# Towards an Express-Diagnostics for Level of Processing and Hazard Perception

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## Abstract

The analysis of eye movements can provide rich information about driver's attention and the course of behaviour in hazardous situations. We present data from a driving simulation study showing that the switching between preattentive and attentive processing is reflected in visual fixations. For this initial analysis, we considered fixations from the prospective of their duration and the amplitude of related saccades. Since fixation durations may change instantaneously from one fixation to the next, we further selected the temporal vicinity of the emerging hazard for a closer analysis of fixations around this time. With this second type of analysis, the fixations that actually "detect" a critical event can be discovered and their duration measured. Upon detection of an immediate hazard, there is an increase in fixation duration and a corresponding increase in occurrence of attentive fixations on the cost of preattentive ones. This switching from one level of processing to another is recognisable on a short, phasic time scale. We finally discuss attentional conditions where overlooked or not sufficiently processed hazards do not lead to the appropriate breaking reaction on the part of the driver.

*Keywords*: levels of processing; eye movements; visual fixations; attention; hazard perception; human errors.

## 1 Introduction

### *1.1 Preattentive scanning versus attentive processing*

Hazard perception refers to the identification of dangerous traffic situations as they arise. It therefore demonstrates a skill, which is of principal relevance for the driving activity (e.g. Crick & McKenna, 1991). According to Nagayama (1978), more than 50 percent of all collisions in road traffic arise from a missing or delayed hazard perception. In a study of road safety Treat et al. (1977) found that

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human error was the sole cause in 57% of all accidents and was a contributing factor in over 90%. Only 2.4% were due solely to mechanical fault and only 4.7% were caused by environmental factors. This failure of drivers to perceive road-traffic hazards is often due to the fact that the driver failed to attend, because his/her mental resources were focussed elsewhere – a phenomenon known as "inattentional blindness" (Mack & Rock, 1998).

Following a long tradition in psychology and neuroscience, visual information processing can be described in terms of a two-level model (e.g. Hoffman, 1999; Trevarthen, 1969; Velichkovsky, 1982). At the first, preattentive level, objects are dynamically localised in the 3D environment – hence the other name for the level, which is 'ambient'. These objects, or rather 'blobs', are identified at the second level, which is variously named as focal, or attentive because it is thought to form an informational bottleneck by operating only on a few objects at a time. For instance, the driver attends a small subset of road-traffic information while ignoring the rest (e.g. Velichkovsky, Dornhoefer, Kopf, Helmert & Joos this volume). Hazards seem to be identified at this second level (Green, 2000). Once there is attentive processing, the eye movements are under endogenous control, which generally leads to longer fixations. The multilevel view is supported by visual search studies of Pomplun (1998). Accordingly, fixations seem to be under control of hierarchical mechanisms – during a visual search-and-compare task, two phases could be distinguished. In the first phase, fixation duration (on average, 150 to 250 ms) is mainly a function of spatial density and configuration. In the second phase, just prior to the solution, fixation duration increases to 500 ms and is no longer controlled by salient physical features, but instead by the complexity of decision, i.e. by higher-level mechanisms, responsible for hypothesis generation and testing.

The two-level model certainly is a simplification as there are levels 'above' the form-oriented focal stage. In particular, conceptually-driven (semantic), and self-referential (or metacognitive) processes characterise these mechanisms that residue in the phylogenetically new frontal structures of brain (Velichkovsky, 2002). Furthermore, training and expertise lead to the automatisation of skills, so that with time their components can be processed at lower levels. Nevertheless the two-level model is a useful first approximation to consider visual fixations from the multilevel perspective. One can expect that higher levels of encoding of visual material may be correlated with longer fixations. Indeed, levels of encoding in visual memory tasks could be isolated by the analysis of fixations (Velichkovsky, 1999). The question is whether these methods of analysis can be applied to driving activity. The purpose of the article is to examine the fixation parameters as indicators of the level of attentional control in hazardous driving situations.

