Psychophysical investigations of gaze and CoI during simulated driving in humans

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Abstract

We have conducted psychophysical experiments to gain deeper insight into the viewing behavior of drivers. Pre-recorded and computer-generated driving scenes were presented to human observers while their gaze behavior was recorded. The patterns of eye movements was analyzed to find out which parts of the scene attract the viewers interest and how his temporal viewing behavior can be parameterized. We focussed particularly on possible conflicts of interest because then the pattern of eye movements is most informative about the attentional processes of the viewer. We were interested in how the direction of gaze related to the momentary flow field, the driving parameters, and the momentary task. Different tasks (heading, obstacle avoidance, etc.) were given to the subjects in order to study the relationship of eye movements to the task. The results revealed several novel and surprising findings about the interplay between optic flow and eye movements. First, in the heading tracking task, it was apparently very difficult to align gaze with the direction of heading. Subjects typically required a series of several saccadic eye movements until they reached the focus of expansion. The first saccade covered only 60% of the required distance to the FOE. Second, in the obstacle avoidance task, subjects were quick to identify obstacles on the path even when the direction of heading changed. Typically the first saccade after a direction change was on target. Since the obstacle avoidance task also required the estimation of the heading the quickness with which the task was completed suggests that heading estimation was much quicker in this tasks than in the heading-tracking tasks described above. Third, in the obstacle avoidance task observers virtually never looked at the FOE. Yet they were able to quickly and accurately estimate heading as demonstrated by the obstacle avoidance performance. This suggests that fixation of the FOE is not required for heading estimation. Fourth, when there was no immediate obstacle on the path subjects adopted a scene scanning behavior in which gaze was directed to irrelevant elements of the scene (either potential obstacles that were not on the path or distractors) and from time to time switched back to the ground in front of the observer in the direction of heading. The results are consistent with a model of attentional resource distribution in which attention is (a) prevalently and immediately directed to obstacles on the course, (b) when idle directed to scanning of the environment irrespective of direct relation to the driving task, (c) from time to time directed back to the course for routine checking, and (d) seldom directed to the FOE.

1 Introduction

Eye movements are an integral part of many visually guided behaviors. We typically shift our gaze to a new object of interest twice every second. These gaze shifts are used to obtain essential visual information through foveal vision. During self–motion, eye movements have a further important function for visual perception. Because self–motion induces image motion on the retina eye movements are needed to counteract the induced visual motion and stabilize the image of the object that is fixated. Eye movements during self–motion have important consequences for the processing of optic flow. On the one hand, they may help optic flow analysis in a task dependent manner. On the other hand they introduce complications for optic flow analysis because they add further retinal image motion.

Reliable and accurate recording of gaze direction during self–motion is a difficult technical problem. First of all, many eye movement recording systems cannot be easily taken along with a moving subject. Secondly, the gaze movements of freely moving subjects are composed of movements of the eye in the head, movements of the head on the trunk, and movements of the trunk itself. It is quite challenging to simultaneously measure all these components. Because of the technical problems involved the eye movement data is typically of low quality and does not allow detailed analysis. A different approach, which is also taken in this work, is the use of simulated driving scenes presented on a computer screen in front of a stationary subject. In this case, eye movements can be recorded and analyzed with high spatial and temporal resolution [8, 9, 12].

Measurements of the allocation of gaze during self–motion and the percentage of time spent on different parts of the visual field have been performed by applied psychological research on driving behavior in automobilists [17]. Basic results showed that gaze during open road driving is typically directed straight ahead, or to the far scenery on the side, to other vehicles, or (very infrequently) to the near parts of the road [11]. The percentage of time spent in these gaze directions increases in this order. But it also depends on the scene and on the task or objective of the driver. More gaze shifts to eccentric positions are made when the driver is asked for instance to attend to all the road signs, memorize the travel area, etc. [11, 5, 10]. Frequent and large gaze shifts occur when crossing an intersection [6].

