Gaze doesn't always lead steering

Citation for the original published paper (version of record):

Lehtonen, E., Lappi, O., Koskiahde, N. et al (2018). Gaze doesn't always lead steering. Accident Analysis and Prevention, 121: 268-278. http://dx.doi.org/10.1016/j.aap.2018.09.026

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Lehtonen, Esko[a] orcid.org/0000-0003-0926-1517
Lappi, Otto[b] orcid.org/0000-0002-7996-7665
Koskiahde, Noora[c]
Mansikka, Tuomas[c]
Hietamäki, Jarkko[c]
Summala, Heikki[c] orcid.org/0000-0001-8905-1178

[a] Department of Mechanics and Maritime Sciences, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
[b] Cognitive Science, University of Helsinki, FI-00014 Helsinki, Finland
[c] Traffic Research Unit, University of Helsinki, FI-00014 Helsinki, Finland

Corresponding author: Esko Lehtonen, esko.lehtonen@chalmers.se, +46 31 772 69 01

This manuscript was accepted for publication in Accident Analysis and Prevention. The published version is available at https://doi.org/10.1016/j.aap.2018.09.026

Abstract

In car driving, gaze typically leads the steering when negotiating curves. The aim of the current study was to investigate whether drivers also use this *gaze-leads-steering strategy* when time-sharing between driving and a visual secondary task.

Fourteen participants drove an instrumented car along a motorway while performing a secondary task: looking at a specified visual target as long and as much as they felt it was safe to do so. They made six trips, and in each trip the target was at a different location relative to the road ahead. They were free to glance back at the road at any time. Gaze behaviour was measured with an eye tracker, and steering corrections were recorded from the vehicle's CAN bus. Both in-car '*Fixation*' targets and outside '*Pursuit*' targets were used.

Drivers often used a gaze-leads-steering strategy, glancing at the road ahead 200-600 ms before executing steering corrections. However, when the targets were less eccentric (requiring a smaller change in glance direction relative to the road ahead), the reverse strategy, in which glances to the road ahead followed steering corrections with 0-400 ms latency, was more common. The observed use of strategies can be interpreted in terms of predictive processing: The gaze-leads-steering strategy is driven by the need to update the visual information and is therefore modulated by the quality/quantity of peripheral information. Implications for steering models are discussed.

Highlights:

- The coordination of gaze and steering was studied in an on-road study.
- Drivers often returned their gaze back to the road ahead before making steering corrections.
- The eccentricity of the off-road target influences gaze-steering coordination.

Keywords: intermittency; distraction; eye movements; steering; predictive processing.

1. Introduction

Most of the time drivers' gaze is directed towards the road ahead. They look approximately two seconds ahead in curves; steering is closely coupled to gaze direction, with the gaze direction anticipating vehicle rotation with a lead time of approximately one second (Land, 1992; Land & Lee, 1994; Lappi, Lehtonen, Pekkanen, & Itkonen, 2013; Lehtonen, Lappi, Koirikivi, & Summala, 2014; Wilson, Chattington, & Marple-Horvat, 2008). These gaze behaviours are known as *guiding fixations,* which are important for steering and make up the majority of fixations in normal driving (Lappi et al., 2013; Lappi, Rinkkala, & Pekkanen, 2017).

However, drivers do not keep their eyes on the road at all times. Often the close correlation between gaze and steering is deliberately broken, for example when performing anticipatory look-ahead fixations at a curve many seconds before any steering action is required (Lehtonen, Lappi, Kotkanen, & Summala, 2013), scanning for potential hazards in intersections (Räsänen & Summala, 2000), or performing an eyes-off-road task while driving (Stutts et al., 2005). This time-sharing between the primary task of steering and other visual tasks—i.e. the *intermittency* of visual sampling—is a fundamental characteristic of natural driving behavior.

Eyes-off-road tasks have been extensively studied from the perspective of driver distraction. Their execution compromises lane-keeping and decreases driving speeds (Engström, Johansson, & Östlund, 2005). Eyes-off-road glances increase the crash risk (Dingus et al., 2016) by delaying reactions in, for example, critical rear-end situations (Lamble, Laakso, & Summala, 1999)—where looking on or off the road often determines if a near-crash becomes a crash (Bärgman, Lisovskaja, Victor, Flannagan, & Dozza, 2015). Increasing driving automation may increase engagement in secondary tasks (Naujoks, Purucker, & Neukum, 2016). Therefore, in the future it will be even more important to understand how drivers self-regulate their gaze behavior.

In this study, we investigated how on- and off-road glances are coordinated with steering corrections. The study had three objectives.

1) The first objective was to investigate if drivers use a *gaze-leads-steering* strategy, in which the gaze returns from off-road to the road ahead to glean guiding information for steering actions just before they are to be performed. This is a 'just-in-time' strategy; gaze is directed at the task-relevant regions at the last moment, to minimize reliance on short-term memory (Ballard, Hayhoe, & Pelz, 1995; Land, 2009; Lappi, 2014). If drivers use this strategy, we should observe that gaze returns to the road ahead and a steering correction is made with a rather fixed latency (the visuomotor lag from processing the visual input). On the other hand, previous studies have shown that drivers can use peripheral vision to keep the car within the lane, even for tens of seconds, without looking back at the road (Bhise & Rockwell, 1971; Summala, Nieminen, & Punto, 1996). This suggests that steering correction would not have to be temporally coupled to road-ahead glances at all; that is, drivers would not necessarily use the gaze-leads-steering strategy.