### *1.2 Distribution of fixation durations and saccades in dynamic scenes*

The first step in investigating eye movements from the perspective of attention deployment is to look at the distribution of fixation times (e.g. Moray, 1993). A further task is to relate these fixation durations to the amplitude of saccadic movements. In experiments with perception of naturalistic pictures, we found three segments of fixation duration that are related to distinct combinations of the amplitude of saccades. The shortest fixations, below 90 ms, often result from large and are followed by very small saccades. They can be interpreted as stops on the way of correcting the eye position. The next two segments, though not as sharply differentiated in the overall distribution, are of more interest for our analysis. Fixations from 90 to about 140 ms produce large saccades of more than 4°, beyond the parafoveal region of retina. In other words, these saccades aim at targets seen as blobs not as individualised objects – a strong case for preattentive processing. Fixations longer then 140-200 ms seem to be related to focal processing: they initiate saccades mainly within the parafoveal region where objects are relatively easily seen and continuously attended (Pannasch, Dornhoefer, Unema, Zapf & Velichkovsky., 2001).

Does this pattern of results also emerge in interaction with motion-flow scenes? Figure 1 shows frequency distributions of fixations and saccades found in a previous driving simulation study (Velichkovsky, Dornhöfer, Pannasch & Unema, 2000). The data are similar to described above with the main difference that the segments of preattentive and attentive processing are now shifted towards longer fixation durations. The reason for this is that static fixations have been transformed into dynamic ones, by including a smooth-pursuit component. Thereafter in the article, the word 'fixation' will be used in the broader sense of 'dynamic fixation'.

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First of all, the distribution of fixation durations is log-normal with the typical positive skew (Figure 1A): the mode (256 ms) lies below the mean (486 ms). In the dynamic data, the segment of 'corrective fixations' is present with a distinct peak around 60 ms. The preattentive fixations with their long-range saccades are now visible on the segment from slightly less than 100 ms to about 250 ms. The attentive processing is prevailing if fixation durations are longer than 280-300 ms. This shift in the segmentation is not the only difference to the static layouts, however. In dynamic scenario in contrast to perception of static pictures, there is a higher similarity in the distribution of preceding and following saccade amplitudes across fixation durations (Figure 1B). These data build up a background for the following investigation of attentional control and eye movement reactions to hazardous events in a simulated driving environment.

## 2 Methods

The results discussed here are derived from a study of eye movements and hazard perception during a driving task realised on a PC-based driving simulator. The 'SIRCA' driving simulator was developed and adapted to our eye tracking system in cooperation with the ARTEC group (Institute of Robotics, University of Valencia). A video beamer with SXGA-resolution (JVC DLA G11) projected a fictive urban scenario with two to four lanes streets and numerous intersections onto a 1.5 x 2 meter screen. The subject was seated at a distance of 3.5 meters resulting in a view of approximately 24° vertically and 32° horizontally. Eye movements were recorded with the EyeLink™ head-mounted system with an accuracy of better than 1° and 250 Hz sampling rate.

Twelve male subjects, aged 24 to 36 years, took part in the study. All of them were holders of a driving licence (for at least 7 years) with a high driving experience ranging from 70 000 to 200 000 km. Subjects were instructed to drive through the urban environment with a recommended speed of 50 km/h or less, following traffic rules and normally keeping the car on the right lane. Before the experiment, subjects were asked to complete a test drive on the simulator in order to get accustomed to it as well as to the eye tracking equipment. The duration of an experimental drive session was ca. 40 min, whereby the first 20 min was used as an extended training phase. The stable virtual environment of the second, test-phase was always the same, while all the dynamic aspect were randomised. The eye tracker was shortly re-calibrated after 10 min of drive. The session was repeated for all subjects 5 times – one time on each of 5 consecutive weeks.

During the experiment, potential and immediate hazards were presented on the road. Subjects had to react to the hazards in an appropriate way. Figure 2 shows typical screenshots with examples of hazards as seen by the subjects.

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Potential hazards, which in average appeared approximately every 50 seconds were defined as situations demanding an attentive monitoring to objects that could turn into immediate hazards (what really happened in the 40% of the cases). As potential hazards, either a green traffic light or a pedestrian facing the road as if intended to cross it (Figure 2A) could be presented well before the subject should take the decision about the braking reaction. Immediate hazards were situations where the driver had to react immediately in order to prevent an accident. The immediate hazards, which always evolved out of potential hazards, could be either a red traffic light (Figure 2B) that was implemented at road crossings only or a pedestrian crossing the street in front of the subject's car. These hazards always appeared at a distance of 25 m. At the prescribed maximal speed of 50 km/h, the distance corresponded to the braking distance just sufficient to react to the hazard on time. In addition to the hazardous events, a variety of traffic-related and traffic-unrelated neutral events were presented, such as cars in other lanes or even in the subject's one but at a sufficient distance from him, as well as pedestrians walking on their respective sidewalks independently of the traffic condition.