During straight driving, gaze stays mostly close to the focus of expansion or the heading of the car [11, 7], presumably because it is important to constantly monitor the way ahead, particularly at the high travel speed in a car. A further characteristic and consistent relationship between gaze direction and driving behavior has been described for the negotiation of curves [7]. During approaching and driving a curve, gaze is directed towards a specific point at the inner edge of the road. This point has been termed the 'tangent point', because it is the point where the tangent to the edge of the road reverses direction. It is also the innermost point of the road edge seen from the driver. The tangent point is a characteristic point of the visual projection of the curve in the drivers display, not a fixed point on the curve in space. As such, the tangent point moves on the edge of the road as the driver continuous to pass the curve. During driving in a curve, gaze is directed towards the tangent point on average 80% of the time. Land and Lee propose that this gaze strategy eases the task of steering because the motion and position of the tangent point provides visual information to estimate the curvature. Thus the fixation of the tangent point could be a special visual strategy for the requirements of driving.

Locomotion on foot comprises entirely different visuo–motor characteristics and requirements than driving a car. The important parameter that needs to be controlled is the placement of the foot in the step cycle. Hollands et al. [4, 3] and Patla and Vickers [14] reported that gaze in walking human subjects was mostly directed towards future landing positions of the feet. Wagner et al. [20] investigated the gaze behavior of walking humans in an outdoor environment. Rather than measure gaze positions with an instrument they simply asked their subjects to report what they looked at as soon as a certain auditory signal was sounded. They took 58 measurements from each of 16 subjects. The results indicated that most often gaze was directed to objects close to the observer. The maximum of the distribution of gaze points lay between 1.5 and 3 meters from the observer. From an analysis of this distribution one might conclude that only a small proportion ($< 10\%$) was near the focus of expansion. The majority of gaze directions deviated quite substantially from the focus of expansion (median deviation about 20 degrees).

From the above studies one may conclude that, first, normal self–motion is accompanied by a large number of eye movements, and, second, that the distribution of gaze depends on the task that is required from the observer. In the experiments described below we will study gaze behavior for identical visual scenes and self-motions but with different tasks to the observer.

A further concern of gaze behavior during locomotion are slow eye movements that occur between gaze shifts. During self motion, the visual image of the world on the retinae of the eyes is also in motion. This retinal image motion creates a problem for stable vision. In order to accurately perceive the environment it is desirable to have a clear and stationary visual image. Several types of compensatory eye movement reflexes exist that attempt to counteract the self–motion induced visual motion and keep the retinal image stable using vestibular, proprioceptive, or visual signals [15, 16, 1, 13]. In stationary subjects that are exposed to a radial optic flow field optokinetic responses can be observed that are associated with linear forward translation [8, 9, 12]. These responses consist of regularly alternating slow tracking phases and saccades, or quick phases, at a frequency of about 2Hz. Eye movements in the slow phases follow the direction of motion that is present at the fovea and parafovea. The slow phases stabilize the retinal image in a small parafoveal region only. During the visual scanning of a radial optic flow stimulus, the visual motion pattern arriving on the retina depends on the direction of gaze. For instance, if one looks directly at the focus of expansion, the visual motion pattern is symmetric and there will be no motion in the direction of gaze. If one instead looks in a different direction retinal slip on the fovea will occur, the direction and speed of which will depend on the gaze direction. Therefore, the eye movement behavior depends on the direction of gaze. The speed of tracking is often considerably lower than the corresponding local stimulus speed [8, 12]. A much higher gain (close to unity) can be observed, however, when subjects are instructed to actively perform a smooth pursuit movement to follow a single element of the flow field [12].

In the case of radial optic flow stimulation, the slow phase tracking movements largely reflect this passive, stereotyped behavior. They are mainly determined by the local stimulus motion. In contrast, the saccades do not share the reflectory nature of the slow phases but rather support an active exploration of the visual scene [9]. During forward locomotion it is necessary to constantly monitor the environment and identify possible obstacles along the path. Saccades in this situation must serve the ocular scanning of the visual scene instead of merely resetting the eye position, as in the rotational optokinetic nystagmus [2].

In earlier experiments with passive viewing of an optic flow stimulus less than 20% of the total distance covered by all saccadic amplitudes were required to compensate the positional changes resulting from the tracking phases [9]. Hence, most saccadic activity must be attributed to exploration behavior. The distribution of saccades and gaze directions depended on the direction of simulated self–motion (the location of the focus of expansion) and the structure of the visual scene.

