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The effect of the driving activity on target detection as a function of the visibility level: Implications for road lighting

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ABSTRACT

The Small Target Visibility model used in road lighting design is based on a strong simplification of the driving task. To specify the driver's visibility needs in a way consistent with state-of-the-art lighting engineering practice, a field experiment was designed in order to investigate target detection performances, comparing driver and passenger status conditions. Sixteen target visibility levels (VL) were used. In the driver status, 34 participants had to press a button as soon as they detected the target stimulus placed on the experimental lighted section. In the passenger status, the same participants had to detect the target stimulus while the experimenter drove. The results show that the passengers' performances (detection distance) were higher than the drivers' performances ($p = .0014$). Furthermore, the higher the VL, the higher the detection distance ($p < .0001$). These results lead up to modify the reference scenario in order to take into account human factor components for road lighting design.

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1. Introduction

1.1. Night-time road safety and road lighting

Driving a motor vehicle at night requires artificial light in order to improve the driver's vision, which is the main sensory channel used by the information acquisition and information processing while driving (Hills, 1980; Sivak, 1996). While the required lighting needs for night driving is provided by vehicle headlamps, road authorities may provide some fixed road lighting, as a tool to improve the driver's perception. Indeed, road lighting plays an important part in road infrastructure design by modifying night visual perception conditions, by emphasizing and obscuring specific regions of the road and of its surroundings, and by improving anticipation. Thus, assessing a driver's ability to see a pedestrian or other relevant item at night (Langham & Moberly, 2003) remains a challenging human factors problem.

In 2007, around 4620 fatalities and 103,301 traffic related injuries were reported in France. Less than 10% of the traffic but 32% of injuries and 44% of fatalities occured at night (ONISR, 2006). However, the relation between road infrastructure (e.g. road lighting) and road safety is problematic, and addresses the public policy evaluation issue. Road authorities' decisions aim at modifying the driver's behaviour towards safer displacement practices. For instance, public policies may improve the interactions between drivers and road environment, e.g. using in-vehicle on-board guidance systems, or improving

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the road readability through landscape modifications. Road lighting is a design tool which contributes both to safety and traffic fluidity at night.

Although the relation between road lighting and road safety is not direct, an overview of field studies made by the *Commission Internationale de l'Éclairage* (CIE) showed a positive correlation between road lighting quality and road safety (CIE, 1992) with the restriction that a bad design may be worst than no lighting at all (Mace & Porter, 2004; Van Bommel & Tekelenburg, 1986). The average effect of the installation of road lighting based on 23 before-and-after studies was a 30% reduction in night-time injury accidents. More recently, Wanvik (2009) showed that for Dutch roads the mean effect of road lighting on injury accidents during the hours of darkness is −50%, and the effect during the hours of twilight is about 2/3 of the effect during the hours of darkness.

If one of the causes of the high night-to-day accident ratio is the inability of drivers to detect and recognize roadway obstacles far away enough to adapt their trajectories, then lighting systems should help target detection at any point of the road surface. Their purpose is to allow the drivers to anticipate emergency situations, thus to increase the accident–avoidance performance.

1.2. Road lighting design and the Small Target Visibility (STV) model

Neither the equipment nor the system design of road lighting is directly specified by government standards. However, the road lighting design is based on technical documents (standards (IESNA, 2000a, 2000b), recommendations (AFE, 2002), norms (European Norm, 2004–2005)) which results in a territory level coherence.

Lighting benefits and quality are difficult to quantify. The technical standards are considered to be the expression of the "social needs" by the authorities (e.g. to decrease the fatalities on the road, to ensure traffic throughput) which decline these needs towards various actors (car industry and equipment suppliers, road industry, road authorities, etc.). The economical costs (including electric power) also contribute to the current stakes of lighting design.

To quantify lighting quality, the link between the driver's perception and the technical lighting system is operationalized by photometry. This includes the use of psychophysical models of human visual performances, in order to select the relevant parameters (contrast, brightness, illumination) and to fix the required performance levels (thresholds). A number of methods have been proposed so far in the scientific and technical literature, including the CIE and the *Illuminating Engineering Society of North America* (IESNA), but actual practice and recommendations on road lighting (European Norm, 2004–2005; IESNA, 2000a, 2000b) broadly stands on expert's agreements rather than on scientific models (Brémond, 2007; Ullman & Finley, 2007). We feel this is mostly due to the weakness of the models which have been proposed so far, in terms of ecological validity in relation to the driving experience.

To adapt the detection threshold from a reference psychophysical task to the specificity of any visual task (e.g. to read, or to detect a target on the road while driving), the CIE (1981) proposed a methodology which proceeds through a detailed analysis of this visual task, without taking into account non-visual aspects of the task. The visual task is split into sub-tasks (ocular fixations, saccadic motions, and the cognitive part of vision), and each subtask is given a specific weight.

Based on Adrian (1989), the visibility level (VL) is the most popular theoretical model used to assess road lighting quality. Its main hypothesis is that the accident rate is lower at night if the lighting system is optimised for the visibility of objects on the road: road lighting reveals objects before automotive lighting can do, and improves anticipation. The VL model may be applied to road visibility using a standard scenario, considering how well a small target on the road can be detected by a driver, at a distance where s/he uses to pick up information. This can be set in terms of driving safety: the lighting installation should be optimised in terms of a visual task which is critical for a given safety hazard (collision with an obstacle).

The VL model uses psychophysical data from laboratory conditions (Blackwell, 1946), in foveal vision, for uniform targets up to 1° of visual angle. The VL is computed as the ratio between the target luminance contrast ΔL against the background, and the threshold contrast ΔL_t needed for 99.93% detection. Adrian's model computes the contrast threshold ΔL_t, knowing the target contrast and apparent size, the contrast polarity (positive or negative, see Fig. 1), the background (adaptation) luminance, the observer's age, possible disability glare, and the observation time. Driving scenarios have been proposed

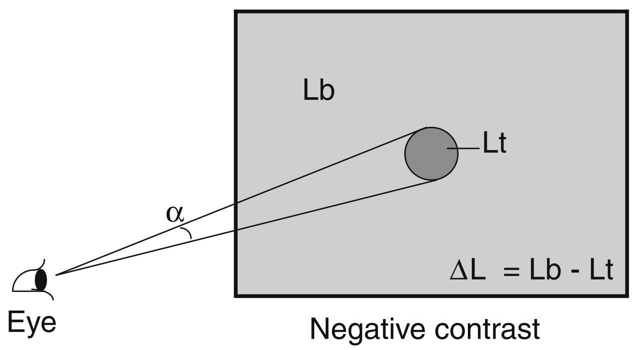

Fig. 1. Visual target of angular size α and luminance L_t seen against the background luminance L_b. The target appears in negative contrast.