## 3 Results

### *3.1 Saccade amplitude and fixation duration*

The overall distribution of fixation durations is presented in Figure 3A. As the distribution described above (Figure 1) it is log-normal, positive skewed with the mode (204 ms) below the mean (400 ms). This time however the distribution had no an apparent peak within the segment of corrective fixations. This can be attributed to a generally lower spatial resolution of the projected scenes in the present experiment.

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Figure 3B shows the combination of preceding and following saccadic amplitudes. Skipping the few corrective fixations of the shortest segment (<90 ms), one can see the familiar pattern. Again, fixations within the segment from about 90 to almost 300 ms are generally related to large-scale ambient exploration, while longer fixations rather demonstrate their involvement into a more piecemeal focal processing. We can conclude that on the basis of the overall distribution, fixations sub-serving preattentive processing can be coarsely dissociated from those in service of attentive elaboration. The rule of thumb here is the following: pre-modal and modal fixations are preattentive, mean and post-mean fixations are attentive.

*3.2 Immediate hazards*

What happens to visual fixations when a critical event occurs? The previous analysis is too crude to answer this question. Since fixation durations may change instantaneously, from one fixation to the next, the duration of the fixation that actually "detects" an immediate hazard may be seen on the background of several preceding fixations. We therefore selected the moment of appearance of the immediate hazard as a starting point, and analysed fixations occurring around this time. Figure 4 shows the average fixation durations plotted over the fixation number relative to an immediate hazard: four fixations before, the fixation that was actually hit by the event (numbered as "0"), and the next five fixations. Data for the 5 consecutive drives are presented to see if the reaction declined over time.

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From the data in Figure 4, a sudden increase in fixation duration upon emerging of an immediate hazard is obvious ($F_{1,11}$= 9.841; $p < .001$). The reaction is not only strong but also surprisingly stable – for example, in difference to oculomotor reactions to meaningless distractors, which usually habituate after several repetitions of the event (Velichkovsky & Pannasch, 2001). Analysis of variance supported this impression by providing evidence that the phasic increase of fixation duration does not change over time ($F_{4,11}$= 0.099, $p > .98$). As is shown in Figure 5, the rather dramatic increase of fixation duration in response to hazardous events seems to evolve on the costs of the proportion of preattentive fixations.

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For the analysis, as in Figure 5, we separated three categories of fixation durations around the appearance of an immediate hazard. It clearly reveals that some categories of fixation durations are more affected by the hazard than others: there was a considerable reduction of relatively short fixations (category 90-300 ms) and the increase of longer fixations 601 ms and more. The intermediate category of 301-600 ms, on the other hand, was not affected by the critical event. Thus, upon detection of an immediate hazard attentive fixations were increased at the cost of fixations with preattentive durations (e.g. fixations within the modal and pre-modal range). The data like this raise the question of whether all longer fixations are equally 'attentive' or perhaps further subdivisions may be necessary. We leave the question until the general discussion at the end of the article.

*3.3 Potential and immediate hazards versus base-line*

For our further analysis the base-line data on fixation duration can be useful. To find their parameters, we randomly selected sequences of 10 fixations from the driving episodes that had neutral but no hazardous (potential or immediate) events. The procedure was repeated 30 times for every of 12 subjects at any of 5 test-drives, what lead to 1800 data sets. The resulting distribution of the mean fixation durations was log-normal, left-skewed with the mean of 412 ms and the median of 387 ms. A percentile analysis demonstrated that 5% and 95% of all estimates corresponded to fixation durations of

295 and 600 ms, respectively. These base-line data are visualised in all figures below – the black line illustrates the median and the dashed lines show 45% deviation below or above the base-line median.