Gaze clustered near the horizon and was biased towards the location of the focus of expansion [8, 9]. This bias was stronger in human subjects than in monkeys [12]. But in both cases, gaze often deviated by several degrees from the focus location. When we presented a flow field simulating movement through a tunnel instead of a ground plane, the pattern of saccadic directions changed accordingly. While in the ground plane environment most saccades were directed parallel to the horizon, for the tunnel environment saccade directions were equally distributed in all directions [9].

2 Overview of the Experiments

In the experiments described below we study the pattern of saccades and the distribution of gaze in different driving related task given to the human observers. One set of experiments used driving scenes recorded with a video camera from inside a car driving in urban or motorway settings. These recordings contained rich scenery and several simultaneous tasks of the driver. The data showed many eye movements that were directed to objects in the scene. The analysis of these data proved difficult, however, because neither the scenery nor the momentary task could be defined rigorously in these sequences as both were depending on elements that could not be controlled by the experimenter (e.g. other cars, the placement of objects in the scene, the momentary movement parameters of the car, etc.). Therefore, in another set of experiments we recored eye movements on computer-generated driving scenes that were under full experimental control. In this study, we used a flow stimulus that simulated movement across a textured ground plane. On this plane a number of black 2D shapes were placed that simulated holes in the surface. In the simulation, subjects were driven along a zig–zag course over the surface such that the direction of self motion changed unpredictably. In successive trials, three different instructions were given to the subjects: (a) passive viewing, no specific task to do, (b) active tracking of the direction of self–motion by pointing gaze towards the focus of expansion, and (c) identifying whether self–motion is towards any of the holes in the surface. This latter condition combines the task of heading detection with the task of obstacle detection.

3 Methods

3.1 Subjects

Six subjects participated in the experiments. All subjects had normal or corrected-to-normal vision and prior experience in psychophysical experiments. Four of them were were naive with regard to the purpose of the present study.

3.2 Eye movement recording

Horizontal and vertical movements of the left eye were measured by a video-based eye movement recording system using custom miniature cameras and high-resolution digital image processing (EyeLink, SMI). Sampling rate was 250Hz. A neck support was used and subjects were instructed to keep their heads still. Any apparent miniature head movements were detected and compensated by the EyeLink system. Gaze position was automatically calculated from eye and head position. Gaze position was calibrated and validated with an EyeLink routine presenting nine fixation targets at specific locations on the screen in random order. Validation was accepted when absolute precision was below 0.5 of visual angle.

3.3 Stimuli

The stimulus was generated on a Silicon Graphic Indigo2 Extreme computer and back projected onto a transparent screen with a video projector (Electrohome ECP 4100). Spatial resolution was 1280 by 1024 pixels with a display refresh rate of 72Hz. The size of the stimulus was 90 by 90 deg. The distance of the subject to the screen was 63cm. The ambient luminance of the laboratory was below 0.01 cd/m.

Visual stimuli simulated movement of the observer within a virtual world. For easier description of the stimuli a distance metric in meters will be used for the virtual world. The virtual scene consisted of a horizontal ground plane 1.1m below eye level. The ground plane was covered with texture (Silicon Graphics texture type gravel) and extended 200m in any direction from the starting point of the movement. The projection of the ground plane was clipped at a virtual distance of 15m so that only a portion of the plane was visible at any time. Because of the truncation, the visible horizon was located 4.2 deg. below the center of the screen. Above the horizon the scene displayed blue sky. 600 black shapes, half of them quadratic, the other half triangular, were placed on the ground plane. They served as obstacles and distractors, respectively. A picture of the scene is shown in Fig. 1.