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using this model. For instance the American standard (IESNA, 2000a, 2000b) uses a 20 cm uniform square as the target, with reflectance of 50%, seen at a distance of 83 m by a 60 years old driver during 0.2 s, leading to an operational lighting quality index called the Small Target Visibility (STV). Most authors follow Adrian in setting a reference target with 10′ angular size.

For example, a VL of 7 means that the target's luminance contrast is seven times the contrast needed for object detection in laboratory conditions. Higher levels of VL result in more visible objects. Adrian's proposal implies, for road lighting applications, to set a specific VL threshold (called a field factor) for a visual detection task while driving, this threshold leading to a reference illumination level for road lighting. Adrian (2004) and Adrian and Stemprok (2005) suggest that a VL of 4 would account for driver unexpectedness and just allows target detection (without identification). Various field factors have been proposed so far, however, with values from 2 to 30 (Adrian, 1987; AFE, 2002; Gallagher & Meguire, 1975; Hills, 1975; IESNA, 2000a, 200b) which shows a lack of consensus, and makes the model of little use for practical applications.

1.3. Introducing the driving activity in road lighting design

Adrian's model is based on a strong simplification of the actual driving task. It uses single task psychophysical data (Blackwell, 1946), whereas target detection is one among the many sub-tasks of driving (Crundall, Underwood, & Chapman, 1999). The reference psychophysical experiment does not take into account the driving task, which involves at the same time vehicle-control activities and information processing.

We have developed a methodology to fill-in the gap between the STV reference scenario (detection of a small target on a lighted road, at a given distance, while driving) and the STV reference data (target detection in laboratory conditions). The standard hypothesis is that a so-called "field factor" would compensate for the difference between these two situations, however, the lack of consensus about the field factor value leads to a dead-end. A number of factors obviously separate the reference scenario from the reference data collection: driving activity vs. single detection task, stimulus eccentricity vs. central vision, complex vs. uniform background, dynamic vs. static situation (in terms of self motion as well as optic flow), anticipation due to prior knowledge vs. abstract task, etc. However, collecting data in the reference scenario is not as simple, and depending on the experimental protocol, the impact of the above factors may take variable importance, and interact in a different way, leading to various field factor values.

In contrast, we propose a comprehensive approach, splitting the main parameters responsible for the field factor, through appropriate and separate experiments. The first step (Mayeur, Brémond, & Bastien, 2008) was to assess, in conditions close to the STV laboratory conditions, the effects of a sensorimotor activity and target eccentricity on target detection threshold under mesopic light levels, which is the range of night driving. The data showed an effect of the tracking task and eccentricity on peripheral event detection: both factors and their interaction were significant. The second step was to assess (Mayeur, Brémond, & Bastien, 2009) the effects of the visual context (road scene vs. uniform background) and dynamic background (static vs. video) on the same target detection performance. The data showed that both the semantic and dynamic contexts decrease the target detection performance.

In the present paper, we go deeper into the investigation of the effect of the driving activity on peripheral target detection. In addition to the two laboratory experiments described above, we conducted a closed-circuit experiment, and set the experimental conditions as close as possible to the STV reference scenario, allowing to assess the effect of the driving activity through comparing two subjects status: driver vs. passenger. This framework allowed to isolate the effect of activity, every other variable being close to the reference STV scenario. The main benefit of conducting a field experiment, compared to laboratory experiments such as those mentioned above, was to use the true reference scenario, which is not possible in laboratory experiments, even with a driving simulator.

The experimental parameters were set in order to allow this comparison. We used an experimental road section in Rouen (France) at the CETE-NC (French Department of Transportation), between March and May 2008. The STV scenario was consistent with the experimental apparatus: a straight road of 450 m (see Fig. 2) without road marking. The luminaries' height and inter-distance were set in such a way that the same physical target (a 20 cm vertical square with 60% reflectance) was seen with contrasts from "not visible" to "easily visible" at a distance of 80 m. Wet driving conditions were avoided, because it would have modified the photometric luminance of both target and pavement, and thus the target visibility. The circuit proposed a low demands on information processing while driving, and a low demand on vehicle handling (no traffic). Traffic cones were introduced in order to increase to some extend the workload demand (see road section 1 in Fig. 2).

The research's aim was to introduce the driving activity in the lighting design in order to understand its "weight" on the detection performance. We compared the passenger and the driver conditions with the same task, which is closely related to the reference scenario of the STV model. While a number of field experiments have been conducted for road lighting applications (see Bullough & Rea (2004), Langham & Moberly (2003) for a discussion), our methodology, comparing a driver and a passenger condition, was not used previously to our knowledge, except, to some extend, by Lee and Triggs (1976) and by Bhise, Meldrum, Forbes, Rockwell, and McDowell (1981). Lee and Triggs (1976) found no effect of the status (driver/passenger) on the detection of peripheral lights (30–70°). Bhise et al. (1981) investigated the road visibility under rainy weather. Their "passenger" condition did not lead to a direct comparison with the "driver" condition, as the car itself was stopped.

The driving activity is highly costly in perceptual, cognitive and motor resources (Allen, Lunenfeld, & Alexander, 1971; Bellet, Bailly-Asuni, Mayenobe, & Banet, 2009). The cognitive workload is a topic of growing interest, due to the increasing use of onboard information systems (including the phone). An absolute workload measurement suffers from a lack of operational definition, so that the main approach is to compare several conditions in terms of workload. Previous studies have

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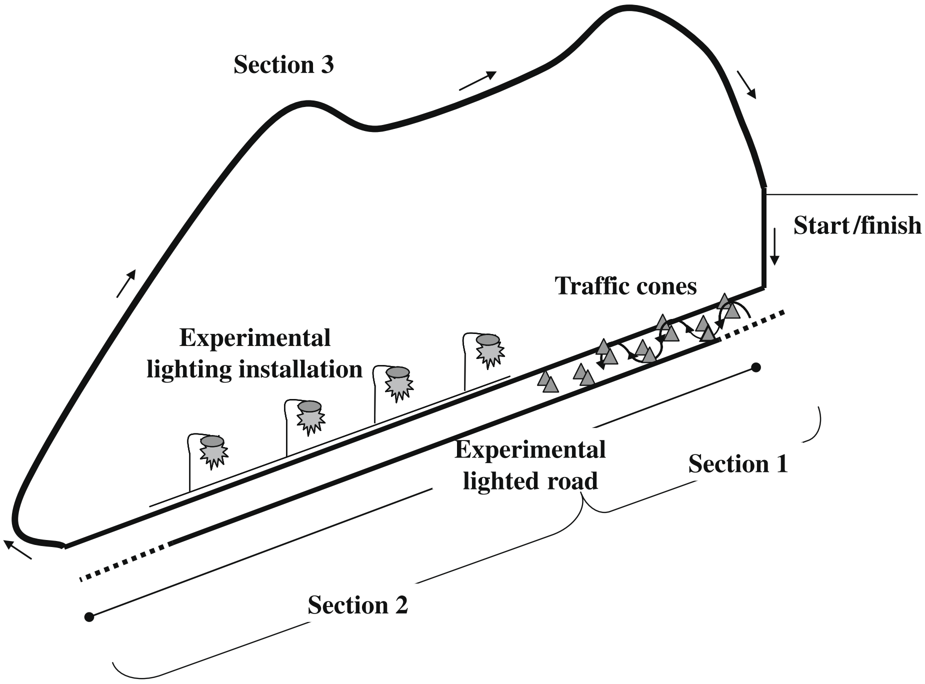