What happens to experienced drivers' visual behaviour when they approach a potential hazard? We analysed fixation duration when potential hazards reached the distance of 25 m (i.e. the distance where they could be transformed into immediate hazards). Assuming the maximal speed of 50 km/h, this is the last chance for drivers to decide if they start braking or drive through. Therefore, subjects need to attentively monitor the potential hazards at this point of time. As can be seen in Figure 6A, there is an increase in fixation duration when potential hazards were at 25 m distance from the driver ($F_{1,11}$= 7.914, p <.001). This increase was not significantly different from than for immediate hazards ($F_{1,11}$ = 1.166 , p >.28). Again, we found no habituation over time ($F_{4,11}$= 0.441, p >.78).

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Another interesting effect can be seen if we compare data in Figures 6A and 6B. Compared to potential hazards in the case of immediate hazards the three subsequent fixations after the critical event are prolonged ($F_{1,11}$= 6.749, p <.017). The same short-term 'freezing' of fixations has been already reported in the driving simulation study mentioned above (Pannasch, Dornhoefer, Unema & Velichkovsky, 2001). It is not completely clear to what extent the effect reflects the driver's attempt to take up additional visual feedback during his braking or it is an inhibitory by-product of the voluntary motor action per se (e.g. Bujakas & Linde, 1976).

Finally, an analysis of the spatial location of fixations is of interest. The gaze position analysis revealed, for instance, that 81% of the immediate hazards were already viewed foveally (eccentricity of the object location, <1°) or, at least, parafoveally (eccentricity <4°) at the moment when they were presented. Furthermore, at the distance of 25 m 74% of all potential hazards were too in the foveal or parafoveal view. Thus, if a potential hazard reaches the critical point for breaking decision most of the experienced drivers already attentively track it and are prepared for an adequate action.

### *3.4 Braking for red versus passing through*

The red traffic light represents a non-ambiguous immediate hazard indicating a reaction imperative: to follow traffic rules and the common sense, the driver definitively has to brake when the red traffic light appears. In this respect, traffic light contrasts to our second class of immediate hazards – walking pedestrians, which can be avoided through a steering manoeuvre. We wanted to know what happens to driver's fixation behaviour when he passes through a red light. Therefore, we compared situations where subjects stopped for red (Figure 7A) with those few cases (N = 12) where subjects accidentally passed through a crossing regardless of the red traffic light (Figure 7B).

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Gaze position was taken into account for this analysis also. In the case of a successful braking, our data show an increase in fixation duration at the "point of no return". This reaction was especially strong when the red light was viewed foveal and parafoveal: ($F_{1,11}$= 12.779, p <.001) compared to ($F_{1,11}$=

3.336, p<.002) in the peripheral condition. In the (para)foveal condition the increase of fixation duration with respect to base-line was almost one second, so that the mean fixation duration was 1380 ms. Nevertheless, subjects showed an increase of fixation duration, even if they did not look at the red light. Furthermore, in the (para)foveal condition the three subsequent fixations after the appearance of the red light were not prolonged in contrast to the peripheral condition. Since in the (para)foveal condition the increased fixation duration at the critical distance was about 400 ms longer than in the peripheral condition, i.e. the driver could get the visual feedback for his braking during this exceptionally long fixation.

Last but not least, the accidental errors of driving on red are of importance. The errors cannot be explained by a shortage of decision time as the driving speed in all the cases was below 50 km/h. Again, data were split according to eccentricity of the eye's position during the critical event (Figure 7B). Due to a small number of observations no regular statistical analysis can be provided, but the (para)foveal condition (N = 8) seems to stand out against the peripheral condition (N = 4) with longer fixations. Indeed, the (para)foveal fixation duration lies above 600 ms, i.e. the 95% threshold of our base-line data. In spite of this significant increase, however, durations of all fixations closely before and after the hazard are under the low (5%) base-line threshold, which is 295 ms. From the point of view of the two-level model of visual perception, these fixations of about 200 ms are preattentive. Thus, the reason for the not (sufficient) attending immediate hazards by some of our subjects in these several cases may simply be that the critical event hit them in their preattentive mode of processing.

