedestrian traffic. Technical Report 115, Commission Internationale de l'Éclairage, Vienna.
- CIE (2002). CIE collection on glare. Technical Report 146, Commission Internationale de l'Éclairage, Vienna.
- CIE (2010). Lighting of roads for motor and pedestrian traffic. Technical Report 115-2, Commission Internationale de l'Éclairage, Vienna.
- CIE-PIARC (1988). Visual aspects of road markings. Technical Report 73, Commission Internationale de l'Éclairage, Vienna.
- Clear, R. and Berman, S. (1990). Speed, accuracy and VL. *Journal of the Illuminating Engineering Society*, 19(2):124–131.
- Cobb, P. W. and Moss, F. K. (1927). The relation between extent and contrast in the liminal stimulus for vision. *Journal of Experimental Psychology*, 10:350–364.
- Cobb, P. W. and Moss, F. K. (1928). Four fundamental factors in vision. *Transactions of the Illuminating Engineering Society*, 23:496–504.
- Cohu, M. (1936). Street and road lighting. *Transactions of the IES*, 1(11):163–169.
- COST-331 (1999). Requirements for horizontal road markings. Technical Report COST 331, European Commission, DG Transport, Luxembourg.
- Cowey, A. and Rolls, E. T. (1974). Human cortical magnification factor and its relation to visual acuity. *Experimental Brain Research*, (21):447–454.
- Crescenzo, G., Villa, C., Brémond, R., Vignali, V., Lantieri, C., and Simone, A. (2019). The shape of road markings for visibility computations. *Transport*, page (in press).
- Cristóbal, G., Perrinet, L., and Keil, M. S., editors (2016). *Biologically inspired computer vision*. Wiley, Weinheim, Germany.
- Dahlstedt, S. and Svenson, O. (1977). Detection and reading distances of retroreflective road signs during night driving. *Applied Ergonomics*, 8(1):7–14.



- de Boer, J. B., Burghout, F., and van Heemskerck Veekens, J. (1951). Fundamental experiments on visibility and admissible glare in road lighting. In *Proc. of the 12th session of the CIE*.
- de Valois, R. and de Valois, K. (1988). *Spatial Vision*. Oxford University Press, Oxford, UK.
- Donges, E. (1978). A two-levels model of steering behavior. *Human Factors*, 20(6):691–707.
- Dubuisson, J.-L. and Paumier, J.-L. (1987). Visibility distances models and measurements for driving. In *Proc. of the 21th session of the CIE*, volume 2, pages 278–281, Venice.
- Dunbar, C. (1938). Necessary values of brightness contrast in artificially lighted streets. *Transactions of the Illuminating Engineering Society*, 3(12):187–195.
- Eastman, A. A. (1968a). Color contrast *vs.* luminance contrast. *Illuminating Engineering*, 63:613–620.
- Eastman, A. A. (1968b). A new contrast threshold visibility meter. *Illuminating Engineering*, 63:37–40.
- Economopoulos, I. A. (1978). Photometric parameters and visual performance in road lighting. Technical report, Technische Hogeschool, Eindhoven, Pays Bas. Doctoral dissertation.
- Elvik, R. (1995). Meta-analysis of evaluations of public lighting as accident countermeasure. *Transportation Research Records*, 1485:112–123.
- Endsley, M. R. (1995). Measurement of situation awareness in dynamic systems. *Human Factors*, 37(1):61–84.
- Enroth-Cugell, C. and Robson, J. G. (1966). The contrast sensitivity of retinal ganglion cells of the cat. *Journal of Physiology*, 187:517–552.
- Finch, D. M. (1959). The effect of specular reflection on visibility. Part I: Physical measurements for the determination of brightness and contrast. *Illuminating Engineering*, 54:474–481.