Fig. 2. Schematic layout of the circuit with location of the experimental lighted road (not to scale). Section 1: starting point and traffic cones; section 2: road lighting installation; section 3: office buildings.

investigated the driver status about phone calls, conversation types, in-vehicle information systems, etc. (e.g. Patten, Kircher, Östlund, & Nilsson, 2004), with different skill levels (novice, expert, professional drivers, e.g. Young & Stanton, 2007). An increase in the driving task complexity, as well as adding non-driving tasks while driving are expected to increase the driver's mental workload (Lemercier & Cellier, 2008). Recarte and Nunes (2003) have studied the effects of mental workload on visual search and decision making in real traffic conditions. The participants had to perform several mental tasks while driving. The study showed a detection deterioration due to the workload (detection delay and identification impoverishment). Falkmer and Gregersen (2005) proved that the driver's experience tends to lower the mental workload. Ma and Kaber (2005) have studied the effect of an Adaptive Cruise Control (ACC) system and of a cell phone, on driving performance and on mental workload. Their results indicated that the use of the ACC system improves the driving performance and reduce the driver's mental workload. However, the mental workload strongly depends on the system characteristics and on the task to be carried out (Young & Stanton, 2004).

All these studies consider the mental workload as a dependent variable. In contrast, very few studies used the workload as a dependent variable in the context of driving. This may be due to the fact that performing a secondary task while driving leads to attentional errors, with potential dramatic consequences. The mental workload theory (Wickens, 1984; Wickens & Holland, 2000; Wickens, Toplak, & Wiesenthal, 2008) argued that attentional errors are linked with secondary tasks achievements. These errors may be related to an overload, due to the limitation in cognitive resources (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). A given task does not produce the same workload for different drivers, depending on their experience, or even for the same driver, depending on her/his state during the driving task. Thus, Wickens and Holland (2000) made the assumption that the workload is defined by the relation between resource supply and task demand, that is to say, the workload is the amount of information processing resources used for task performance.

Many authors have discussed the road environment impact on the mental workload (Fastenmeier & Gstalter, 2007; Hollnagel, 2006; Hollnagel, Nabo, & Lau, 2003; Summala, 1996, 1997). For example, Summala (1996, 1997) suggested that the road environment (e.g. the increase of road curvature) may lead the drivers to decrease their speed in order to keep the vehicle control, due to a corresponding increase in workload. Some authors have studied the overload due to a secondary task while driving, using the divided attention protocol (Nunes & Recarte, 2002) and the Peripheral Detection Task (PDT) protocol (Jahn, Oehme, Krems, & Gelau, 2005; Patten, Kircher, Ostlund, Nilsson, & Svenson, 2006; Patten et al., 2004; Törnros & Bolling, 2006; Young & Stanton, 2007). In the PDT protocol, the driver is asked to report the appearance of a peripheral target (on the vehicle windshield), the reaction time (RT) being taken as a measure of the driver's performance. The divided attention protocol being uneasy to implement in a driving context, the PDT protocol is considered as a promising method to assess the driver's workload.

The present study investigated the target detection performance, comparing driver and passenger conditions. The main independent variables were the visibility level (VL) of the targets to be detected, and the status of the participants (driver vs. passenger). The dependent variable was the detection distance of the targets, which was defined as the distance to the target when a subject pressed a button. Our main hypothesis was that even in this low demanding conditions, passengers would

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have better performances than drivers, because the target detection task alone is less demanding in information processing than a primary task of driving together with a secondary task of target detection: the passengers' workload is smaller than the drivers' workload. The subjects in this study may be described as alerted, as they were instructed to look for targets. As the driving context was not manipulated in our experiment, our results are limited to the low demanding driving conditions of the study (no traffic, no crossing, straight lane, low complexity of the landscape).

2. Method

2.1. Participants

Thirty-four adults (11 women and 23 men) with a mean age of 36 years old ($SD = 8.0$) served as subjects. They were recruited from the French National Agency for Employment and were paid 55 euros for their participation. None of the participants was familiar with the hypotheses under investigation. They were required to be in good general health, to have a current driving license for at least five years. All the participants reported to drive regularly. A written informed consent was obtained after the study was fully explained, and they had the option to withdraw from the study at any time.

The subjects were randomly assigned to one of two groups. The first group (A) was composed of 18 subjects (6 women and 12 men) with a mean age of 36.5 years old ($SD = 7.7$). The second group (B) was formed of 16 subjects (5 women and 11 men) with a mean age of 35.5 years old ($SD = 8.6$). No statistical difference was observed between these two groups in terms of age ($t(32) = 0.33$, $p = 0.74$).

All participants passed a visual acuity test (Visiotest). A corrected binocular visual acuity of 5/10 was required to participate to the experiment. Subjects wore the optical correction that they normally wear while driving, if any. Group A had a mean acuity of 10.11 ($SD = 0.41$) and Group B of 11.12 ($SD = 0.36$). No statistical difference was observed between these two groups in terms of acuity ($t(32) = -1.84$, $p = 0.077$). All subjects had at least 8/10 corrected binocular acuity.

2.2. Apparatus

2.2.1. Closed-road circuit

The experiment was conducted under night-time conditions on a closed-road circuit of 1.2 km long (see Fig. 2). This roadway is designed to serve as a full-scale research facility to test, evaluate, and validate roadway lighting (e.g. Ménard & Cariou, 1994). The experiment was restricted to dry weather conditions (no rain, dry road surface). The circuit is free of road marking and was free of other vehicle during the experiment. An experimental road approximately 450 m long and 8 m wide was used for data collection. The fixed lighting installation uses 135 m of this road (Section 2 in Fig. 2). The pavement on this section classifies as R2 in the CIE road surface classification system (CIE, 1984) (R1 is for light surfaces, R4 for dark surfaces). The areas surrounding the test site mostly consist of trees and shrubs; the ambient illumination was thus uniform. The rest of the circuit (Section 3 in Fig. 2) was lighted at night and includes office buildings (unlighted at night).

