Effect of Task and Eccentricity of the Target on Detection Thresholds in Mesopic Vision: Implications for Road Lighting

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Objective: The aim of this work is to assess how adding a driving-related task affects the detection of objects in peripheral vision, under mesopic conditions. **Background:** The main index used to assess the quality of road lighting installations refers to simple detection tasks in foveal vision, which raises methodological and practical questions. **Method:** The experimental design consisted of a three-phase experiment. In the first phase, two groups (control and experimental) performed a peripheral detection task (simple task). Based on these results an individual detection threshold was computed for each participant and eccentricity. A tracking task was performed in Phase 2 for both groups (steering a tracking target along a circuit, on a screen). In the third phase, the control group performed the same task as in Phase 2. The experimental group performed a double task, with a tracking (primary) task and a peripheral detection (secondary) task. **Results:** The data show an effect of the tracking task and eccentricity on peripheral event detection. The tracking task caused detection performance to decrease from 84.2% to 67.5%, $p < .001$. **Conclusion:** The small target visibility model used in road lighting may be improved, taking into account the effects of task and eccentricity on target detection. **Application:** This study supports improved roadway lighting design by guiding consideration of sign eccentricity and task load.

INTRODUCTION

In the United States in 2003, almost 3 million people were injured and 42,643 people died in road accidents. For the past 25 years, 50% or more of the fatal crashes have occurred at night, despite the lower volume of traffic (Federal Highway Administration, 2007). A large number of these accidents involve perception failures, including those associated with information acquisition and information processing (Hills, 1980) for which vision is the main sensory channel. Road lighting is a tool for road authorities to improve the drivers' perception. Even though the relation between road lighting and road safety is not direct, an overview of field studies by the Commission Internationale de l'Éclairage (CIE) shows a positive correlation between road lighting quality and road safety (CIE, 1992b).

The main function of road lighting is to compensate for the low performance of the human visual system at night in terms of both contrast sensitivity and color discrimination. This low performance is attributable to the low sensitivity of the cone photoreceptors in mesopic vision (between 0.01 and 3.0 cd/m^2; Wandel, 1995), which is in the range of night driving. Road lighting increases the drivers' performance both in foveal and peripheral vision for object detection and recognition by increasing the visual adaptation level and lowering glare effects. Better visual performance improves the drivers' anticipation of hazards and makes them feel safer during the dynamic task of driving, which may have various implications in terms of risk or risk perception (Wilde, 2001) and, thus, road safety.

The main quality indexes in road lighting are related to the concept of visual performance (Rea, 1982), which comes from psychophysical sciences. The practitioners characterize a lighting installation with an estimation of the visual detection threshold for a small target on the road, at a distance the drivers use to pick up relevant information. This can be set in terms of driving safety: The

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lighting installations should be optimized in terms of a visual task that is critical for a given safety hazard (collision with an obstacle). To adapt the detection threshold from a laboratory psychophysical task to any visual task (e.g., to read or to detect a target on the road while driving), the CIE (1981) proposed a methodology that proceeds through a detailed analysis of this visual task, without taking into account the nonvisual aspects of the task. The visual task is split into several subtasks (ocular fixations, saccadic motions, and the cognitive part of vision), and each subtask is given a specific weight.

The small target visibility (STV) model (Adrian, 1989) considers the ability to detect a standard small target (18-cm uniform square) standing on the road at a given distance ahead (86 m) as a quality index of the lighting installation. It computes the detection threshold, ΔL_t, of the reference target from psychophysical data in the laboratory situation for a given lighting installation. Then, the visibility level (VL) index is computed as the ratio between the actual contrast, ΔL (between the target and its background – i.e., the road surface), and ΔL_t. For example, a VL = 7 means that the target's luminance contrast is seven times the contrast needed for object detection for a standard observer in laboratory conditions. Higher VLs result in more visible objects.

Adrian's (1989) proposal for road lighting applications sets a specific VL threshold for a visual detection task while driving, this threshold leading to a reference illumination level for road lighting engineering. Several threshold values have been proposed, ranging from 4 to 30 (Adrian, 1987; Association Française de l'Eclairage, 2002; Gallagher & Meguire, 1975; Hills, 1975), which shows a lack of consensus.

Thus, engineering practice in outdoor lighting lacks a scientific foundation (Ullman & Finley, 2007). A number of methods have been proposed in the scientific and technical literature, including those by the CIE and the Illuminating Engineering Society of North America (IESNA), but actual practice and recommendations (Association Française de NORmalisation [AFNOR], 2004–2005; IESNA, 2000) broadly stand on experts' agreements rather than on scientific models (Brémond, 2007).

