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ORIGINAL ARTICLE

The Role of Retinal Adaptation in Night Driving

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ABSTRACT: *Purpose.* Driving is essentially a visuomotor task, and there is now compelling evidence that the disproportionate number of road accidents under night driving conditions is linked to changes in visual performance resulting from reduced lighting. The objective of this article is to establish the extent to which vision is either rod- or cone-dominated under night driving conditions. *Methods.* Visual thresholds are measured under lighting conditions that simulate urban lighting. Dark adaptation curves are obtained under three ambient lighting conditions ranging from low (0.1 cd/m^2) to high (5 cd/m^2) mesopic levels of retinal adaptation using circular discs of different sizes (1°, 2°, 3°, and 5°) presented at retinal eccentricities of 0°, 10°, 20°, 30°, and 40°. *Results.* The dark adaptation curves exhibit the classic inflection point between rod and cone activity for the lower levels of ambient illumination but a simple monophasic function for the high mesopic levels (>0.5 lux). Adaptation rates are four times faster for the higher compared with the lower illumination level and twice as fast for central compared with peripheral presentation. *Conclusions.* The data suggest that vision is mediated by cone pathways at 5 lux and by rod pathways at 0.5/0.1 lux. This shift does not profoundly affect sensitivity, but because rod pathways are known to be slower than cone pathways, it will certainly affect observers' ability to respond to rapidly changing viewing conditions such as are encountered when driving at night. (Optom Vis Sci 2005;82:682–688)

Key Words: rods, cones, mesopic, dark adaptation, night driving

Driving at night is one of the most hazardous situations commonly faced by the driver. It has been shown that low light levels encountered when driving at night,[1,2] especially on roads that have no street lighting,[3] can account for the disproportionately high observed nighttime accident rate. The effect of lighting on accidents involving pedestrians is even more pronounced, with pedestrians being three to seven times more vulnerable in the dark than in the daylight.[4,5]

A credible physiological explanation for the importance of good lighting when driving is based on the poor spatial and temporal characteristics of rod photoreceptors, which are largely responsible for visual perception at low light levels. As a result of these characteristics, many aspects of visual performance deteriorate under reduced lighting conditions (see Charman[6] for a review), including spatial resolution,[7-9] contrast discrimination,[10,11] stereoscopic depth perception,[12] accommodation response,[13-15] and visual reaction time.[3,16,17] This degradation of visual performance under low illumination is more pronounced in the elderly [7,18-21] and has been linked to their involvement in motor vehicle collisions.[22-25]

The visual field of the driver is subject to continuous illumination changes. The driver is exposed to a remarkably wide range of luminance values, which necessitates variations in his state of adaptation, sometimes of a rapid and extensive nature. Obvious adaptation problems occur when moving from one level of ambient lighting to another, e.g., when driving from a well-lit tunnel (or a highly lit commercial area) into an adjacent unlit area. It is clear that, in these situations, it will take some time before the driver's vision has reached its maximal sensitivity.

A key factor in relation to the role of adaptation state in visual performance is the actual level of road lighting at night, which is typically found to be in the mesopic region, between 0.5 and 10 lux.[15,16] The aim of the present study is to assess the state of retinal adaptation under conditions that simulate road lighting when driving at night, namely a roundabout associated with a high accident risk. This might reveal the underlying mechanisms that dictate visual perception. Moreover, because most of the visual field used while driving is peripheral[26,27] (e.g., traffic signs, pedestrians, cyclists, other vehicles), and it is obvious that most unexpected objects must be detected in the periphery, a range of retinal eccentricities and target sizes is tested. A final point involves the estimation of the speed of recovery of visual sensitivity; this is essential because it is known that the adaptation level is subject to rapid changes as a result of the presence of other light sources such as the headlights of oncoming vehicles.

METHODS

Subjects

Three young subjects (aged 21, 25, and 26 years) participated in the study. They were optically corrected for any refractive error with glasses and their monocular visual acuity was better than 6/5. No ocular pathology was detected. Two of the subjects (LL and ES) were naive to the objectives of the experiment.