2.2.2. Lighting system

The lighting installation remained unchanged all along the experiment. It was a one-side arrangement of aluminum poles, with adjustable spacing. The requirements lead us to choose a 45 m spacing leading to a lighted area around 150 m (Section 2 in Fig. 2, see also Fig. 3). The mounting height of the luminaries was set to 8 m for the experiment. Each luminary contained

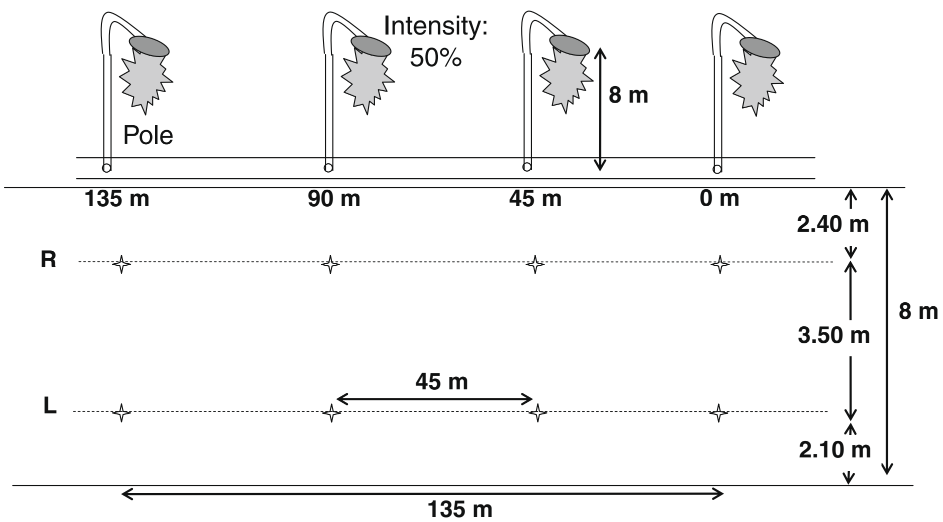

Fig. 3. Schematic layout of the experimental lighted section (not to scale), Section 2 in Fig. 2.

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a 150 W High Pressure Sodium (HPS) light source provided by Thorn Lighting. Output lumens were controlled by potentiometers, which allowed modulating the light power to 50% of the nominal value. The intensity was selected in order to lower the visual performance, avoiding too easy detections from the entering end of the experimental road.

In the lighted portion of the circuit, a small white point was paint every meter on the two sides of the road (L and R in Fig. 3), allowing the experimenters to put the targets accurately on the road. Eleven pairs of traffic cones, with the same lateral (4 m) and longitudinal separations (20 m), were situated on the first section of the circuit (Section 1 in Fig. 2). Such traffic cones were already used in a field experiment by Van Bommel and Tekelenburg (1986) in order to increase the workload.

2.2.3. Instrumented vehicle

The instrumented vehicle was a 2002 Peugeot 806. Speed and lane positions were measured using an internal vehicle sensor (Garmin Streetpilot 2650 GPS). A participant pressing a button located on the steering wheel actuated the recording of his/her position. The distance detection was computed as the vehicle distance from the target at the moment when the subject responded. Low-beam headlights were active during all tests to certify safety and to catch up with ecological validity. One experimenter sat in the instrumented vehicle (on the back seat or driving, depending on the status, described later), while the other stayed around the Section 2 in order to change the target position (he was not visible when the car was on Sections 1 and 2).

2.2.4. Target specifications

Twenty cm width square flat targets are generally used in roadway visibility research. While the use of this standard target is discussed (Lecocq, 1999), we decided to use it in this experiment, in order to be consistent with previous researches and with current practice (see Fig. 4). The target material avoided any risk for the participants in case of collision. The luminance contrast was modified by a physical target displacement on various locations on the non-uniform lighted pavement (see Fig. 5).

Sixteen target locations were chosen in order to get relevant luminance contrast values, allowing to investigate the study's hypotheses. Exploratory experiments suggested that contrasts ranging from 0 to 0.7 and located along the lines L and R could produce a detection distance between 20 m and 200 m, due to the contrast range.

2.3. Photometric measurements and computation

Photometric measurements were performed in order to compute the target contrasts and visibility levels (VL) for a standard observer, assuming a seeing distance of 30 m and an observation height of 1.20 m, leading to an observation angle of 2.29° (see Fig. 6), which is the standard geometry for road marking photometry (European Norm, 2007). The luminance is the amount of light reflected in a given direction (in our case, towards the driver), and is measured in candela per square meter (cd/m^2). The lighting design modifies the target and pavement luminance, so both measures were necessary (for each target position) in order to compute the contrasts for the 16 selected target positions.

From the contrast and background luminance, the VL values were computed using Adrian's model (Adrian, 1989), for a 23 years old subject. A large range of contrasts and VL could be found with a single target moved to several locations on the experimental road, with 16 contrast values between 0.016 and 0.608, and VL between 0.20 and 16.9 (VL = 1 is the detection threshold in laboratory conditions when the target is seen with 10′ of angular size). In the experiment, each target location was associated to the corresponding contrast value and VL (Fig. 6). The VL was thus a controlled independent variable in

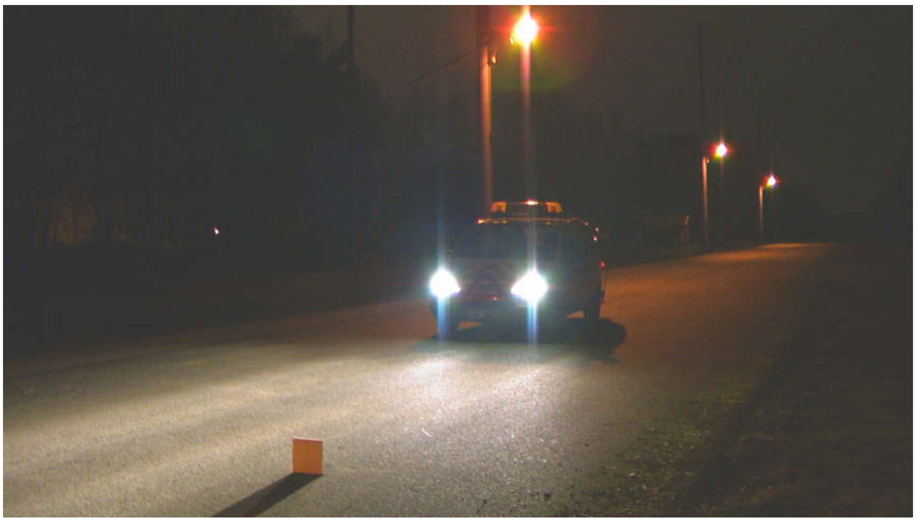

Fig. 4. Instrumented vehicle and target on the experimental lighted section.