## 4 General Discussion

In the recent years, a variety of physiological functions and indices has been considered with respect to their diagnostic value for the hazard perception in driving tasks (see Groeger, 2000). The oculomotor parameters are only one source of this information, but also one that can be highly promising for the needed 'express-diagnostics' of driver's attention. As Chapman & Underwood (1998) noticed, eye movements provide important insights for understanding the driving tasks and for developing training strategies and accident countermeasures. The results of the present experiment demonstrate that eye tracking is useful to analyse not only the direction but also the level of attention. In particular, visual fixation responses to hazardous events were strong, reliable and fast with an increase of 100 and more percent in fixation duration upon detection of a hazardous event. There was also remarkable stability of these reactions over time, even if the laboratory situation as well as the virtual environment became more and more familiar to the subjects.

Although the phasic response of visual fixations to hazards was strong and always highly significant, this parameter alone was not sufficient to predict what subjects exactly did. For instance, nearly the same response was registered to the potential hazards, which were finally ignored, as to the immediate one, which were acknowledged by braking and stopping the car. When subjects erroneously drove through a crossing on the red light, a significant prolongation of the visual fixation also was found (see Figure 7B). This is the reason why a more theoretical approach to the analysis of driver's oculomotor behaviour is needed.

We attempted to provide such a theoretical framework in terms of two-level model. The distinction between preattentive scanning and attentive elaboration in visual search seems to be supported by the data. The two-stage search process can be recognized by inspection of fixation behaviour. On a preliminary basis, we propose that fixations sub-serving preattentive scanning are dissociable from those in service of attentive elaboration on the basis of their duration as well as saccade amplitudes. Of a practical interest is that this information can be obtained without taking into account the exact spatial location of eye. By the categorization of the level of processing (preattentive, or ambient versus focal, or attentive) and by the monitoring phasic changes in duration of fixation a more reliable diagnosis for the course of driver's behaviour can be made.

At the present time, it is hardly possible to propose an elaborate version of a cognitive architecture that would describe perceptual and cognitive aspects of driver's behaviour. Anderson's ACT-R theory is a good candidate for the role (see Salvucci & Liu, this volume) and we certainly can hope that further investigations will bridge the gap between this computational approach and more neurophysiologically oriented work as it is reflected in the two-level model of visual processing. Indeed, beside empirical data the last model is mainly supported by the neurophysiological data on the existence of dorsal and ventral systems of human brain (e.g. Milner & Goodale, 1995). In its evolution the two-level model should include higher-order mechanisms corresponding to control structure of frontal lobes with their metacognitive and self-referencial types of processing (Velichkovsky, 1999, 2002). These control functions are at the heart of the global cognitive models like Anderson's ACT-R or Newell's Soar. At least then a synthesis will be possible. The road is long but the intermediate goals are known and within reach.

## 5 Conclusion

A high-speed monitoring of visual fixations can be used to evaluate driver's attentional state and interpret variation in fixation duration and saccadic amplitude in a simulated driving task. Especially, driver's reaction to potential and immediate hazards demonstrates that eye movement data can be used for an express-diagnostics of behaviour. An important precondition of this development is however a reliable differentiation of the ambient and focal processing modes as well as of the higher – semantic and metacognitive - levels of information processing).

## 6 Acknowledgements

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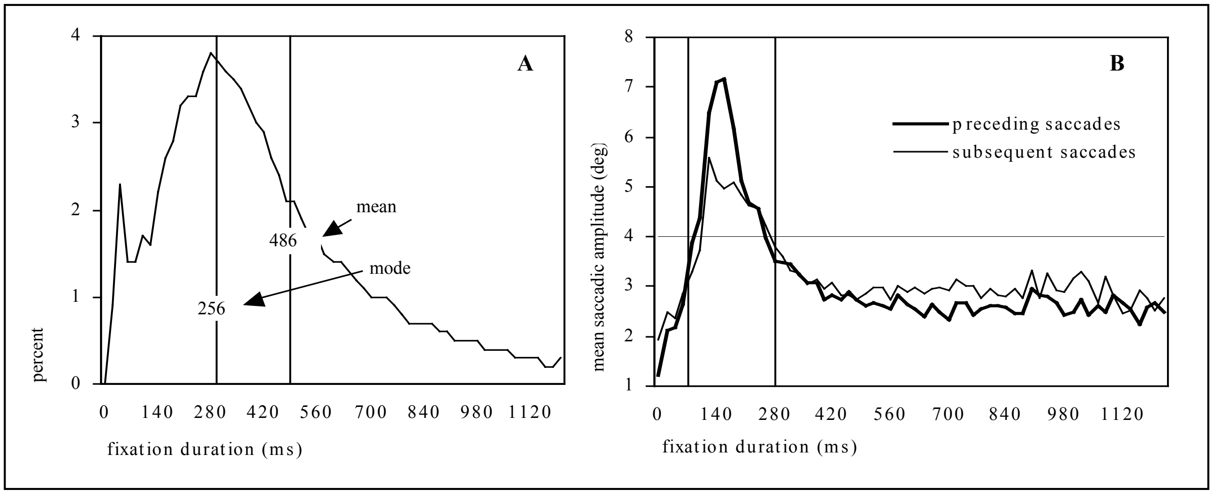