Instrumentation

Dark adaptation curves were obtained using a slightly modified Goldmann-Weekers adaptometer (Haag-Streit AG, Ophthalmological Instruments, Bern, Switzerland) (see Fig. 1). The instrument contained an opal glass test target. The test field was illuminated by white light from an incandescent bulb having a correlated color temperature of 2250°K. Intermittent illumination of the test field was produced with the operation of a revolving diaphragm at a frequency of 0.5 Hz. The field luminance was controlled by neutral density filters (7 log units) and was calibrated with a digital spotmeter (Photo Research 1500; Micron Techniques Limited, London, U.K.) so the data from the raw records could be converted to candelas per square meter (cd/m^2). Stimuli were viewed through natural pupils; thus, luminance rather than retinal illuminance units were used in our measurements. In all cases, pupil size was bigger than 5 mm.

Circular field stops were mounted on the opal glass, which allowed the angular subtense of the diameter of the target to be varied from 1° to 5° of visual angle. The test field was surrounded by a matt black cone (funnel) of low reflectance to eliminate reflections on the surface of the test field caused by ambient lighting.

Four small, dim, and red light-emitting diodes were used to control eccentric fixation. They were mounted on four adjacent housings at 10°, 20°, 30°, and 40° in the temporal visual field of the subject; only one fixation target was present for each threshold measurement. For central fixation, the subject was asked to fixate at the center of the test field. The fixation targets were placed at the same plane as the test field to avoid any accommodation differences.

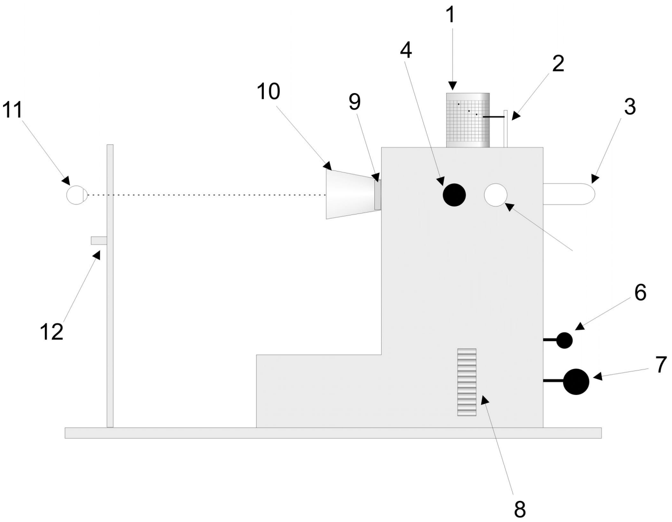

FIGURE 1.

Schematic diagram of the Goldmann-Weekers adaptometer (Haag-Streit AG, Ophthalmological Instruments, Bern, Switzerland) used in the study. The observer (11) was fixating at a light-emitting diode (placed at various eccentricities) while being aware of the flashing test field (9), surrounded by a funnel (10), and illuminated by a bulb (3). The luminance of the target was varied by adjusting a knob (7). The data were recorded in an analog format with the aid of a recording arm (2) and a calibrated drum (1).

Initial light adaptation was achieved using a hemisphere of 30 cm diameter. Its internal surface was coated with matt white paint that gave a uniform light adaptation of the entire field. The preadaptation exposure time was 1 min and the luminance level 3200 cd/m^2, estimated to produce a retinal illuminance of 4.12 log trolands (assuming a pupil of 2.3 mm diameter).

Retinal thresholds were obtained under different levels of artificial lighting. Apart from the test field and the fixation target, the rest of the visual field during adaptation was a "yellow" diffusing surface (reflectance approximately 90%) uniformly lit to a controllable level of illuminance (ranging from 0.1 to 5.0 lux at the surface of the test field) with the aid of two lightboxes covered by broadband yellow filters (with these filters, 80% of the overall spectral energy of the source is contained between 540 and 650 nm). The level of ambient illuminance was calibrated with a digital lux meter (OM 210; Robin Electronics Ltd., U.K.). These spectral/illuminance characteristics were purposely chosen to simulate urban lighting conditions like found at a local roundabout, which was illuminated by low-pressure sodium lamps and was associated with a high accident risk. Under these conditions, horizontal illuminance ranged between 1.0 and 8.7 lux when standing on the pavement, which reduced to values between 0.2 and 1.4 lux from inside the vehicle (as a result of the transmission effects of the windscreen and the roof of the vehicle).