- Fotios, S. and Cheal, H. (2013). Using obstacle detection to identify appropriate illuminances for lighting in residential roads. *Lighting Research and Technology*, 45:362–376.
- Fotios, S. and Gibbons, R. (2018). Road lighting research for drivers and pedestrians: The basis of luminance and illuminance recommendations. *Lighting Research and Technology*, 50:154–186.
- Fotios, S. and Uttley, J. (2018). Illuminance required to detect a pavement obstacle of critical size. *Lighting Research and Technology*, 50:390–404.
- Fotios, S., Uttley, J., Cheal, C., and Hara, N. (2015). Using eye-tracking to identify pedestrian’s critical visual tasks. I: Dual task approach. *Lighting Research and Technology*, 47:133–148.
- Foulsham, T., Walker, E., and Kingstone, A. (2011). The where, what and when of gaze allocation in the lab and in the natural environment. *Vision Research*, 51(17):1920–1931.
- Fry, G. A. (1947). The relation of the configuration of a brightness contrast border to its visibility. *Journal of the Optical Society of America*, 37(3):166–175.
- Fry, G. A. (1965). Physiological irradiation across the retina. *Journal of the Optical Society of America*, 55(1):108–111.
- Gallagher, V. P. and Meguire, P. G. (1975). Driver visual needs in night driving. Technical report, Transportation Research Board, Washington DC.
- Gibson, J. J. (1979). *The ecological approach to visual perception*. LEA, Hillsdale, NJ.
- Gibson, J. J. and Crooks, L. E. (1938). A theoretical field-analysis of automobile driving. *The American journal of psychology*, 51(3):453–471.
- Ginsburg, A. P. (1986). Spatial filtering and visual form perception. In Boff, K., editor, *Handbook of perception and visual performance, Vol II*, pages 34.1–34.41, NY. Wiley & Son.

- Ginsburg, A. P. and Easterly, Y. J. (1983). Contrast sensitivity predicts target detection field performance of pilots. In *Proc of the 27th Human Factors Ergonomic Society Annual Meeting*, pages 269–273.
- Goodman, T., Forbes, A., Walkey, H., Eloholma, M., Halonen, L., Alferdinck, J., Freiding, A., Bodrogi, P., Varady, G., and Szalmas, A. (2007). Mesopic visual efficiency IV: A model with relevance to night-time driving and other applications. *Lighting Research and Technology*, 35:365–392.
- Güler, O. and Onaygil, S. (2003). The effect of luminance uniformity on visibility level in road lighting. *Lighting Research and Technology*, 35(3):199–215.
- Halvorson, C. (1936). Highway lighting — principles and sources. *Electrical Engineering*, 6:735–746.
- Herrick, R. M. (1956). Foveal luminance discrimination as a function of the duration of the decrement or increment in luminance. *Journal of Computational Physiological Psychology*, 49(5):437–443.
- Hills, B. L. (1975a). Visibility under night driving conditions. Part I: Laboratory background and theoretical considerations. *Lighting Research and Technology*, 7(3):179–184.
- Hills, B. L. (1975b). Visibility under night driving conditions. Part II: Fields measurements using disc obstacles and a pedestrian dummy. *Lighting Research and Technology*, 7(4):251–258.
- Hills, B. L. (1976). Visibility under night driving conditions. Part III: Derivation of  $(\Delta L, A)$  characteristics and factors in their application. *Lighting Research and Technology*, 8(1):11–26.
- Holladay, L. L. (1926). The fundamentals of glare and visibility. *Journal of the Optical Society of America*, 12:271–319.
- Holladay, L. L. (1927). Action of a lightsource in the field of view in lowering visibility. *Journal of the Optical Society of America*, 14:1–15.
- IESNA (1990). *American National Standard Practice for Roadway Lighting — Proposed standard RP-8-90*. Illuminating Engineering Society of North America, NY.

- IESNA (2000a). *American National Standard Practice for Roadway Lighting. RP-8-00*. Illuminating Engineering Society of North America, NY.
- IESNA (2000b). *Lighting Handbook. Reference and application*. Illuminating Engineering Society of North America, NY.
- IESNA (2014). *Roadway Lighting. RP-8-14*. Illuminating Engineering Society of North America, NY.
- Inditsky, B., Bodmann, H. W., and Fleck, H. J. (1982). Elements of visual performance. Contrast metric — visibility lobes — eye movements. *Lighting Research and Technology*, 14(4):218–231.
- Janoff, M. S. (1992). The relationship between visibility level and subjective ratings of visibility. *Journal of the IES*, 21(2):98–107.
- Johnson, J. (1958). Analysis of image forming systems. In *Image intensifier Symposium*, pages 249–273, Fort Belvoir, VA.
- Joulan, K., Hautière, N., and Brémond, R. (2011a). Contrast sensitivity functions for road visibility estimation in digital images. In *Proc. 27<sup>th</sup> session of the Commission Internationale de l’Eclairage*, Sun City, South Africa.
- Joulan, K., Hautière, N., and Brémond, R. (2011b). A unified CSF-based framework for edge detection and edge visibility. In *CVPR workshop on Biologically-consistent Vision*, Colorado Springs.
- Judd, D. B. and Eastman, A. A. (1971). Prediction of target visibility from the colors of target and surround. *Illuminating Engineering*, 66(4):256–266.
- Kelly, D. H. and Magnuski, H. S. (1975). Pattern detection and the two-dimensional Fourier transform: circular targets. *Vision Research*, 15:911–915.
- Koenderink, J. J. and van Doorn, A. J. (1984). Invariant features of contrast detection: an explanation in terms of self-similar detector arrays. *Journal of the Optical Society of America*, 72:83–87.
- Kokoschka, S. (1985). Zeichenkontrast und visuelle Leistung am Bildschirm. In Bodmann, H., editor, *Aspekte der Informationsverarbeitung*, pages 254–300, Berlin. Springer Verlag.