Figure 1: (A) Typical frequency distribution of fixations (over 50.000 counts) as found in a simulated driving task (after Velichkovsky et al., 2000); (B) Distributions of preceding and following saccade amplitudes across the range of fixation durations.

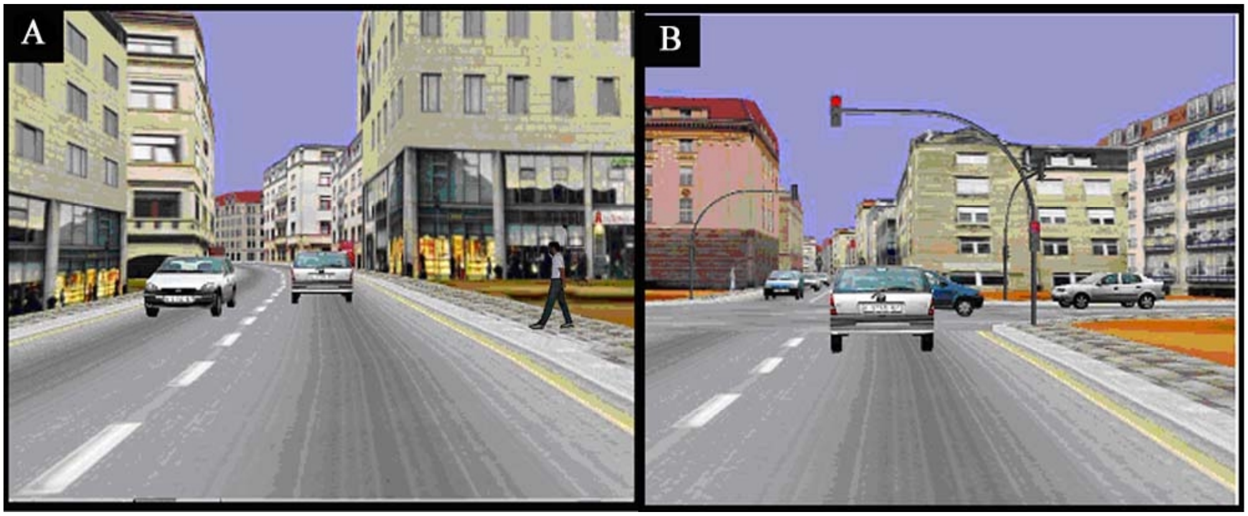


Figure 2. Sample screenshots taken from the experiment. (A) A potential hazard: a pedestrian facing the street; (B) An immediate hazard: the red traffic light at a crossing.