EXPERIMENTAL PROCEDURES

Each observer was seated in the experimental room. The normal lights in the room were turned off. After a lapse of approximately 1 min, the retinas of both eyes were bleached by exposure to the standard 3200 cd/m^2 light source for 1 min.

The observer was seated at the dark adaptometer with his or her left eye covered by a patch. A constant head position was maintained by an adjustable chin and forehead rest placed 41 cm from the target. The subject was instructed to look at the red fixation target, which was placed at various eccentricities, while being aware of the flashing test field. The subject's task was very simple and involved determining the minimum luminance (threshold), by adjusting a knob, at which he or she could just see the test field. The threshold was measured using the method of ascending limits (from nonseeing to seeing). The first observation was made within the first 15 to 30 s after the termination of the bleaching light. Then, as many readings as possible were taken until the thresholds reached a steady level (fully adapted threshold).

RESULTS

Retinal Adaptation Under Mesopic Conditions

Figures 2A and 2B show results of retinal adaptation at different ambient illuminance levels (5.0, 1.0, 0.5, and 0.1 lux) as compared with the typical dark adaptation curve for subjects SP and LL. It is obvious that the retinal adaptation curve alters markedly with am-

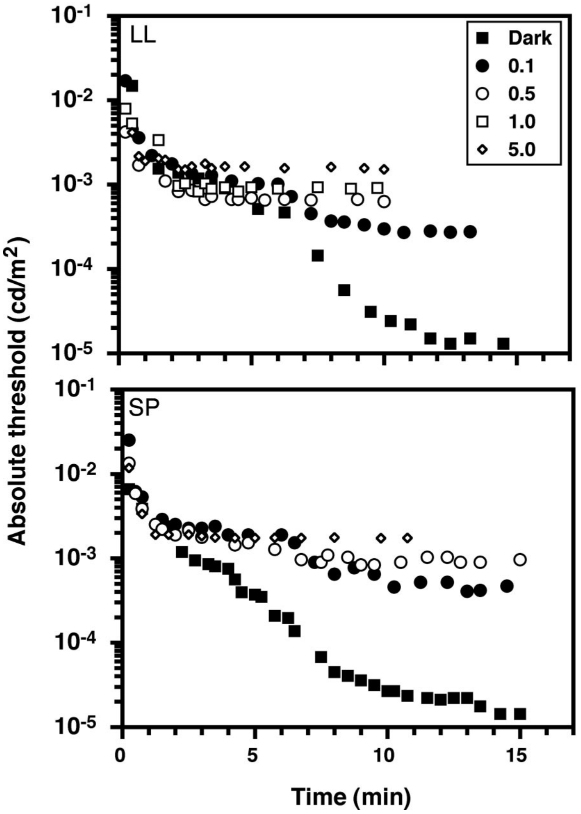

FIGURE 2.

Retinal adaptation curves compared with the classic dark adaptation curve (filled squares) for two subjects (SP, upper; LG, lower). Four mesopic levels (5.0—triangles, 1.0—squares, 0.5—circles, and 0.1 lux—filled circles) of background illuminance are tested. Test field size is 3°. Pretest bleaching time is 1 min.

bient lighting. In total darkness, there is a clear discontinuity in the curve, which is attributed to two distinct regions of recovery, dominated initially by cone and subsequently by rod photoreceptor function. However, at upper mesopic levels (5.0 lux), the curve consists of one portion undergoing a monotonic increase in sensitivity possibly attributed to cones only. Similarly, at 0.5 lux, no break is evident, suggesting that the rod recovery is desensitized by the cone system, which dominates at these levels. If ambient illuminance is decreased to 0.1 lux (low mesopic levels), there is a slight inflection followed by a second rod-dominated phase of adaptation. Presumably, the discontinuity between the first and second segments represents the transfer from cone to rod vision. Identifying the extent of this dichotomy is one of the main objectives of the present project.