We feel this is mostly because of the weakness of the models that have been proposed, in terms of ecological validity in relation to the actual driving experience. For instance, the STV model fails in setting VLs, partly because of its weak relevance to real driving situations. In this paper, we propose a methodology that improves the scientific foundation of this model in terms of ecological validity, in the sense that some basic aspects of the target detection task during driving will be taken into account in the model, rather than being included in a heuristic threshold level. It is a first step toward technical recommendations that are best fitted to road engineers' needs.

Adrian's (1989) model is based on a strong simplification of the actual driving task. It uses data from a single psychophysical task – target detection – which is only one among the many subtasks of driving (Crundall, Underwood, & Chapman, 1999). More precisely, psychophysical experiments do not take into account the driving task, which involves vehicle control activities and information processing. Another limitation of Adrian's (1989) model is its focus on foveal detection without taking into account peripheral detection: Driving requires the simultaneous use of central and peripheral vision. For target detection, peripheral vision is of dramatic importance (Owsley & McGwin, 1999). This point is consistent with the idea that public lighting should provide peripheral visibility so that potential hazards at any location on the road surface can be detected (Bullough & Van Derlofske, 2004). Therefore we designed a laboratory experiment in order to investigate these two weaknesses of the STV model.

The purpose of this experiment was to evaluate how a tracking task would affect target detection thresholds in mesopic vision, for various eccentricities, consistent with the process of seeking information from the road surface during driving. Three phases were designed (see Figure 1).

Phase 1. The first phase of the experiment (single task: peripheral target detection) used a psychophysical protocol close to the one used by Blackwell (1946). The purpose of this first phase was to measure the individual detection thresholds (IDTs) in peripheral vision for every participant and for three eccentricities (1.5°, 4° and 7°) in a single-task experiment. The IDT data collected during this first phase were compared with those in the double-task condition in Phase 3.

Phase 2. The second phase of the experiment involved a tracking task, on the same screen used in Phase 1, in which a tracking target was moved along a circuit with two crank handles. The aim of

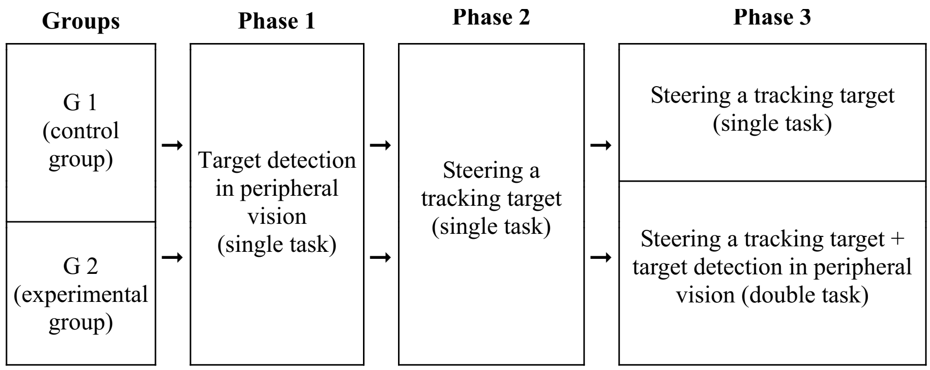

Figure 1. Schematic description of the experimental design.

this phase was to evaluate participants' performance in a simple sensory-motor task before adding a secondary task and to control for possible group differences in Phase 3.

Phase 3. The third phase, based on the double-task paradigm (Posner & Boies, 1971), consisted of the tracking task used in Phase 2 (steering a tracking target on a circuit) together with the peripheral detection task used in Phase 1. The peripheral stimuli were presented at the same eccentricities as those in the first phase of the experiment. The contrast was set for each participant and each eccentricity at the IDT for that participant, computed from the data gathered in Phase 1. The control group performed the same task as in Phase 2. The purpose of Phase 3 was to assess the impact of a primary task (tracking) on the peripheral detection task.

The decrease in peripheral detection performance with increases in target eccentricity strongly depends on the adaptation level. Moreover, peripheral detection performance is reduced in the mesopic range (relevant for night driving) as compared with the photopic range (daylight; Wandel, 1995). This made it desirable for the adaptation luminance in our experiment to be in the range relevant for night driving. In reference to a driving situation, we investigated eccentricities of up to 7°, which includes any point on the driver's lane more than 15 m ahead of the vehicle. This assumes a fixation at the center of the lane, which is of course a simplification of actual drivers' eye gaze behavior (Underwood, Chapman, Bowden, & Crundall, 2002).