- Kountouriotis, G., Floyd, R. C., Gardner, P., Merat, M., and Wilkie, R. M. (2012). The role of gaze and road edge information during high speed locomotion. *Journal of Experimental Psychology: Human Perception and Performance*, 38(3):687–702.
- Lamar, E. S., Hecht, S., Schlaer, S., and Hendley, C. D. (1947). Size, shape, and contrast in detection of targets by daylight vision. I. Data and analytical description. *Journal of the Optical Society of America*, 37(7):531–545.
- Lamar, E. S., Hecht, S., Schlaer, S., and Hendley, C. D. (1948). Size, shape, and contrast in detection of targets by daylight vision. II. Frequency of seeing and the quantum theory of vision. *Journal of the Optical Society of America*, 38(9):741–755.
- Land, M. F. and Lee, D. N. (1994). Where we look when we steer. *Nature*, 369(6483):742–744.
- Lappi, O. (2014). Future path and tangent point models in the visual control of locomotion in curve driving. *Journal of Vision*, 14(12):1–22.
- Laurent, M. and Thomson, J. A. (1991). Anticipation and control in visually-guided locomotion. *International Journal of Sport Psychology*, 22(3-4):251–270.
- Lecocq, J. (1991). Visibility level in outdoor lighting: Adrian model applied to spherical cap targets. In *Proc. of the 22th session of the CIE*, pages 48–51, Melbourne, Australie.
- Lecocq, J. (1997). Visibility in road lighting: correlation of subjective assessments with calculated values. In *Lux Europa*, pages 22–36, Amsterdam, Pays Bas.
- Lecocq, J. (1999). Calculation of the visibility level of spherical targets in roads. *Lighting Research and Technology*, 31(4):171–175.
- Lecocq, J. (2000). Small target visibility as a quality criterium in roadway lighting. In *Proc. of the CIE annual meeting*, pages 32–41, Toronto, Canada.
- LeCun, Y., Bengio, Y., and Hinton, G. (2015). Deep learning. *Nature*, 521:436–444.

- Loe, D. M. and Waters, D. M. (1973). Visual performance in illumination of differing spectral quality. Technical report, Environmental Research Group, University College, London, UK.
- Luckiesh, M. and Moss, F. K. (1935). Visibility: its measurement and significance in seeing. *Journal of the Franklin Institute*, 220:431–466.
- Marr, D. (1982). *Vision*. W. H. Freeman, San Francisco, CA.
- Marr, D. and Hildreth, E. (1980). Theory of edge detection. *Proceedings of the Royal Society of London. Series B, Biological Sciences*, 207:187–217.
- Mayeur, A., Brémond, R., and Bastien, C. (2008). Effect of task and eccentricity of the target on detection thresholds in mesopic vision: implications for road lighting. *Human Factors*, 50(4):712–721.
- Mayeur, A., Brémond, R., and Bastien, C. (2009). Effect of the viewing context on peripheral target detection. Implications for road lighting. *Applied Ergonomics*, 41(3):461–468.
- Mayeur, A., Brémond, R., and Bastien, C. (2010). The effect of the driving activity on target detection as a function of the visibility level: implications for road lighting. *Transportation Research Part F: Traffic psychology and behaviour*, 13(2):115–128.
- McNelis, J. (1973). Human performance — a pilot study. *Journal of the Illuminating Engineering Society*, 2:190–196.
- Ménard, J. and Cariou, J. (1994). Road lighting: Assessment of an installation based on the contrast of a standard target. *Lighting Research & Technology*, 26(1):19–22.
- Michon, J. A. (1985). A critical review of driver behavior models: What we do know, what should we do? In *Proc. International Symposium on Driver Behavior and Traffic Safety*, pages 485–520, NY. Plenum Press.
- Moon, P. and Cettei, M. S. (1938). On the reflection factor of clothing. *Journal of the Optical Society of America*, 28(8):277–279.
- Moore, R. L. (1952). Rear lights of motor vehicles and pedal cycles. Technical report, Road Research Technical Paper, London.