To summarize, there is a suggestion that vision may be qualitatively different for low-mesopic (0.5-lux) and high-mesopic (5-lux) conditions, with the former being mainly rod-mediated and the latter mainly cone-mediated. Fully adapted sensitivity increases as ambient illumination decreases, and the maximal sensitivities under mesopic light levels are reduced at least 2 log units compared with complete darkness. Because rods are more common in the peripheral than central retina, we might expect this to be reflected in a sensitivity versus eccentricity function. The data for this experiment are described in the next section.

It is also evident in Figure 2 that for a background illuminance of 0.1 lux, the changeover point between the two parts of the adaptation curve is delayed by approximately 1 min compared with that for absolute darkness. This implies that the rate of adaptation for cones is slower under high-mesopic than low-mesopic conditions. To test this idea in subsequent experiments, an index of the rate of adaptation, i.e., of the speed of recovery of retinal sensitivity after the initial bleaching, is calculated. It is assumed that when the retinal adaptation curve consists of only one phase, it could be represented by the general equation:

$$\log T = Ae^{-kt} + B$$

where T is the absolute threshold, t is time, A is the initial level of adaptation, and B is the level of the asymptote of the curve. Taking natural logs give:

$$\ln[\log T - B] = \ln A - kt$$

i.e., a plot of $\ln[\log T - B]$ against time, t, should be a straight line of slope -k, which represents the rate of retinal adaptation. B is calculated by the mean of the last five values of the asymptote. Figure 3 tests this hypothesis. It should be noted that as a result of the rapidly changing threshold, there are not many data points for analysis.

Effect of Stimulus Location on Retinal Adaptation

Figure 4 depicts the fully adapted threshold of the three subjects for different eccentricities in the temporal retina at the two different ambient lighting levels (0.5 and 5.0 lux). It is clear that overall, as the stimulus is presented more temporally (at eccentricities higher than 10°), the eye requires more stimulus intensity for detection. For two subjects, there is an approximate linear decrease in sensitivity with eccentricity and the slope of the graph is approximately the same for low and high illumination. For subject LL, the two functions converge so that at 40°, they are approximately the same. Crucially, at 0.5 lux, the maximum sensitivity shifts to approximately 10° of retinal eccentricity for subjects SP and ES, indicating rod-dominated perception under these conditions. This

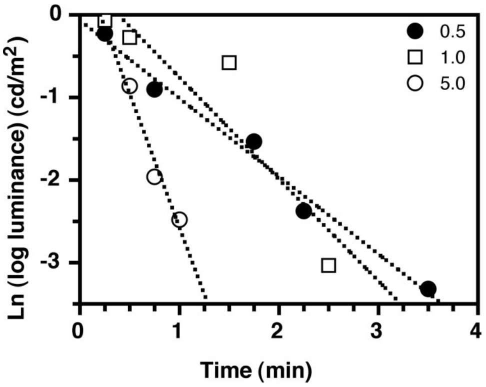

FIGURE 3.

Double log transformation (ln[log T-B]) of retinal adaptation curves for subject LL under mesopic light levels (5.0, 1.0, and 0.5 lux). The result is a family of straight lines. Their slopes (-k) represent the rate of retinal adaptation (a high slope value indicates a fast rate). Correlation coefficient, r, is 0.98, 0.92, and 0.99, respectively.

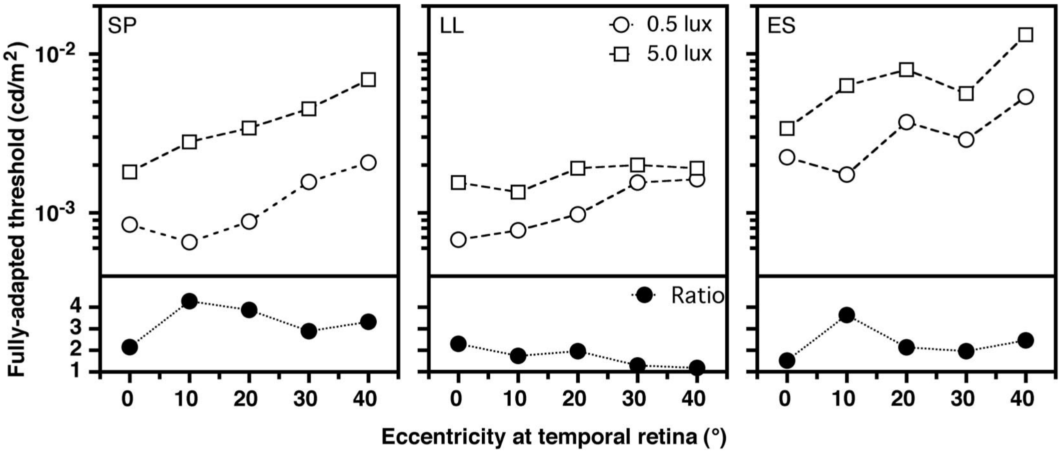

FIGURE 4.