Experimental data have shown that the complexity of the foveal task may or may not increase the contrast threshold for a peripheral detection task, depending on the target eccentricity. On the other hand, the detection task may or may not have an effect on the foveal task, depending on the complexity of the foveal task (Leibowitz & Appelle, 1969). However, in previous experiments, the foveal task was either purely visual (Ikeda & Takeuchi, 1975) or cognitive (Chan & Courtney, 1993; Plainis, Murray, & Chauhan, 2001); there was no sensory-motor component.

Those results led us to choose a tracking task, which is more relevant to a driving task. In our study, the tracking task consisted of steering a tracking target with two crank handles on a circuit displayed on a screen. This tracking task is adapted from a psychomotor test from Lahy (1933) that is still broadly used in France by transport operators in their recruitment test battery. This test measures psychomotor functions in the context of sustained attention. In the third phase of the experiment, the tracking task was considered the primary task because the main drivers' activity consisted of driving the car (guiding, steering, etc.). Thus the secondary task was the target detection task in the peripheral field of view.

METHOD

Participants

Thirty-nine adults (13 women and 26 men) with a mean age of 35.5 years ($SD = 11.2$) served as participants. They were all licensed drivers and had normal or optically corrected vision. All participants were naive to the purposes of the experiment. They were recruited from the Laboratoire Central des Ponts et Chaussées and from the Paris Descartes University.

The participants were assigned to one of two groups. Group 1, the control group, was composed of 19 participants (6 women and 13 men) with a mean age of 36 years (*SD* = 12.5). The second group, the experimental one, was formed of 20 participants (7 women and 13 men) with a mean age of 35 years (*SD* = 9.8). No statistical difference was observed between these two groups in terms of age, t (37) = 0.271, p = .781.

Apparatus and Experimental Room

The experiment took place in a room where the photometry is controlled (no windows, walls painted black). The experiment was carried out using a screen, a video projector, a pedal that recorded the participants' responses, and a computer that carried out the experimental protocol (see Figure 2). For all conditions, the screen background luminance was mesopic (0.65 cd/m^2), which is consistent with road lighting recommendations (between 0.5 and 1.5 cd/m^2; e.g., IESNA, 2000). The angular field of view of the screen was 30° in height (1.50 m) and 40° in width (2 m; Figure 2).

Phase 1: Target Detection in Peripheral Vision (Single Task)

Stimulus characteristics. Throughout the first phase of the experiment, a fixation target, which consisted of a black square (luminance 0.1 cd/m^2) 0.25° in visual angle, was displayed at a viewing distance of 2 m. One second after a beep (warning tone), a 150-ms target appeared randomly over a 3-s period at different eccentricities and contrasts. The target stimulus consisted of a 0.25° visual angle square.

The first independent variable was the *eccentricity* of the stimuli. Three eccentricity values were chosen: 1.5°, 4°, and 7°. These values allowed the presentation of the stimulus in three areas of the visual field: (a) proximity of the fovea, (b) the parafoveal region, and (3) the perifovea (Legrand, 1972). The second independent variable was the *luminance contrast* of the target. Luminance contrast was defined as the Weber fraction $C = (L_t - L_b)/L_b$, in which L_t is the target luminance and L_b the background luminance. An exploratory experiment suggested that a positive contrast ranging from 0 to 0.6 could produce a detection rate of 100% for the higher contrasts at the three eccentricities. Six contrast values were used in this experiment (0, 0.1, 0.21, 0.33, 0.41, and 0.60).

Procedure. Participants were seated 2 m from the screen with one foot on the pedal. After an 8-min adaptation period to the mesopic illumination (0.65 cd/m^2 on the display screen), the participants were instructed to stare at the fixation square and to press the pedal as soon as they detected a target stimulus. One hundred eighty stimuli (10 presentations × 3 eccentricities × 6 contrasts) were presented randomly to each participant. The stimulus position was chosen on a circle radius corresponding to one of the three eccentricities, with a random angular position.

During the experiment, a computer recorded the task performance (number of correct and false answers). Correct answers are answers given between the stimulus appearance and the next warning tone. The IDT for a given participant and a given eccentricity was defined as the smallest of the six contrasts detected for at least 70% of the corresponding stimuli. These individual contrast values were later used in the double-task condition (see Figure 1).