- Muck, E. and Bodmann, H. W. (1961). Die Bedeutung des Beleuchtungs-niveau bei Praktischer Sehtätigkeit. *Lichttechnik*, 13:502–508.
- Naka, K. I. and Rushton, W. A. (1966). S-potentials from luminosity units in the retina of fish (cyprinidae). *Journal of Physiology*, 185:587–599.
- Narisada, K. and Karasawa, Y. (2001). Reconsideration of the revealing power on the basis of visibility level. In *Proc. of the International Lighting Congress*, pages 473–480.
- Narisada, K., Karasawa, Y., and Shirao, K. (2003). Design parameters of road lighting and revealing power. In *Proc. of the 25th session of the CIE*, volume D4-10, San Diego, CA.
- Narisada, K. and Yoshikawa, K. (1974). Tunnel entrance lighting effect of fixation point and other factors on the determination of requirements. *Lighting Research & Technology*, 6(1):9–18.
- Nolan, G. F. (1957). On the functional relation between luminous energy, target size, and duration for foveal stimuli. *Journal of the Optical Society of America*, 47:394–397.
- Okafuji, Y., Mole, C., Merat, N., Fukao, T., Yokokohji, Y., Inou, H., and Wilkie, R. M. (2018). Steering bends and changing lanes: the impact of optic flow and road edges on two point steering control. *Journal of Vision*, 9:14.
- Overington, I. (1982). Towards a complete model of photopic visual threshold performance. *Optical Engineering*, 21(1):2–13.
- Paulmier, G., Brusque, C., Carta, V., and Nguyen, V. (2001). The influence of visual complexity on the detection of targets investigated by computer generated images. *Lighting Research and Technology*, 33(1):197–205.
- Ranney, T. A. (1994). Models of driving behavior: a review of their evolution. *Accident Analysis and Prevention*, 26(6):733–750.
- Rea, M. S. (1982). An overview of visual performance. *Lighting Design and Application*, 12(11):35–41.
- Rea, M. S. (1986). Towards a model of visual performance: foundations and data. *Journal of the Illuminating Engineering Society*, 15(2):41–57.

- Rea, M. S., Bullough, J. D., Fressinier Nova, J. P., and Bierman, A. (2004). A proposed unified system of photometry. *Lighting Research and Technology*, 36:85–111.
- Rea, M. S., Bullough, J. D., and Zhou, Y. (2010). A method for assessing the visibility benefits of roadway lighting. *Lighting Research and Technology*, 42:215–241.
- Rea, M. S. and Jeffrey, I. G. (1990). A new luminance and image analysis system for lighting and vision. I: Equipment and calibration. *Journal of the IES*, 19(1):64–72.
- Rea, M. S. and Ouelette, M. J. (1988). Visual performance using reaction times. *Lighting Research and Technology*, 20(4):139–153.
- Rea, M. S. and Ouelette, M. J. (1991). Relative visual performance: a basis for application. *Lighting Research and Technology*, 23(3):135–144.
- Roper, V. J. and Howard, E. A. (1938). Seeing with motor car headlamps. *Transactions of the Illuminating Engineering Society*, 33:417–438.
- Schmitt, T. M., Chen, S.-K., and Hattar, S. (1969). Some interesting and useful biomimetic transforms. In *3rd Int. Biophysics Congress*, page 297.
- Schnell, T. and Zwahlen, H. T. (1999). Visibility of rectangular targets as a function of length and width. In *Proc. Human Factors and Ergonomic Society 43th Annual Meeting*, pages 1367–1371, Houston, TX.
- Schnell, T. and Zwahlen, H. T. (2000). Computer-based modeling to determine the visibility and minimum retroreflectivity of pavement markings. *Transportation Research Records*, 1708:47–60.
- Schreuder, D. A. (1978). Relation between lighting parameters and transportation performance. *Transportation Research Records*, 681:43–47.
- Sekuler, R. (1975). Spatial vision. *Annual Review of Psychology*, 25:195–232.
- Shannon, C. (1948). A mathematical theory of communication. *Bell System Technical Journal*, 27:379–423 & 623–656.
- Simmons, A. E. and Finch, D. M. (1953). An instrument for assessment of night visibility on highways. *Illuminating Engineering*, 48:517–523.