Plots of fully adapted thresholds as a function of retinal eccentricity for two lighting levels (0.5 lux—circles, 5.0 lux—squares). Data from three subjects are shown. Test field size is 3° and bleaching time 1 min. The lower part of each figure plots the ratio of thresholds for the two light levels.

is seen as a peak in the ratio of the sensitivities for the 0.5 versus 5 lux conditions.

Figure 5 shows plots of the rate of adaptation for the same stimulus conditions and light levels. There is a decline in the rate of adaptation with increasing retinal eccentricity; this is more evident at the higher mesopic levels (5.0 lux). This is not surprising because it is known that cones adapt at faster rates than rods and that spatial density of cones decreases outside the fovea.

These data further emphasize the rod–cone dichotomy between the low and high illuminations. They suggest that although there may be little or no difference in sensitivity of the two detecting mechanisms, it is likely they will have very different temporal characteristics, and as outlined in the “Discussion,” this is crucial when driving.

Effect of Stimulus Size on Retinal Adaptation

In Figure 6A, fully adapted thresholds and rates of adaptation are plotted as a function of stimulus size for 0.5 lux. Data for only one subject are presented, but they are representative of observations made with the other two. For central fixation, no significant difference in absolute threshold with stimulus size is observed above a critical size of approximately 2°. However, for the peripheral part of the retina (20° and 30° temporal eccentricities), the critical sizes above which there are no improvements in sensitivity are approximately 3° at 20° eccentricity and above 5° for 30° eccentricity. Note that for 30° eccentricity, there is a roughly linear relationship between stimulus area and retinal sensitivity.

Although larger stimuli produce summation of signals in periphery, this does not necessarily improve the recovery rate of sensitivity, probably as a result of the fact that detection is still rod-dominated. This is confirmed in Figure 6B, which illustrates that there is little change in the rate of adaptation with increasing stimulus size for both central and peripheral parts of the retina.

DISCUSSION: IMPLICATIONS FOR DRIVING

Level of Adaptation

By studying retinal adaptation levels under light levels that simulated those encountered when driving at night, it was found that absolute thresholds ranged between 5.2×10^{-3} (at 5 lux) and 4.7×10^{-4} cd/m² (at 0.1 lux). These values are slightly higher than those described by Davey and Sheridan,[28] who reported dark adaptation thresholds of 1.2×10^{-4} cd/m² when driving in the

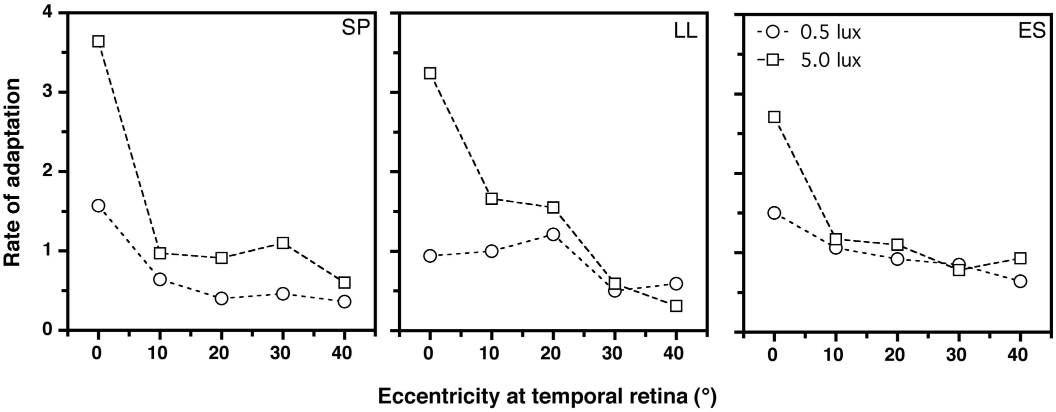

FIGURE 5.