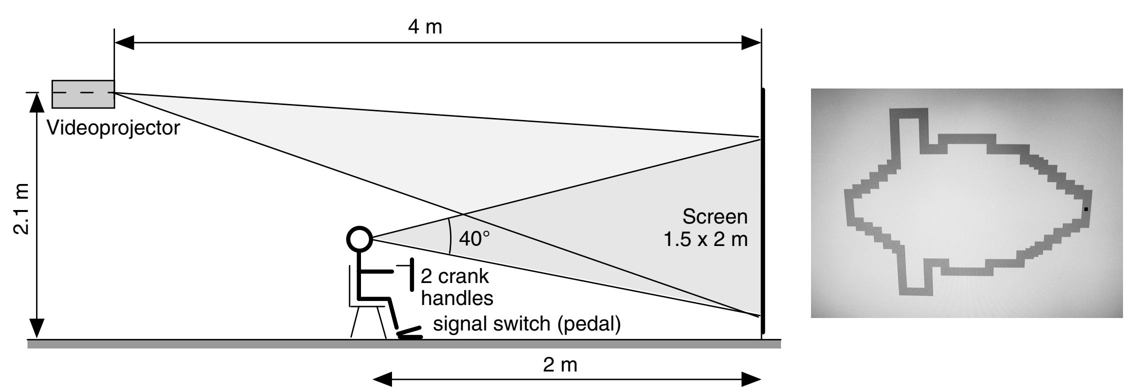

Figure 2. Schematic layout of the experimental room (left, not to scale) and circuit displayed on the screen (right).

Phase 2: Steering a Tracking Target (Single Task)

Apparatus and stimulus characteristics. A circuit (16° in maximal width, 14° in maximal height, 0.8° of thickness; see Figure 2) was displayed on the screen used previously. The background luminance was the same as in Phase 1, and the circuit luminance was 0.36 cd/m^2. A black square of 0.25° in visual angle, with the same properties as the fixation square used in the preliminary phase, was used as the tracking target unit. Its contrast with the background circuit was 0.56.

The participants could move this square with the help of two crank handles: The left crank handle allowed vertical motion (up and down), whereas the right one allowed horizontal motion (left and right). Tracking coordination was needed in order to move the tracking target square along the circuit because the horizontal and vertical speed increased with the rotation speed of the corresponding handle. The difficulty of this task, which was exacerbated by the low contrast between the tracking target and the circuit, was designed to ensure that the participants' gaze followed the tracking target.

Procedure. In this condition, participants in both groups sat in front of the screen with a hand on each crank handle. The only task was the displacement task. No peripheral target was presented during this phase. The participants were asked to drive the tracking target as fast as possible, without exiting the circuit. Two performance indexes were measured for the tracking task: the distance covered in 5 min and the number of exits from the circuit.

Phase 3: Effect of a Tracking Task on Target Detection in Peripheral Vision (Double Task)

In the third phase of the experiment, participants in the control group were instructed to repeat the Phase 2 (tracking) task. Participants in the experimental group were also instructed to conduct this tracking task, but in addition they were required to detect a peripheral target.

Stimulus characteristics. The eccentricities of the peripheral targets were the same as in the first phase of the experiment. Sixty stimuli were presented to each participant. Thirty peripheral targets (10 repetitions × 3 eccentricities) were presented to the participants in the individualized contrast (for each eccentricity), which had been computed during the first phase of the experiment (IDT). Moreover, 15 targets with null contrast (5 repetitions × 3 eccentricities) were presented in order to allow us to check (invisible stimuli) for possible false alarms, and 15 with a contrast value double that of the IDT (5 repetitions × 3 eccentricities) were also presented in order to include (high contrast) stimuli with a high probability of being detected.

The stimuli locations were chosen so as to avoid intersections between the targets and the circuit, which would have changed the target contrast. The eccentricity of each peripheral stimulus was computed on the assumption that the participants stared at the moving tracking target. Tracking target movements during the stimulus presentation (150 ms) were not considered when computing the stimulus position.

Procedure. In the double-task condition (experimental group), the tracking task was the primary task and peripheral detection was the secondary task. The same peripheral targets as those in the first phase were used. The participants were asked to press the pedal whenever they detected a target in peripheral vision while moving the tracking target square. They were asked to respond as quickly as possible, but without stopping the displacement task, which was their priority task. For the control group, the conditions and instructions remained the same as in Phase 2 (tracking condition).

RESULTS

Peripheral Detection Thresholds (Phase 1)

On average, the mean detection rate decreased from 57.2% for 1.5° of eccentricity to 44.4% and 30.7% for 4° and 7° of eccentricity, respectively. Moreover, the mean detection rate increased from 1% to 91.2% across the contrast values. It should be noted that only 1.2% of false detections were reported, making irrelevant an analysis based on signal detection theory (Wickens & Hollands, 2000).