- Simonson, E. and Brozek, J. (1948). Effects of illumination level on visual performance. *Journal of the Optical Society of America*, 38(4):384–397.
- Sivak, M. (1996). The information rate driver uses: is it indeed 90% visual? *Perception*, 22(1):49–52.
- Sivak, M., Flannagan, M. J., and Miyokawa, T. (2000). Quantitative comparisons of factors influencing the performance of low-beam headlamps. *Lighting Research and Technology*, 31(4):145–153.
- Smith, F. C. (1938). Reflection factors and revealing power. *Transactions of the Illuminating Engineering Society*, 3:196–206.
- Smith, S. W. and Rea, M. S. (1978). Proofreading under different levels of illumination. *Journal of the Illuminating Engineering Society*, 7:47–52.
- Stiles, W. S. (1929a). The effect of glare on the brightness difference threshold. *Proceedings of the Royal Society of London*, 104B:322–355.
- Stiles, W. S. (1929b). The nature and effects of glare. *Illuminating Engineering*, 22:304–312.
- Stiles, W. S. and Crawford, B. H. (1933). The liminal brightness increment for white light for different conditions of the foveal and parafoveal retina. *Proceedings of the Royal Society of London, Series B*, 116(796):55–102.
- Tarel, J.-P., Dumont, E., Joulan, K., and Brémond, R. (2015). Comparison between optical and computer vision estimates of visibility in daytime fog. In *Proc. 28<sup>th</sup> session of the Commission Internationale de l’Eclairage*, Manchester, UK.
- Van Bommel, W. J. M. and Caminada, E. (1982). Considerations of the lighting of residential areas for non-motorized traffic. In *CIBSE National Lighting Conference*, Warwick, UK.
- Van Bommel, W. J. M. and Tekelenburg, J. (1986). Visibility research for road lighting based on a dynamic situation. *Lighting Research and Technology*, 18(1):37–39.
- van Nes, F. L. and Bouman, M. A. (1967). Spatial modulation transfer in the human eye. *Journal of the Optical Society of America*, 57:401–406.

- Waldram, J. M. (1938). The revealing power of street lighting installations. *Transactions of the Illuminating Engineering Society*, 3(12):173–186.
- Waldram, J. M. (1950). The development of street lighting in great britain. *Transactions of the Illuminating Engineering Society*, 15(8):285–313.
- Wandell, B. (1995). *Foundations of vision*. Sinauer, Sunderland, MA.
- Wanvik, A. (2009). Effects of road lighting: an analysis based on dutch accident statistics 1987-2006. *Accident Analysis and Prevention*, 41(1):123–128.
- Watanabe, A., Mori, T., Nagata, S., and Hiwatashi, K. (1968). Spatial sine-wave response of the human visual system. *Vision Research*, 8:1245–1263.
- Weston, H. C. (1943). Proposals for a new lighting code. *Transactions of the Illuminating Engineering Society (London)*, 8:17–39.
- Weston, H. C. (1945). The relation between illuminance and visual performance. Technical report, Industrial Health Research Board and the Illumination Research Committee, London.
- Wilkie, R. M. and Wann, J. P. (2002). Driving as night falls: The contribution of retinal flow and visual direction to the control of steering. *Current Biology*, 12(23):2014–2017.
- Wilson, G. H. (1942). Street lighting: Past, present and future. *Transactions of the IES*, 7(10):111–120.
- Wilson, H. R. and Bergen, J. R. (1979). A four channels model for threshold spatial vision. *Vision Research*, 19:19–32.
- Wilson, H. R., McFarlane, D. K., and Phillips, G. C. (1983). Spatial frequency tuning of orientation selective units estimated by oblique masking. *Vision Research*, 23:873–882.
- Wood, L. A. S. (1936). Better visibility needed on highways at night. *Electrical Engineering*, 55(6):614–618.
- Zuidema, P., Koenderink, J. J., and Bouman, M. A. (1983). A mechanistic approach to threshold behavior of the visual system. *IEEE Transactions on Systems, Man & Cybernetics*, 13(5):923–934.

Zwahlen, H. T. (1985). Driver eye scanning, the information acquisition process and sophisticated in-vehicle information displays and controls. In *Proc. 9th Congress of the international Ergonomics Association*, pages 508–510. Taylor & Francis.