Movement simulation depicted the changing view of a virtual camera that moved parallel to the ground plane. The view of the camera was displayed on the projection screen in front of the subject. During any single trial, movement was always constant in speed but randomly changed direction after random time intervals. Thus, neither the motion direction, nor the time when it

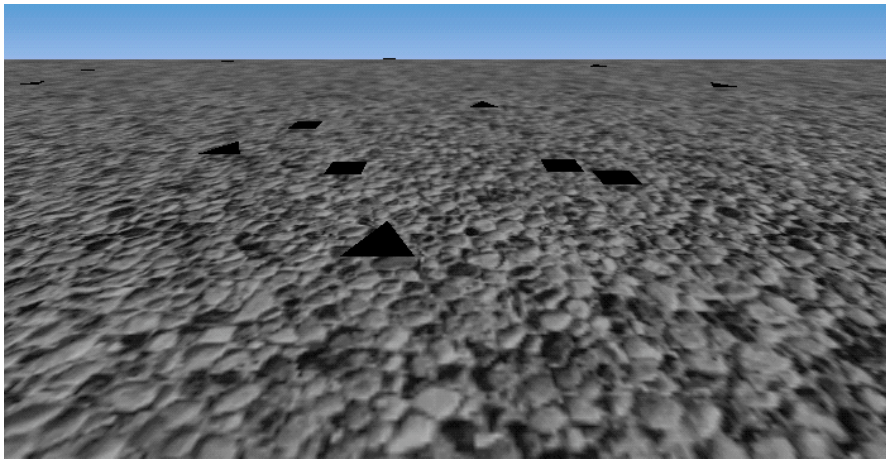

Figure 1:
Single view of the virtual world employed in the movement simulation.

changed could be predicted by the subject. Between trials, speed changed as well.

3.4 Experimental procedure

Eye movements were recorded in three different experimental conditions:

Free viewing condition Subjects look at the stimulus without any particular instruction. They were free to move their gaze to where they wished.

Heading condition Subjects were asked to continuously look into the direction in which they moved. They were told that the movement direction may changed at random and that they should try to follow these changes as fast and as accurately as possible.

Obstacle condition Subjects were instructed that the black squares on the ground plane represent obstacles that may or may not lie on the future path of the movement depending on the current heading. Their task was to identify whether an obstacle was located on the path in the heading direction and, if true, press a button which would remove that obstacle from the scene. Hence, subjects were not told to perform a particular eye movement behavior, specifically they were not told or encouraged to look at the obstacles, but they were asked to perform the task of obstacle avoidance in passive driving to the best of their ability, allowing free gaze movements. Subjects knew that they could not influence the motion direction but could remove obstacles and thus avoid hits if they acted appropriately. This condition was reminiscent of typical situations in video games involving driving simulations and was judged as a valid driving simulation by the participants of the study.

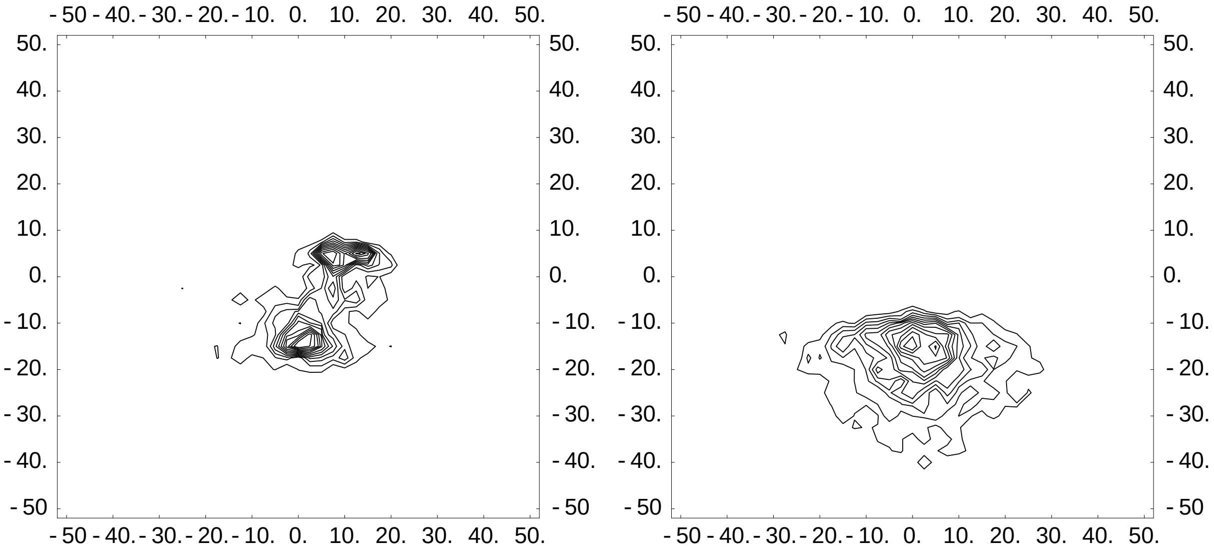

Figure 2:
Distribution of gaze direction relative to the focus of expansion in the heading task (left) and in the obstacle task (right).