Based on these results, an IDT was calculated for each participant. Figure 3 presents the number of participants with a given IDT value for each of the three eccentricities. The repeated-measures ANOVAs computed on the IDT, Eccentricity (3) × Group (2), indicate that the group effect, $F(1, 116) = 0.04$, $p < .8497$, is not significant. The eccentricity factor appears significant, $F(2, 116) =$

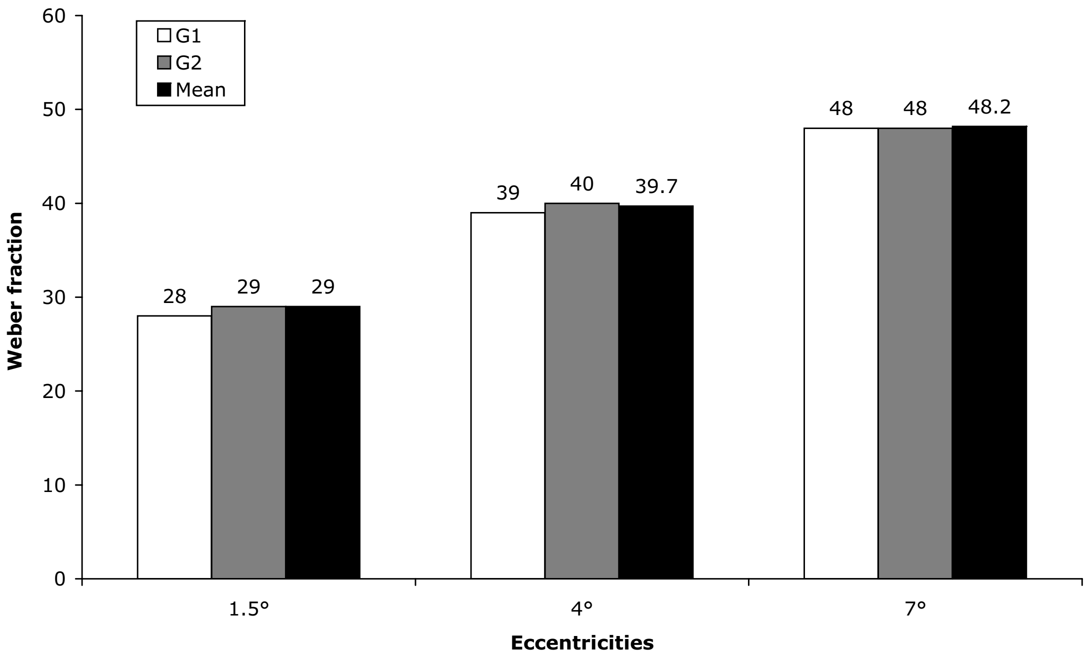

Figure 3. Mean IDT values (Weber fraction) and eccentricity for Groups 1, 2 and mean. G1= Group 1 (control group); G2 = Group 2 (experimental group).

124.73, $p = .0000$. The interaction of the two factors is not significant, $F(2, 116) = 0.12$, $p < .8892$.

Effect of the Detection Task on the Tracking Task (Comparing Phases 2 and 3)

Two performance indexes for the tracking task were recorded: the distance covered in 5 min (in pixels or fraction of circuit rounds completed) and the number of exits from the circuit. Figure 4 shows the mean distance covered and the number of exits for Phase 2 (tracking, Groups 1 and 2) and Phase 3 (single task: Group 1; double task: Group 2).

The repeated-measures ANOVAs computed on the distance covered, Group (2) × Phase (2), revealed a significant effect of the phase factor, $F(1, 77) = 25.32$, $p < .0001$. The group factor, $F(1, 77) = 0.001$, $p = .9799$, and the interactions are not significant. On average, the distances covered increase from Phase 2 ($M = 4109.36$ pixels – i.e., 4.566 turns completed) to Phase 3 ($M = 4709.56$ pixels – i.e., 5.233 turns completed).

In terms of exits from the circuit, the repeated measures ANOVAs indicate a significant effect for the phase factor, $F(1, 77) = 12.89$, $p = .0010$. The mean number of exits decreased from 41.5 to 31 from Phase 2 to Phase 3. The group factor, $F(1, 77) = 0.04$, $p = .8367$, and the interactions are not significant. On the average, there were 34.5 exits in Group 1 and 38 exits in Group 2.

Globally, the effect of the phase and the addition of the secondary task present the same tendencies as the distance covered and the number of exits. In other words, repetition of the task induced better performance: The distance covered increased and the number of exits decreased. The absence of a significant interaction indicates that the secondary task (peripheral detection) had no impact on the primary task.