Plots of the rate of adaptation (in ln(log cd/m²) min^{-1}) as a function of retinal eccentricity at two lighting levels (0.5 lux—circles, 5.0 lux—squares). Data from three subjects are shown. Test field size is 3° and bleaching time 1 min.

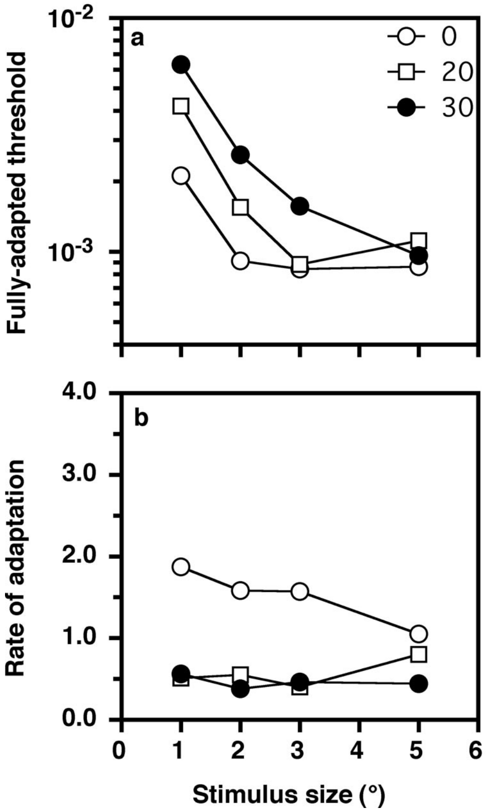

FIGURE 6.

Plots of (a) absolute thresholds (in log $(cd/m^2)^{-1}$) and (b) rates of adaptation (in ln(log cd/m^2) min^{-1}) as a function of stimulus size and for three eccentricities (0°—circles, 20°—squares, and 30°—filled circles). Ambient illuminance is 0.5 lux. Data from subject SP are shown.

city center compared with 2.3×10^{-5} cd/m^2 on unlit roads. This denotes lower levels of adaptation in the present study, probably resulting from improvements in road lighting over the years, which have led to higher levels of ambient illuminance. Moreover, our experiments took place in a uniformly lit environment, which simulated lighting levels encountered at night but cannot apply to a real driving scene, where the visual field of the driver is usually subject to continuous illumination changes. Also, it has to be stressed that these values apply for drivers; pedestrians are expected to show higher sensitivity,[29] which means that the pedestrian's visual system is better primed to detect targets than the driver and that therefore pedestrians may overestimate their own visibility and thus take undue risks.[30]

It was also shown that the critical level of illuminance, where the rod-dominated second phase appears, lay in the region between 0.1 and 0.5 lux for young observers. As a result, it is expected that in the absence of road lighting, the rod system will tend to dominate perception, improving detection of objects of interest, but also leading to increased response times. However, it is almost certain that as a result of rod–cone interactions, this level may be varied depending on the spatiotemporal characteristics of the stimulus.[31-33] It is expected that older subjects would show an increased critical level of illuminance and a slower recovery of sensitivity[18,34] because of the reduced amount of light reaching their retina (e.g., pupillary miosis, increased ocular media density), changes in retinoid cycle, and degeneration of visual pathways.[20,21,35]

A point that is particularly relevant to the observations described in this article is that usually when driving in urban/residential roads, most of the field is of similar luminance. On rural roads, however, most of the field will be dark and only a part of the field will be illuminated by vehicle headlights, which causes further problems for the adaptation level of the driver.

The Importance of Peripheral Visual Sensitivity

The driver depends on peripheral vision to rapidly identify hazardous situations. Therefore, data based solely on human foveal visual detection capabilities may be inadequate to predict practical performance, especially when objects first appear in the periphery of a driver's visual field. Our findings (see Fig. 4) confirm that the luminance of targets, when placed in the far periphery (approximately 40°) of the subject's visual field, must be increased by a factor of 2 in comparison with foveal targets to assure visual detection. Furthermore, the decline in the rate of retinal adaptation with increasing eccentricity shows a slower recovery of sensitivity for peripheral targets.