In the experiment, subjects were first fitted with the eye tracker, then the eye tracker was calibrated and recording of eye data started. Next, the eye tracker sent a trigger signal to the stimulus generator which ensured that data recording on the two machines was synchronous. The stimulus generator displayed the movement scene and registered button presses by the subject as well as the times at which heading changed along with the respective new heading parameters. The stimulus generator also noted the positions of all obstacles in the scene and the position and orientation of the camera as it moved through the scene.

3.5 Data analysis

Recorded eye position were first filtered with a Gaussian of 4ms width. Eye velocity was obtained by digital differentiation of the eye position data. Saccadic eye movements were detected by a velocity level criterion which was set to 35/s. from the eye position data and the parameter files of the movement simulation gaze points in the scene were calculated over time. For each saccade, the start and end position, duration, and velocity was computed. Also determined were the latency with respect to the last heading change and the distance of the gaze point from the direction of heading and from the next impending obstacle.

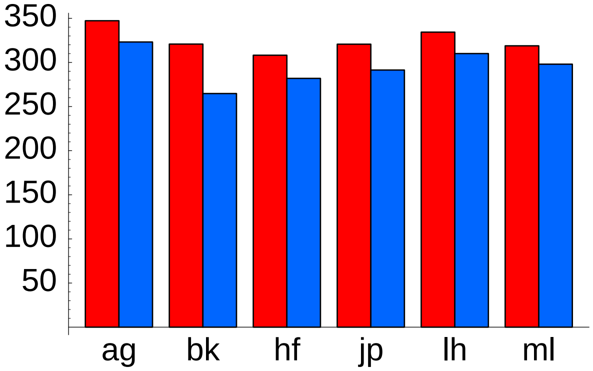

Figure 3:
Median reaction times of saccades towards the new heading after a heading change. Red bars show saccadic reaction times of each subject during the heading task. Blue bars show saccadic reaction times of each subject during the obstacle task.

4 Results

4.1 Distribution of gaze

When the subjects merely viewed the flow stimulus without any specific task, gaze was clustered near the focus of expansion. The same was found when the subjects were explicitly instructed to look in to the heading direction. The left panel of Fig. 2 shows a contour density plot of the distribution of gaze relative to the focus of expansion for the heading task. One cluster of gaze is near position $(0, -10)$ which is close to the true heading direction (at $(0, 0)$ in this plot) along the horizontal direction but a bit below the true heading in the vertical direction. The vertical offset probably arises because the visible horizon is at -4.2 deg and subjects prefer to look at the heading directions close to the horizon. A second cluster of gaze directions is above the horizon and slightly displaced to the right. This cluster is due to the data from one subject which preferred to look above the horizon. However, it is important to note that both clusters are very tightly focused.

In contrast, when the subjects were required to identify obstacles along the simulated path of self–motion (obstacle task) saccades were directed to the obstacles or to the ground plane immediately in front of the subject. Virtually no saccade was directly targeted at the focus of expansion. The distribution of gaze direction relative to the focus of expansion in the obstacle task is shown in the right panel of Fig. 2. Clearly, the distribution covers a much larger area than in the heading task (left panel of Fig. 2). Also, the peak of the distribution is about 10 deg below the horizon and 14 deg below the vertical location of the focus of expansion. The comparison of the two figures shows that there is much more scanning of the scene in the obstacle task.

4.2 Latency of saccadic reactions to heading change

In both the heading and the obstacle task, subjects have to monitor changes in heading direction and react quickly and accurately to the new direction of heading. In the heading task, subjects are required to align their gaze with the heading direction. In the obstacle task, subjects are required to estimate the new path from the changed heading and determine any obstacles that lie on the path. As Fig. 2 suggests and as will be detailed further below subjects in this case direct their gaze to candidate obstacles that are close to the current motion path. To analyze gaze behavior in the two conditions we first look at saccadic latencies, i.e. the reaction time of the subject in response to the heading change.