Effects of a Tracking Task on Peripheral Target Detection (Comparing Phases 1 and 3)

To assess the effect of the sensory-motor task on peripheral target detection, we compared the performance of participants in Group 2 (experimental group) between Phases 1 and 3 for stimuli at the IDT. For the peripheral detection task, the mean variation between Phase 1 (single task) and Phase 3 (the double-task condition) is presented in Figure 5 for eccentricities of 1.5°, 4° and 7°. Moreover, in the double-task condition the false alarm rate was only 1.2% (null stimuli) and only 6% of the stimuli at 2 × IDT were not detected.

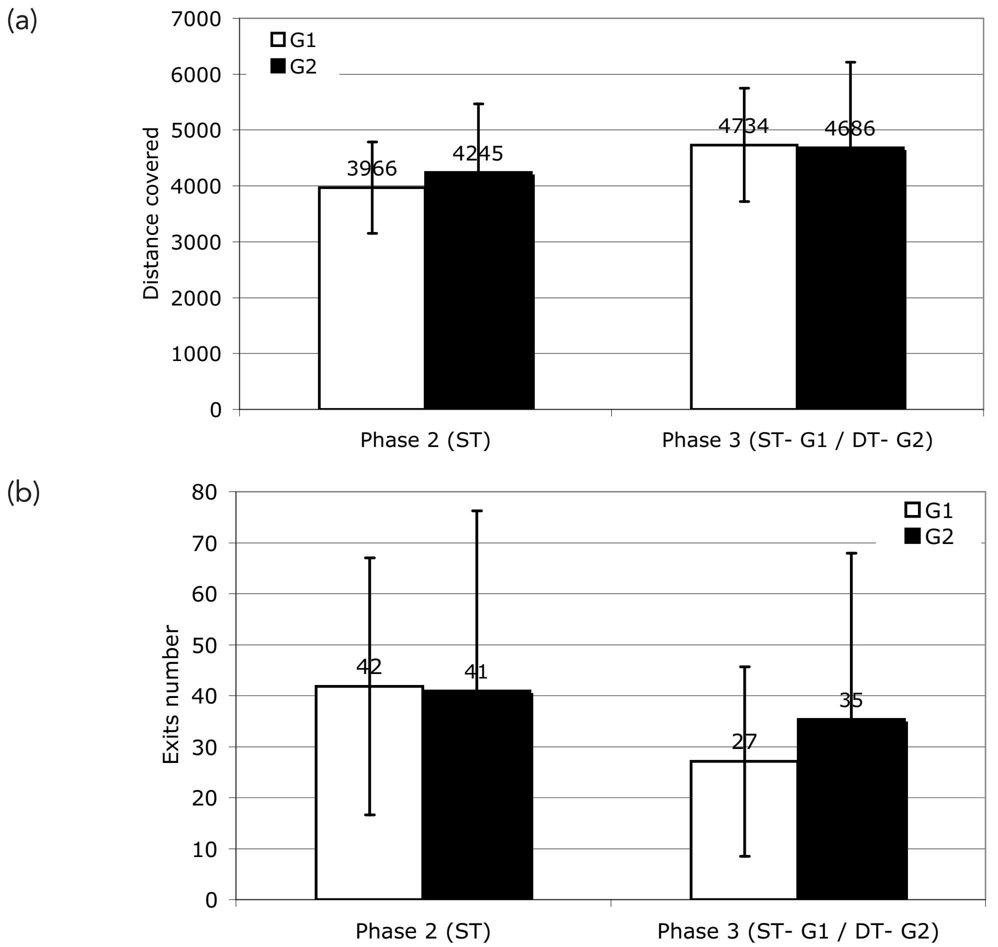

Figure 4. (a) Mean distance covered and (b) number of exits from the circuit for the tracking task in Phases 2 and 3 of the experiment. The conditions for Phase 3 are single task (ST) for Group 1 (G1) and double task (DT) for Group 2 (G2). Note: The greater the distance, the better the performance.

When we compared target detection performance from the single- and double-task conditions, we found a global decrement: Detection performance decreased from 84.2% to 67.5%, $F(1, 119) = 32.31, p < .001$. Performance also differed according to the degrees of eccentricity, $F(2, 119) = 5.34, p = .009$. Contrasts indicate that there is no statistical difference in terms of performance between 1.5° and 4° of eccentricity (F [1, 39] = 0.07, $p = .793$). However, performance for the 7° eccentricity differed significantly from that for both the 1.5°, $F(1, 39) = 11.14, p = .0019$, and 4° eccentricities, $F(1, 39) = 12.97, p = .0009$.