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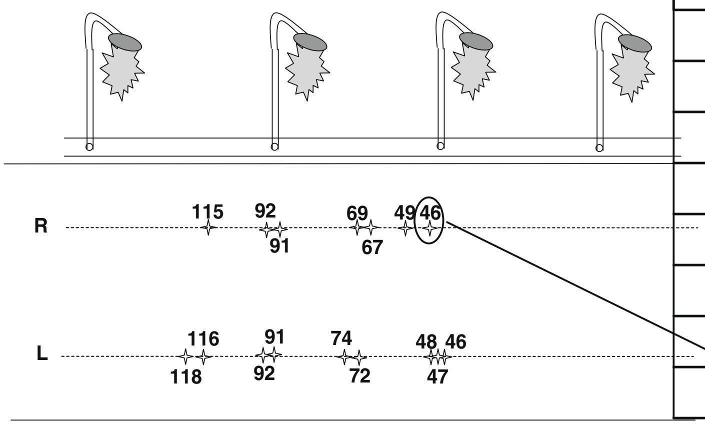

Target	Position	VL	Target	Position	VL
1	116 L	3.4	9	115 R	2.5
2	49 R	16.9	10	92 L	5.5
3	74 L	0.5	11	67 R	6.5
4	69 R	1.7	12	91 R	6.8
5	48 L	9.8	13	47 L	4.4
6	91 L	3.0	14	118 L	0.2
7	92 R	13.9	15	72 L	1.5
8	46 R	7.1	16	46 L	1.9

Fig. 5. Schematic layout of the experimental lighted section (not to scale): target positions and visibility levels (VL).

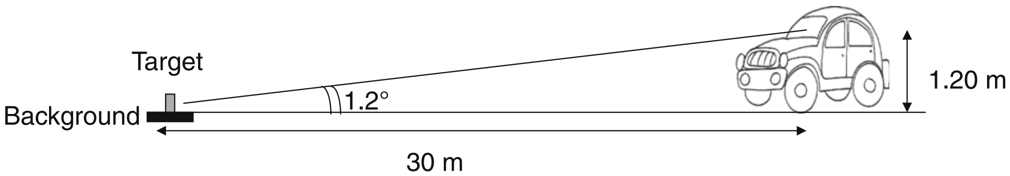

Fig. 6. Geometric scenario for the luminance measurements.

the experimental design. However, it was interesting to compute, from the same data, after the experiment was completed, posterior visibility levels (denoted VL_d in the following, d is for *detection*), using the actual detection distance for each condition instead of the conventional value of 10′ angular size. This allowed to compare our data to Gallagher and Meguire (1975) (see Section 4 of this paper).

All measurements were performed in standard road photometry conditions, that is, without taking the vehicle headlamp into account. Supplementary illuminance measurements were made in order to check for the changes in target contrasts and VL due to the headlamps, which were tuned to low power, and directed in order to focus on the nearest part of the road. The measurements showed that the changes in contrast did not alter the target visibility for distances greater than 35 m; for smaller distance, and depending on the target position, the headlights may have modified the contrasts.

2.4. Procedure

Subjects were split in two groups (A and B) and completed 32 laps in two Phases (see Table 1). Phases 1 and 2 were counterbalanced within the Groups A and B. Two status conditions were defined: Passenger (P) and Driver (D). In the Driver status, subjects had to press a push button located at the steering wheel as soon as they detected the target stimulus placed on the experimental lighted section. In the Passenger status, the same participants had to detect the target stimulus while the experimenter drove (the push button was in the subject's hand). The experiment duration did not exceed 2 h (including 45 min driving). During those nights when experiments were conducted, two subjects participated. In order to control the circadian rhythms effects, one participant began the experiment at 21 h, and the other at 23h30.

In the driver condition, the subjects were instructed to drive through the traffic cones at 30 km/h (first part of the experimental lighted road, Section 1 in Fig. 2) and then to drive straight between the L and R points at 40 km/h (lighted part of the

Table 1
Description of the experimental design.

Groups	Phases	
	1	2
A	Passenger (P) 16 laps (16 VL) 2 schedules (21 h/23h30)	Driver (D) 16 laps (16 VL) 2 schedules (21 h/23h30)
B	Driver (D) 16 laps (16 VL) 2 schedules (21 h/23h30)	Passenger (P) 16 laps (16 VL) 2 schedules (21 h/23h30)

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experimental road, Section 2 in Fig. 2). They were asked to drive naturally and to follow the traffic rules. Each participant was given a practice run without target (two laps of the circuit) in order to familiarize with the car, the road, and the driving task.

After the two Phases were completed, a "static" condition was added. In this condition the participant was a passenger, and the experimenter drove very slowly (5 km/h). The participant had to press the push button as soon as s/he detected the target stimulus. Only one VL was tested in this condition, with the same target position as in the first lap (VL = 3.4).

2.5. Statistical model

All data were checked for normality prior to analysis. Despite the instructions of driving through the traffic cones at 30 km/h and straight between the cross line at 40 km/h, the speed at the moment of target detection was not homogenous in the two groups, nor between the Phases. Forty-eight (out of 1088) outliers were identified within the speed data (see Fig. 7) and subsequently eliminated (Keppel & Wickens, 2004). Violations of sphericity were corrected using Greenhouse–Geisser adjustments; however, the degrees of freedom reported in the text are based on the study design. Detection performance were measured repeatedly for all 34 participants across 16 VL conditions and two Phase conditions. Then, detection distance measures were analysed using a mixed repeated measures ANOVA with the Group and Schedule as between-subject factors, Phase and VL as within-subject factors (Group (2) × Schedule (2) × Phase (2) × VL (16); Speed as covariate). The Status factor was measured by *post hoc* contrast tests. For each demonstrated effect, the effect size was computed using Omega^2 (ω^2). In behavioural sciences, a ω^2 value of .15 or greater is considered a large effect, .06 is seen as a medium effect and .01 or smaller is a small effect (Keppel & Wickens, 2004). The threshold for statistical significance was set to .05.

3. Results

Fig. 7 (right) shows that the greater the speed, the smaller the detection distance. To take this fact into consideration, the speed was included in the statistical model as a co-variable (see Table 2), which increased the power of *F*-tests by reducing the error term. The Acuity factor, $F(1433) = 3.47$, $p = .063$, and the Age factor, $F(1433) = 1.53$, $p = .217$, did not co-vary with the detection distance and were not considered as co-variables in the ANOVA model.

On the average, the detection distance was 118.85 m for Group A and 128.35 m for Group B (Table 3): the Group effect, $F(1, 30) = 3.34$, $p = .0775$, was not statistically significant. The mean detection distance at 21 h was 119.23 m compared to 128.56 m at 23h30. The Schedule factor was not statistically significant, $F(1, 30) = 0.31$, $p = .5828$.

The mean detection distance was 112.63 m in Phase 1 and 135.42 m in Phase 2; the Phase effect, $F(1, 29) = 39.47$, $p < .0001$, was significant. The effect size, however, was small, $\omega^2 = .015$. Furthermore, we observed that the higher the VL, the higher the detection distance ($F(15, 465) = 29.12$, $p < .0001$), with a medium effect size, $\omega^2 = .13$ (see Fig. 8). A Spearman correlation coefficient revealed a significant positive association between VL and detection distance ($r = .47$, $p < .0001$). These results are consistent with common knowledge that the VL is a relevant road visibility index.