These results are in agreement with previous studies,[36,37] which reported that the ability of subjects to detect and identify suprathreshold targets (e.g., road signs) decreases considerably as visual angle increases.

The Importance of Stimulus Size

Obviously, it is visual size (angular subtense) rather than physical size, which is a basic parameter in determining the visibility of an object to a driver. Also, the conspicuity of an object, among other factors, increases for larger sizes. The visual size of road traffic objects (vehicles moving in the same or opposite direction, cyclists, pedestrians, road signs, signal lights, and so on) varies with distance. Hills[38] reported how visibility distance increases with the visual size of an object. Similar calculations based on our data are displayed in Table 1.

As expected, the results presented show that retinal sensitivity increases as the size of the target increases (Fig. 6). Moreover, it seems that there is a critical size of the target that gives maximal sensitivity, which varies with eccentricity (see Table 2). For central targets, there is no increase in sensitivity for sizes larger than 2° (at 0.5 lux illuminance), whereas at 20°, the critical size is 3° and at 30°

TABLE 1.

Calculations of distances determined by the visual size of traffic objects based on the following parameters: car: width 1.70 m/height 1.50 m, pedestrian: width 0.50 m/height 1.80 m, traffic sign: width 0.60 m/height 0.60 m[a]

	Distance (m)		
Visual Size (°)	Car	Pedestrian	Traffic Sign
1	103	54	32
2	52	27	16
3	34	18	11
5	21	11	6

[a] The objects are assumed to be equivalent to a disc of the same area. Calculations are based on data displayed in Figure 6.

TABLE 2.
The factor by which sensitivity increases for different stimulus sizes at three eccentricities[a]

	Retinal Eccentricity		
Stimulus Size(°)	0°	20°	30°
1	1.0	1.0	1.0
2	2.3	2.6	2.4
3	2.5	4.7	3.9
5	2.5	3.9	6.6

[a] Ambient illuminance is 0.5 lux illuminance. Data from subject SP are used.

larger than 5°. Therefore, unless the luminance (or contrast) of an object is adequate for its size and position in the visual field, it may not be sufficiently conspicuous to be detected by drivers.

It should also be mentioned that when a pedestrian or a traffic sign are relatively near to the driver (e.g., located on the right-/left-hand side of the road), they are frequently detected by peripheral vision. Therefore, although their visual size increases, the retinal sensitivity may not improve, because sensitivity is relatively low in the periphery (see Fig. 4).

CONCLUSIONS

This study investigated the state of retinal adaptation under typical nighttime ambient illuminances. It was shown that at levels close to 0.1 lux, the rods inhibit perception, and although retinal sensitivity increases, the adaptation rate of the system slows down notably. We have previously shown that this leads to increased reaction times.[3,39] Furthermore, both retinal sensitivity and speed of recovery are considerably decreased in the near periphery, and this is of critical importance if we consider that most of the visual field used while driving is peripheral. The interaction between size and eccentricity is also important. Although sensitivity increases with object size in the peripheral field, for central targets, there seems to be a "critical" size, which achieves maximal sensitivity beyond which it does not increase.

The experiments in this work involved stationary targets. However, objects to be perceived by the driver are rarely stationary but generally move with differing speeds and directions relative to the driver. Second, the driver is in motion while driving and is constantly making head and eye movements, thus displacing retinal image locations. This may or may not increase object visibility depending on the spatial and spectral characteristics of the targets.

Finally, our measurements refer to a driver who is alert, is looking in the right place, and is not distracted by nearby objects competing for his attention. However, there is strong evidence that peripheral sensitivity to a simple light is reduced when combined with a foveal, cognitive task.[40,41] This means that some features of interest falling on a driver's peripheral retina may go unnoticed under conditions of excessive driver visual workload or fatigue.[42] Such distractors may be in the road environment (e.g., a complex road network in an unfamiliar city) or an in-vehicle device (e.g., a mobile phone,[43] an advanced information display[44]), and they undoubtedly contribute to a reduction in the driver's functional field of view.[45-47] This may be more pronounced in conditions of reduced visibility, encountered when driving at night, when degradation of "focal" vision is noticeable.[48,49]

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