DISCUSSION

The aim of this study was to evaluate the effect of the addition of a tracking activity on target detection performance in peripheral vision, at various eccentricities relevant for a driving task. Luminance levels were chosen in the mesopic domain relevant for road lighting applications, as in Plainis et al. (2001), and a tracking task was chosen in order to mimic driving task activities, which had not been done before in this context, to our knowledge.

We investigated a range of eccentricities from 1.5° to 7°, where the cone photoreceptors seem to be dominant in a driving task without traffic (Bullough & Rea, 2000). This range is different from that used by Plainis et al. (2001), who explored eccentricities ranging from 5° to 30°, and allowed us the use of photopic luminance definition and measurements, which would not be possible at greater eccentricities (Bullough & Rea, 2000). However, the eccentricity range we selected

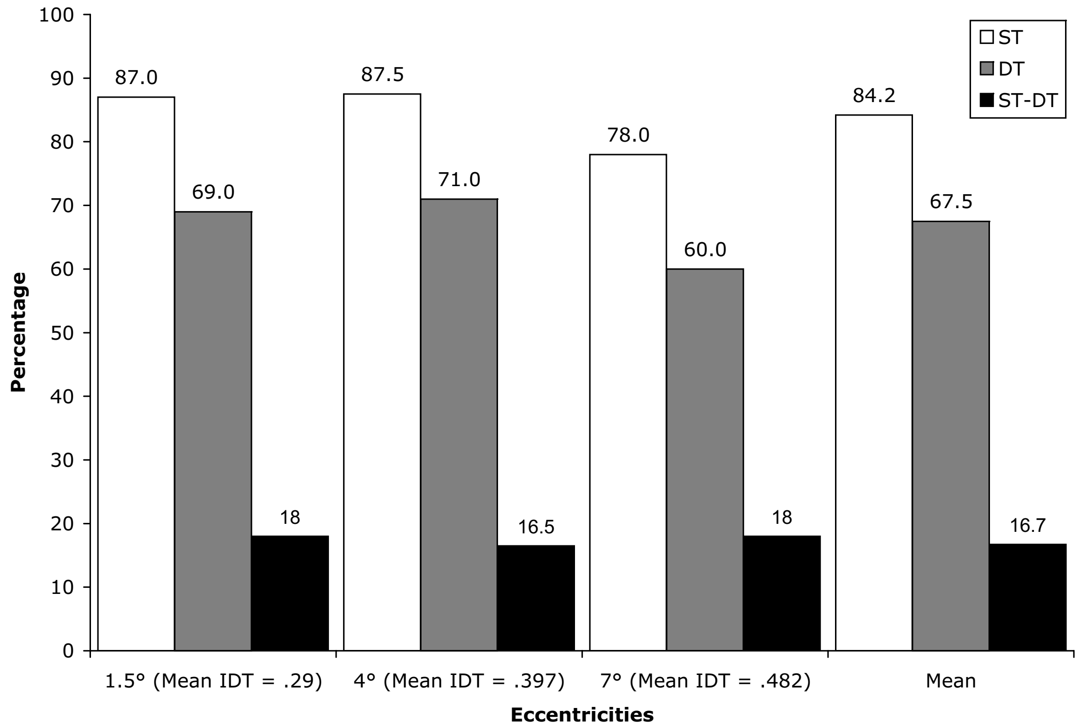

Figure 5. Mean performance value (percentage of correct detection) for the peripheral detection task for contrast values at the individual detection threshold (IDT). Data are extracted from the single-task (ST; peripheral detection) condition of Phase 1 and from the double-task (DT) condition of Phase 3 for Group 2 participants only.

for our experiment was based on the road lighting objective of improving the detection of targets on the road surface.

In the peripheral detection condition, individual contrasts allowing a detection rate greater than 70% were computed. These IDTs were used in the double-task condition to measure the impact of steering a tracking target on this detection rate. The position of the stimuli in the double-task condition was computed with the assumption that the attention demand for the tracking task was high enough to keep the gaze on the tracking target. This could not be assessed with oculomotor data, but the apparent effect of eccentricity on target detection for both the single-task (Phase 1) and double-task (Phase 3) conditions is consistent with this assumption.