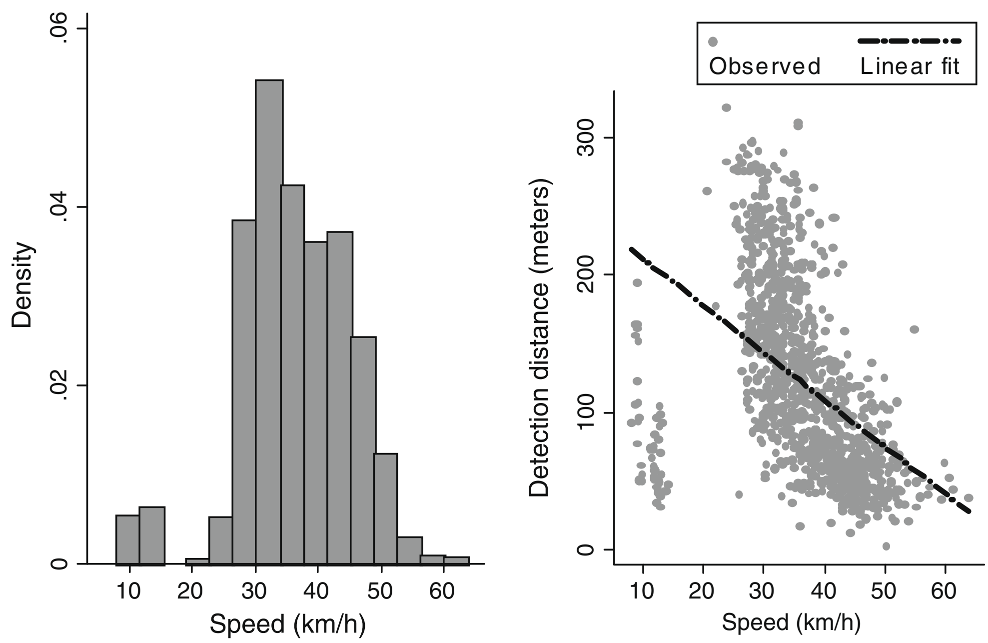

Fig. 7. Histogram of the speed (left) and speed according to the detection distance (right), for the 34 subjects.

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Table 2
Effects of phase, group, schedule, VL and speed on the detection distance.

Factors	*F*-value	*p*-Value
Group	3.34	.0775
Phase	39.47	.0000
VL	29.09	.0000
Schedule	0.31	.5828
Speed	67.85	.0000
Interactions		
Schedule × group	1.05	.3132
Phase × VL	4.92	.0000
Phase × group	12.57	.0014
Phase × schedule	0.00	.9714
VL × group	1.28	.211
VL × schedule	0.72	.769

Table 3
Mean (and standard deviation) detection distances for Groups A, B, according to the Phases 1, 2.

Groups	Phases		Total
	1	2	
A	111.21 (72)	127.97 (73)	118.85 (73)
B	114.23 (54)	142.42 (52)	128.35 (60)
Total	112.63 (64)	135.42 (68)	123.52 (67)

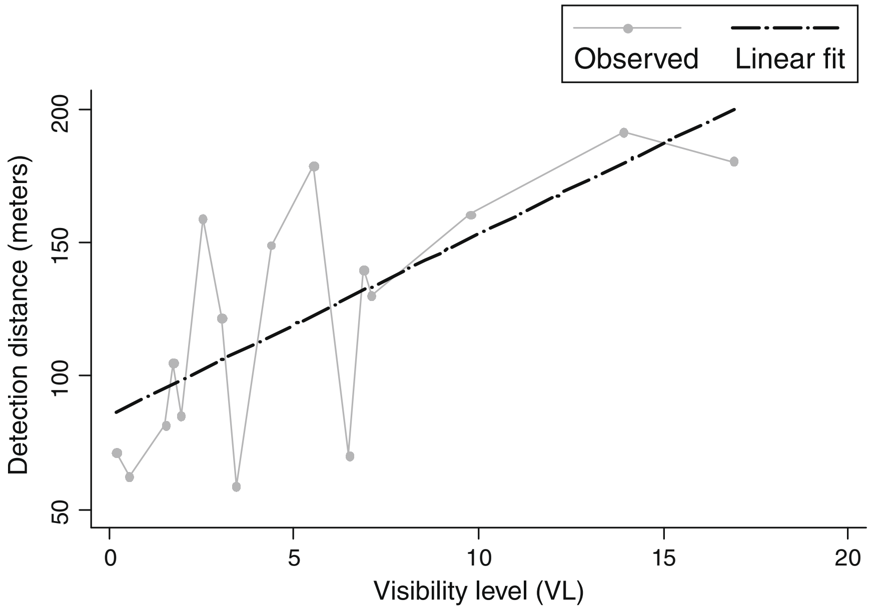

Fig. 8. Mean detection distance according to the VL.

The Passengers' mean performance was 126.81 m, compared to 121.1 m in the Driver status. The *post hoc* analysis indicated that the difference between the Driver and Passenger status was significant, $F(1, 29) = 12.41$, $p = .0014$, with a small effect, $\omega^2 = .005$.

The interaction between the Phase and the Group factors was significant ($F(1, 29) = 12.57$, $p = .0014$), with a small effect, $\omega^2 = .005$. During Phase 1, the mean detection distance was 111.21 m for passenger Status (Group A) and 114.23 m for driver Status (Group B), and this difference was not statistically significant, $F(1, 32) = 1.39$, $p = .2476$. During Phase 2 however, the mean detection distance was 127.97 m for the driver Status (Group A) and 142.42 m for the passenger Status (Group B), which was statistically different $F(1, 30) = 8.36$, $p = .0071$.

Furthermore, the interaction between the Phase and VL factors, $F(15, 433) = 4.92$, $p < .0001$, was significant (Fig. 9): the VL effect was higher in Phase 2. The strength of the relationship between the VL and detection distance in Phase 1 was medium

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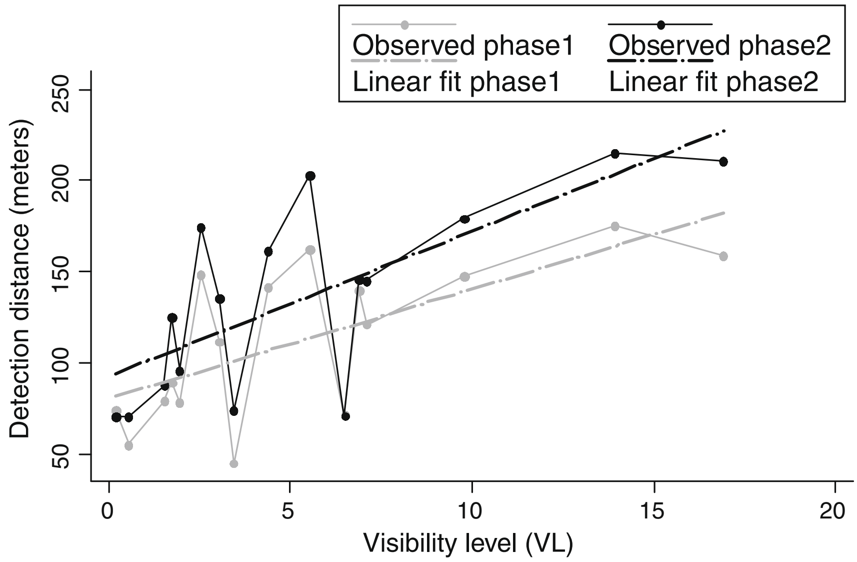

Fig. 9. Mean detection distance and linear fit according to the VL, and the Phases 1 and 2 (interaction VL × Phases).