From the continuous driving simulation we collected all times at which heading changed and subdivided the trial sequence into phases of constant heading. The beginning of each such phase marks a point in time at which heading has just changed. Beginning from that point in time we determined the first saccade that was directed towards the new motion path. The time of occurrence of this saccade, counted from the beginning of the sequence, i.e. from the time of the heading change, was regarded as the saccadic reaction time. Fig. 3 shows the median saccadic reaction times for the six subjects in the two tasks. For each subject, reaction time in the obstacle task was shorter than in the heading task. The mean saccadic reaction time across subjects was 295 in the obstacle task and 325ms in the heading task. The difference was highly significant (t-test, $p < 0.01$). This result suggests that performance is higher in the obstacle task even though this task consist of two sub-tasks, monitoring the direction of heading and finding obstacles based on the current direction of heading, while the heading task is a single task. We speculate that the obstacle task has better performance because it is a more relevant task for the subject and better related to normal driving behavior.

A further particularity of the obstacle task is the fact that it involves stronger temporal requirements. If the subject is on collision course with an obstacle it is of imminent importance to identify the obstacle quickly. In that regard, the obstacle task puts higher demands on timing than the heading task, which does not require fast reactions. If this reasoning were true one would expect that the saccadic reaction time also depends on the immediacy of the collision with the obstacle. Therefore we analyzed whether reaction times of saccades to obstacles in the obstacle task depend on the time to collision with the obstacle. For each constant heading phase we determined the initial distance to the first obstacle on the path and calculated the time to contact with that obstacle. We the binned all phases by their time-to-contact value in 2sec bins and calculated median reaction time of the first saccade over all phases in a given bin. The result is shown in Fig. 4. The figure shows that saccadic reaction time in the obstacle task is independent of time-to-contact with the next obstacle. Thus saccadic reactions are faster in the obstacle task not because the obstacle task puts a greater time pressure on the subject but because it is easier to perform.

4.3 Accuracy of saccadic reactions to heading change

A difference between the two tasks is also apparent in the accuracy of the saccadic reactions to heading change. For each constant heading phase, we estimated the initial distance of gaze

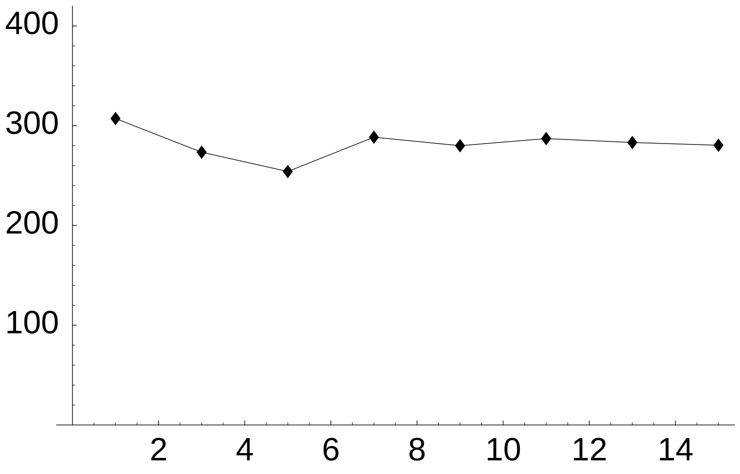

Figure 4:
Median reaction times of saccades towards the new heading after a heading change in the obstacle task as a function of the time-to-contact of the next imminent obstacle.

from the new heading and calculated for each successive saccade in that phase the distance from the heading direction after the saccade, expressed as the ratio of current distance and initial distance. The result for the two tasks is given in Fig. 5. This figure shows how gaze moves progressively closer to the path as more saccades are being performed. In the heading task (left panel of Fig. 5), the distance ratio is 0.61after the first saccade, 0.28 after the second saccade, and 0.12 after the third. Thus, the first saccade covered only 39% of the distance to the heading and the successive saccades covered 54% and 57% of the respectively remaining distance. Thus, each individual saccade heavily underestimated the momentary distance to the heading direction.