Our results show that targets are detected with more difficulty when people are simultaneously engaged in a tracking activity, and they extend previous findings on the effect of a foveal task on peripheral detection (e.g., Leibowitz & Appelle, 1969) to a situation closer to a night driving context. The control group allowed us to show that the addition of the peripheral detection task had no significant effect on performance on the tracking task, which may be discussed in terms of complexity of the peripheral detection task (Chan & Courtney, 1993). This suggests that the tracking task used in our experiment may be less demanding than actual driving in terms of cognitive and attention resources.

These results give evidence that the STV models developed for road lighting applications, based on experiments with a single detection task, are limited. Although the presented situation is still an artificial task, it can be regarded as a step toward more ecological studies in the field of road lighting.

In addition to task load and peripheral detection, other factors should be taken into account with reference to actual driving. Critics of the STV model have raised a number of 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 small and uniform square target detection ignores the importance of the visibility of more realistic targets, such as pedestrians; and the VL computation does not take into account the effect of car headlights. Another point is that STV models focus on target detection, which is only the first step of the detection-identification-reaction process. The driving task is not purely visual. It has simultaneous visual, cognitive, and motor components (Boyce, 1995). Information extraction from the target stimulus (visual component) is interpreted (cognitive component) and enables appropriate action (motor response).

The STV model is based on a reference scenario and a visibility criterion. The criterion is luminance contrast, and the scenario involves the static detection of a standard target standing on the road at a given distance ahead, in foveal vision. We have introduced two important parameters to the reference scenario: peripheral detection instead of foveal detection and the double task instead of simple detection task. Our findings address two key human factors (detection of peripheral targets and task load) and suggest important changes in road lighting design.

On the one hand, the contrast criterion still is the key visual factor in target detection and, thus, is relevant to the assessment of road lighting enhancement. On the other hand, the reference scenario should be modified in order to take into account the main components of night driving. We showed that peripheral detection and task load are among these components, and further work may allow more components to be included in a modified STV model. One interesting point of this incremental approach is that it may be more easily accepted by lighting practitioners than a more radical approach would be.

Thus, our approach could be included in a broader framework. In our study, we have considered actual road visibility models, as defined by road engineers and lighting practitioners. More realistic driving situations should be addressed in order to improve road lighting specifications on a scientific basis, including other relevant aspects of driving in the experimental task and the use of various experimental situations, such as video display, driving simulations, and field experiments.

Driving simulators allow better control of the experimental situation than do field experiments. For instance, Lingard & Rea (2002) addressed off-axis detection at mesopic light levels with a driving simulator (video game). Their results suggest an effect of the spectral distribution power of the light sources for low-contrast targets over a range from 12° to 29°. However, the ecological validity of these tools with regard to driver perception is still a key issue (Kemeny & Panerai, 2003), so studies that use them should take their limits into account.

Driving simulation has been likened to video display (Martens & Fox, 2007) in terms of visual behavior, and road videos have been used to assess visual cues in a driving context (Crundall et al., 1999). However, field experiments have been more popular on road visibility issues (see Bullough & Rea, 2004, and Langham & Moberly, 2003, for a discussion). As far as road lighting is concerned, these studies focused on setting a visual performance threshold (Gallagher & Meguire, 1975; Hills, 1975; Van Bommel & Tekelenburg, 1986). As seen before, no consensus emerged, partly because of the difficulty in generalizing the results from specific field studies to actual illuminations.

The general framework for future work will include a field experiment under road lighting conditions and experimental data from laboratory experiments, using both video display and driving simulation. Video displays allow the semantic, dynamic, and (to some extent) photometry of the visual environment to be taken into account. Driving simulations allow the driving task to be taken into account and also allow strong control over the experimental parameters, while reducing the risk, but at the cost of a less realistic visual and proprioceptive environment. It is a step-by-step approach that allows one to discriminate among the effects of most of the main aspects of night driving on vision (CIE, 1992a) in order to build a more comprehensive road visibility index. We hope that this strategy will contribute to a more useful model of road visibility at night and will lead to road engineers' specifications for lighting design.

ACKNOWLEDGMENTS

The authors are grateful to the participants, to Ludovic Simon for assistance in apparatus design, and to the anonymous reviewers for many suggestions that improved the manuscript. The authors would like to express their gratitude to Réseau Autonome des Transports Parisiens (RATP), which made available the two crank handles. This study was supported by a grant from Laboratoire Central des Ponts et Chaussées (LCPC).

The effects of task and eccentricity on detection thresholds in mesopic vision, and their implications

for road lighting, are the subject of an ongoing study conducted at the Division for Road Operation, Signalling and Lighting of the Laboratoire Central des Ponts et Chaussées, Paris, France.

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Date received: October 8, 2007
Date accepted: April 19, 2008