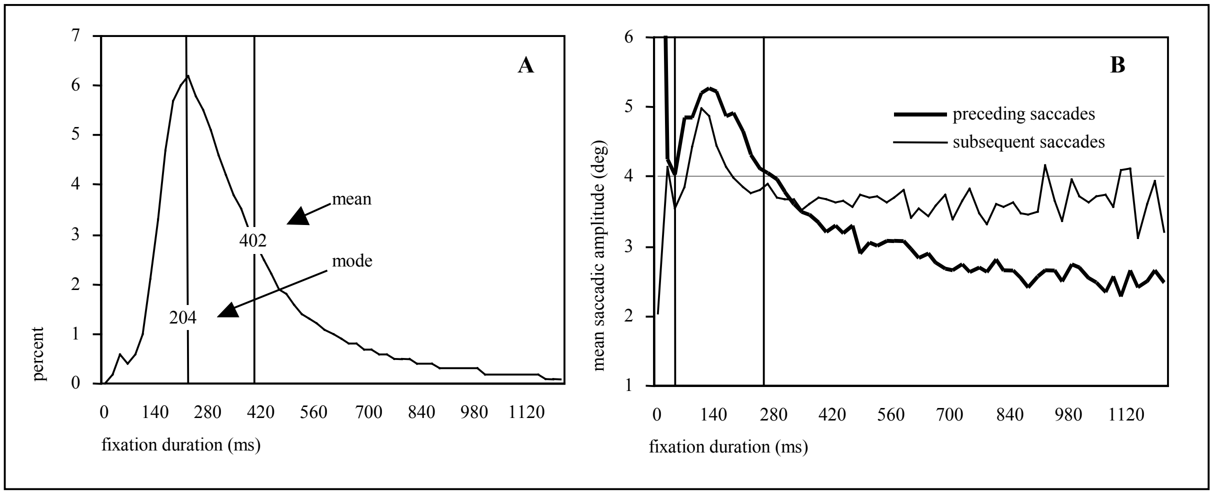


Figure 3: (A) The frequency distribution of fixations (131 654 counts) from the experiment; (B) Distributions of preceding and following saccade amplitudes across the range of fixation durations.

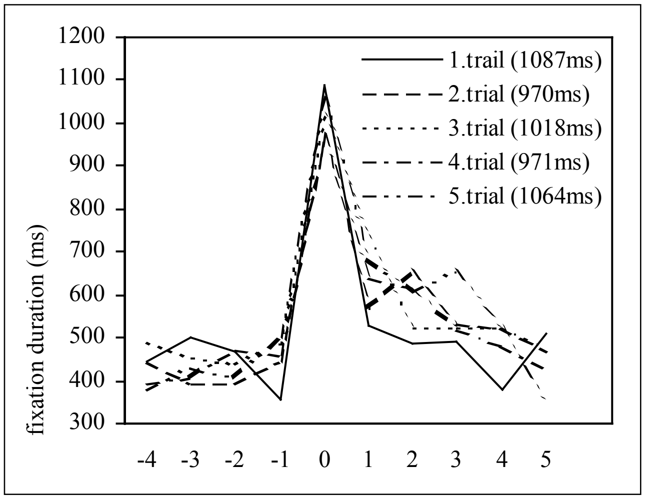


Figure 4: Mean duration time for fixations around the appearance of an immediate hazard (overall 375 counts; "0" corresponds to the fixation at the moment of the critical event), separately for 5 consecutive drive trials.

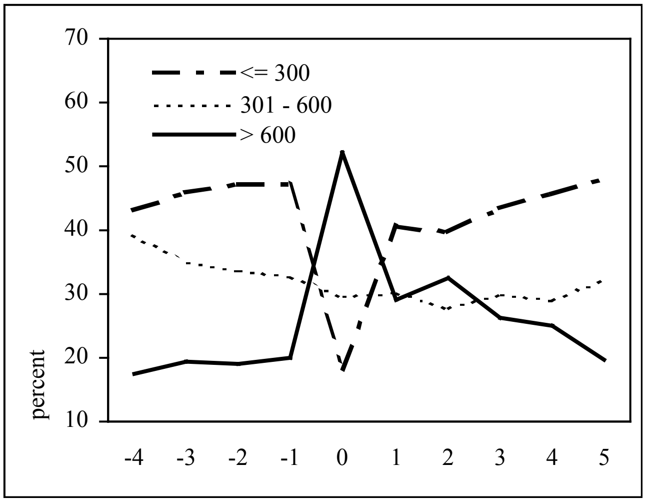

Figure 5: Frequencies of fixation durations of three categories around the time of appearance of an immediate hazard (“0” corresponds to the fixation at the moment of the critical event).