For the obstacle task (left panel of Fig. 5), the decline of the distance to the heading is much steeper. The distance ratio is 0.36 after the first saccade and 0.09 already after the second saccade. The first saccade covered 64% of the distance to the heading and the second saccade covered 75% of the remaining distance. Thus, accuracy of saccade behavior is much higher in the obstacle than in the heading task. When one considers that in the obstacle task the center of the next obstacle may in fact not lie exactly on the path but could be a bit offset one may assume that often the first saccade is already landing on the obstacle.

5 Conclusion and Discussion

Gaze strategies and performance during simulated driving depend on the task of the observer. When asked to look into the direction of heading, the observer's gaze clusters near the focus of expansion but it slow and inaccurate in tracking it when heading changes. Typically the observer needs a sequence of three to four saccades to align gaze with the new heading. When asked to identify obstacles on the path, the observer's gaze scans the scene, particularly the visible obstacles and, after a change of the heading direction, quickly and accurately targets imminent obstacles. Performance is higher than in the pure heading task, even though the obstacle task

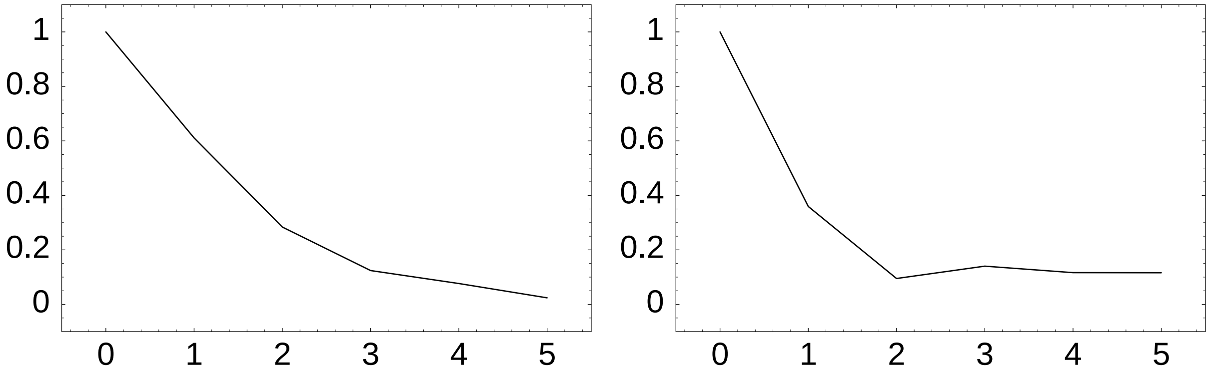

Figure 5:
Temporal evolution of the distance of gaze from heading over successive saccades for the heading task (left) and the obstacle task (right). The x-axis gives the number of saccades in a sequence that began at the time at which heading changed. The y-axis gives the ratio of the distance form heading after the respective saccade and the distance from heading at the beginning of the sequence.

also involves estimation of the new heading direction.

Eye movements are often used as an indicator of the distribution of interest when viewing a visual scene. In this sense, the results from the obstacle task suggest that the interest of the observer is mainly directed to the obstacles and not to the current heading direction or the focus of expansion. The observation that performance in this task is higher than in the heading task suggests that this distribution of interest is related to performance in the task and that saccades towards the focus of expansion are neither helpful in estimating the current heading nor particularly easy to perform. Why then did earlier investigations often found that gaze was clustered around the focus of expansion during driving. Presumably, the direction of heading is a likely direction from which new obstacles may appear, for instance when other cars are approaching. In this case it may be sensible to look there, especially when there are no other obstacles in the view of the road ahead. Secondly, when a driver trails a car in front of him, the direction of heading and the direction of the most immediate potential obstacle is identical. In this case, the obstacle behavior would also suggest that gaze is best directed straight ahead. The situation is more divers when more potential obstacles are in the view, for instance when the driver has to cross an intersection. In that case, frequent gaze shifts towards obstacles have been observed [6], consistent with the proposed obstacle viewing behavior.

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