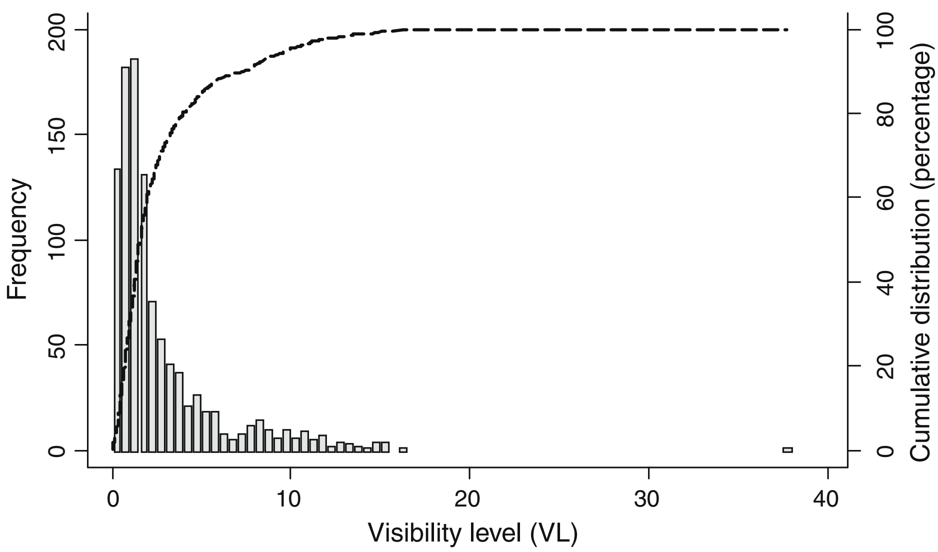

Fig. 10. Frequency and cumulative distribution of VL_d.

($\omega^2 = 0.12$): the VL explained 37% of the model's variance. The relationship between the VL and detection distance in Phase 2 had a large effect ($\omega^2 = 0.17$), and VL explained 46% of the variance.

For target 1 (VL = 3.4), the mean detection distance was 85.47 m for the Static condition, 62.29 m for the Passengers and 55.92 m for the Drivers, and the effect was statistically significant $F(2, 60) = 29.23$ $p < .0001$. The Dunnett test showed that the difference between the Driver and Static conditions, $F(1, 29) = 19.60$ $p < .0001$; and between the Passenger and Static conditions $F(1, 33) = 46.62$ $p < .0001$, were both significant. Comparing the mean detection distance between the static condition (85.47 m), Phase 1 (45.15 m) and Phase 2 (74.37 m), the effect is statistically significant $F(2, 60) = 50.32$ $p < .0001$. The Dunnett test showed that the difference between Phase 1 and the Static conditions, $F(1, 32) = 52.93$ $p < .0001$, and between Phase 2 and the Static conditions $F(1, 30) = 29.86$ $p < .0001$, were also both significant.

A posteriori visibility levels VL_d were computed using Adrian's model (Adrian, 1989), with the detection distance instead of the conventional 10′ target angular size. Fig. 10 shows the cumulative distribution of VL_d for the 1088 data, with $VL_d = 5.0$ for the 85th percentile, and $VL_d = 10.0$ for the 95th percentile.

4. Discussion

The aim of this study was to assess the difference in a detection task at night between passenger and driver status while driving on a circuit under road lighting. The detection distance was slightly underestimated because the reaction time be-

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tween visual detection and motor response (pushing a button) was not taken into account. Effects of the VL and of the Status were found, which validates the hypothesis under investigation. The VL effect was significant, and a Phase effect was found in favour of Phase 2, showing a practice effect.

4.1. The passengers' performances are higher than the drivers' performances

The hypothesis under study was validated: the passengers' performances were higher than the drivers' performances. This result suggests significant changes in road lighting design. It is a new step in the direction taken by the authors in previous laboratory experiments (Mayeur et al., 2008, 2009) where several weaknesses of the STV model were investigated: the restriction to foveal vision, the task load, and the background complexity and dynamic. These new results confirm that the STV model developed for road lighting applications, based on experiments with a single detection task, are limited; and that further work would allow more components to be included in a modified VL model. The current study shows that it is more difficult for a subject to detect targets when s/he is driving than when s/he is a passenger, even with a very low demanding driving task (no traffic, straight lane). These results suggest a modification of the reference scenario in order to take into account human factors components (workload) for road lighting design.

In our study, participants were asked to detect targets while driving. A lot of studies use the PDT as a workload measure while driving. (Jahn et al., 2005; Patten et al., 2004, 2006; Törnros & Bolling, 2006; Young & Stanton, 2007). For example, Patten et al. (2004) recruited professional, experienced drivers (taxi drivers and couriers) who were used to phone while driving. They measured the effects of hand-free and hand-held mobile phone-use on the drivers' ability to perform a PDT. While driving along a highway, subjects were instructed to press a button when one among a set of small red lights was illuminated for 2 s in peripheral vision. The PDT is considered by Jahn et al. (2005) as a promising method to measure driver's workload, and to assess safety-relevant workload due to the use of in-vehicle information systems. In our study, the target to be detected was outside the vehicle, nevertheless this task allows to assess the workload due to the driver activity compared to the passenger activity. However, the workload has a multivariate neuro-physiological, perceptual and cognitive nature, which suggest that an array of assessment tools and methodologies may be needed to adequately reflect driver workload in a driving situation (Baldwin, Freeman, & Coyne, 2004).

The difference between the driver and passenger status was statistically significant, however, the effect was small. This may be due to the low complexity of the driving task in the experiment: there was no traffic and the circuit proposed a low demand on information processing and a low demand on vehicle handling. A lot of studies have investigated the use of the PDT in simulated and real driving, using various levels of environment complexity. Jahn et al. (2005) investigated the sensitivity of the PDT compared to alternative workload measures, in a driving task including a route guidance system. They used either a high demand on information processing and a high demand on vehicle handling (HH), or a low demand on information processing and a low demand on vehicle handling (LL). As expected, they found that detection and RT performance on the HH sections were lower than on LL sections. The effect of mobile phone conversation was studied in various traffic environments by Törnros and Bolling (2006) on a driving simulator. A main effect of the environment was found: the RT was higher in complex urban environment than in the other environments. Patten et al. (2006) investigated the driver experience and the cognitive workload in various traffic environments (HH, medium, LL). The low mileage drivers' RT performance (PDT) did not significantly differ when comparing between the medium and the HH traffic environment. The high mileage drivers' performance did, however, noticeably deteriorate from the medium to the HH traffic environment complexity.