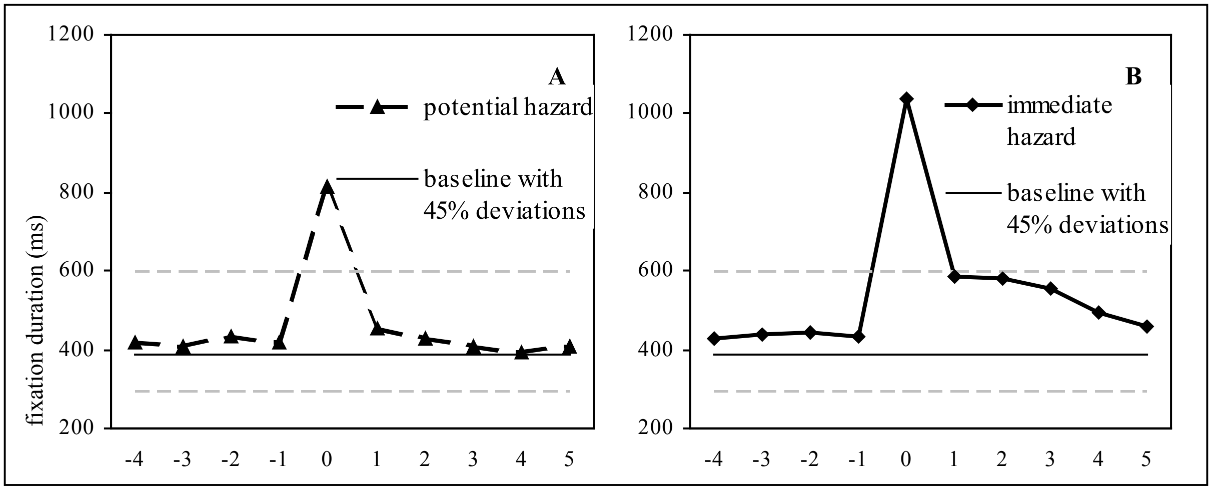


Figure 6. (A) Mean fixation durations around the point of no return for potential hazards ("0"corresponds to fixation when the driver is at the distance of about 25 meters to hazard); (B) Mean fixation duration for immediate hazards.

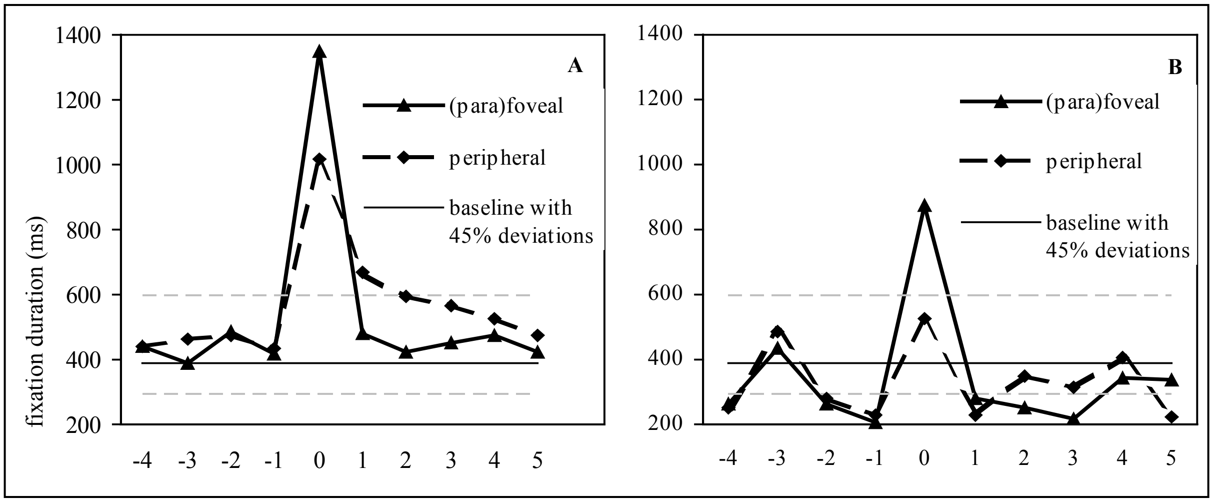


Figure 7: (A) Mean fixation durations around the appearance of red light in the cases of successful braking, categorized by eccentricity. (B) Mean fixation durations for the passing through red light ("0" corresponds to the fixation at the moment of switching to red), categorized by eccentricity.