The present study and the literature suggests that road lighting design should take the environment complexity into account, for instance to modulate the VL field factor.

4.2. Detection distance, visibility level and field factor

Field experiments have been conducted to extend findings about visual performance under mesopic light levels to a driving context. For instance, Wood and Owens (2005) showed that the Contrast Sensitivity Function (CSF) is more predictive of the driver's recognition performance at night than the photopic visual acuity. Some authors have investigate the effect of various light sources with respect to a complex driving task (e.g. Akashi, Rea, & Bullough, 2007), but only a few studies focused on the visibility level in a dynamic driving situation. Ising, Fricker, Lawrence, and Siegmund (2003) used experimental data from Olson, Aoki, Battle, and Flannagan (1990) to compute visibility levels with Adrian's model, without road lighting. Olson et al. (1990) tested 25 subjects driving at 40 km/h along a private rural road. They were instructed to alert when they detected "pedestrian" targets (dummies) standing on the roadside. Subjects were told on which side of the road the target would appear. Ising et al. (2003) also considered unalerted drivers, which is closer to the ecological driving condition. Based on Roper and Howard (1937), who showed that the detection distance of unalerted drivers was on average half the detection distance of alerted drivers, Ising et al. (2003) analysed their data to account for the driver's unexpectedness. They computed that VL_d (without road lighting) ranges between 1 and 23 for the 50th percentile of alerted subjects, and between 13 and 210 after correction for subjects' alertness. Recently, Ising (2008) proposed to modify Adrian's visibility model to incorporate the CIE General Disability Glare Equation (CIE, 2002). Using the same detection data from Olson et al. (1990), he found average threshold visibility levels between 0.1 and 18 for alerted drivers, and between 14 and 89 for unalerted drivers. Note that these VL are proposed with vehicle headlights but without road lighting.

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Gallagher and Meguire (1975) have explored the empirical relationship between the driver's visual performance under road lighting (time to target when the target is detected) and several visibility indexes. They have analysed the visual performance of 941 drivers and found VL_d values between 4 and 12 at the moment of detection. The visibility of a pedestrian dummy and of discs of varying size and contrasts were also measured under dynamic night driving condition by Hills (1975). The three subjects of the study had to press a button when the target was just visible, and gave a verbal answer about the nature of the object. He found that a VL of 4 was required as a "just visibility criterion", whereas a VL up to 30 may be required for unexpected appearance of obstacles. Mace and Porter (2002, 2004) have investigated the relationship between road lighting design, visibility and driver comfort. They used the STV model (IESNA, 2000a, 2000b) in a dynamic driving situation, in order to describe the various (9) tested road lighting designs. The study's aim was not to propose a VL range or field factor, but to compare the lighting designs. The results suggest that medium levels of illumination provide comparable visibility as higher levels, when the lighting design produces non-uniform luminance. In addition, they found that some lighting designs provide less visibility than no lighting at all.

When reading the literature, it appears that various VL thresholds are found, based on various experimental protocols with and without road lighting. We have computed VL_d values at the moment of target detection, using the actual detection distance in Adrian's computational model. This led us to use VL_d as a dependant variable (with no direct link to the independent variable VL in our experimental design). Gallagher and Meguire (1975) used such a VL_d, arguing that public lighting should allow 85% (or 95%) of the drivers to detect the targets at a safe distance. In our study, this leads to VL = 10.0 for the 95th percentile. The comparison is not straightforward, but the data from Gallagher and Meguire (1975) lead to a comparable value of VL = 8.3 for the 95th percentile at 40 km/h.

4.3. General discussion and practical implications

In the present study we used a predefined target, whereas in an ecological driving context there is no such predefined search targets (except for some road signs). The expectations are assumed to guide visual search, with strong top-down control. The stronger the expectations are, the less active is the information processing (Martens & Fox, 2007). Few studies have examined visual search in a dynamic driving environment without predefined search targets. To our knowledge, Roper and Howard (1937), who studied unexpected target detection with unalerted subject are the only ones (the drivers were unaware that they were engaged in a test). Their approach is very interesting and more ecologically validated in relation to the driving activity, but such experimental design would be difficult to replicate nowadays. The subjects in our study may be described as alerted, as they were instructed to look for targets. We may guess that with unalerted subjects the detection distance recorded in a similar situation would be lower.

One result of the current study, the "static" condition, compared to the driving condition, extends the results from a previous experiment (Mayeur et al., 2009): the mean detection distance was higher for the "static" condition than for the two dynamic conditions (passenger and driver status): the speed (and thus, apparent motion) decreases the detection performance. The spatial and temporal dynamics (velocity, optic flow, etc.) of the driving activity, whatever the status, is thus an important component of the driving task at night.

Critics of the VL index raise several classical objections (e.g. Lecocq, 1999; Mace & Porter, 2004; Raynham, 2004): the standard target is more difficult to detect than most obstacles on the road. The emphasis on a small uniform square target ignores the importance of more realistic targets such as pedestrians which differ in terms of size, shape complexity and texture. Moreover, the VL computation does not take into account the car head lighting effect, etc. Finally, the STV is not a measurable characteristic, but a construct, which is not easily verified in the field (Mace & Porter, 2004). The STV model also fails in setting a VL threshold, partly because of its weak relevance to real driving situations. Our studies give to a better understanding of some weaknesses of the VL approach. We hope that our work may contribute to improve the scientific foundation of this model in terms of ecological validity, in the sense that some basic aspects of the target detection task may now be taken into account in a future road visibility index.

The results presented in this paper showed that the driving activity, even with a low demand on information processing and a low demand on vehicle handling, should be included in future road visibility indexes. One may guess that in a more complex environment, the difference between driver and passenger status would be higher. To improve night-time road safety, the road lighting design should also take into account the various levels of environment complexity (urban road, roadway, etc.), leading to various levels of driver workload.

The framework for future work would include the study of more components of the night driving task. On the basis of the present study, direction of future research includes understanding the impact of the traffic and of the environment complexity on road visibility. The same experimental protocol could be used with more complex environments, but it may be difficult to control the variables. At least, a definition of visual complexity is needed. Driving simulators allow a better control of the experimental situations than do field experiments while reducing the risk, however, at the cost of a less realistic visual and proprioceptive environment. For instance, one may consider using a driving simulator in order to study the "alertness" factor, without ethical drawback. The ecological validation of driving simulators with regard to driver perception is still a key issue (Kemeny & Panerai, 2003), so one should take their limits into account, especially for night driving simulations (Petit, Brémond, & Vienne, 2009).

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