2) The second objective was to investigate whether the availability of peripheral visual information from the road ahead influences the use of the gaze-leads-steering strategy. The availability of peripheral visual information depends primarily on gaze *eccentricity,* the visual angle between the

current gaze direction and the road ahead. When the road ahead is very eccentric to the line of sight, the peripheral visual information is lower in quality and/or quantity (Lamble et al., 1999; Summala et al., 1996; Warren & Kurtz, 1992). Therefore, to compensate, drivers have been found to foveate the road ahead more often during visual secondary tasks as the eccentricity between gazes at the task and at the road ahead increases (Summala et al., 1996).

In addition to eccentricity, asymmetry in the spatial resolution of human vision also influences the ability to use peripheral vision. Spatial resolution of human vision is more acute in the lower versus upper peripheral visual field, a phenomenon called 'vertical meridian asymmetry' (Talgar & Carrasco, 2002). Therefore, it may be that more peripheral visual information enters from the road when a target is at the level of the windscreen instead of down at the dashboard—because the road ahead is visible only in the upper visual field. Thus, targets that are equally eccentric in terms of the visual angle between the target and the road may still differ in the amount of visual information that is available peripherally, if one of the targets is lower down, at the dashboard level.

Consequently, we hypothesized that the gaze-leads-steering strategy would become more predominant as refreshing the visual information from the road ahead with a fixation became more important (due to increases in target eccentricity and/or vertical meridian asymmetry). It was also expected that the off-road glances would become shorter as the availability of peripheral vision decreased.

3) The third objective was to explore if there are any differences between targets inside and outside the car. Drivers tend to have longer glances to roadside advertisements than to in-car locations (Chan, Pradhan, Pollatsek, Knodler, & Fisher, 2010). It can be hypothesized that because a target outside the car is allocentrically stable (relative to the outside world, not to the car and driver) it might be used as input for controlling steering through optic flow, parallax, and/or depth perception; in contrast, since in-car targets are egocentrically stable (stable relative to the car and driver), they contribute no useful control information. Also, targets within the car are clearly very close to the driver, but targets out in the world are at distances more comparable to where gaze would normally focus on the road. Thus, looking at outside targets would be less likely to produce diplopia (double vision). For these reasons, it could be expected that off-road glances to targets in the outside world are 'easier' than in-car glances, enabling drivers to take longer off-road glances and even perform steering actions while looking off-road.

2. Methods

2.1. Task

In this study, the temporal coordination between visual sampling and steering control was studied using a self-paced peripheral viewing task. The intermittency in visual sampling was elicited by asking participants to look at either an inside or an outside target while they drove on a motorway with an instrumented car. A simple looking task was used, to keep the attentional and working memory requirements of the secondary task minimal.

Participants were instructed to look at the designated target as much as possible, but always while prioritizing safe driving—including the maintenance of lane position and monitoring of other vehicles. They were also told to drive in the right lane of the motorway at a speed of 90 km/h (according to the speedometer), but to always keep a reasonable safety margin (a distance of two lamp posts) when there was another car in front of them. An accompanying researcher, who had access to the eye-tracking data in real time, monitored participants' compliance with all instructions.

In total, six different trials were performed. Five of them were '*Fixation*' trials, and the sixth was a '*Pursuit*' trial, which used a series of targets outside the vehicle (see Figure 1 for target locations). Each Fixation target remained stable in egocentric coordinates in the vehicle frame of reference. In contrast, the outside targets remained stationary in the environment, thus drivers had to pursue them with their gaze.

All participants drove the test route (Figure 2) six times, once for each trial. The trial order was varied between participants. The first participant made the trips with the targets in this order: Down-Far, Down-Near, Up-Near, Up-Middle, Up-Far, and Pursuit (Figure 1, inset). For the second the order was reversed. The third started from the Down-Near target and ended with Down-Far, and the fourth reversed the sequence of the third one, etc.

The drivers' capability to acquire information from the road via peripheral vision was manipulated by varying the vertical and horizontal eccentricity of the Fixation targets: Three of the targets were up on the windscreen and two down on the dashboard. We included a Pursuit trial, with a series of targets outside the vehicle, to explore the potential effect of inside vs. outside targets. Consecutive street lamps in the median barrier of the motorway, appearing at regular intervals, were the outside targets (Figure 1). Drivers were asked to track the top of a lamp post with their gaze as it approached. When the lamp post became occluded by the roof of the car, or was considered too eccentric, they were instructed to switch their gaze to the next lamp post.

Each Fixation target was a black, circular, 3-cm diameter sticker with the white numbers "6983" (Times New Roman, 18pt) in the middle. The participants were asked to look at the target "so that they could read the numbers", because we wanted to encourage all the participants to use the same strategy. (It is possible to look at a close target without focusing on it, holding the gaze direction on the target but binocularly converging elsewhere—on the scene behind, or infinity).

The windscreen targets' locations were chosen to approximate the location of the Pursuit targets in the driver's visual field. Since the Fixation targets were fixed in the car, their exact position in the driver's field of view and eccentricity relative to the road ahead varied somewhat with each driver (Table 1), even though the seat was adjusted so that the drivers' heads would (as far as possible) always be at the same height.

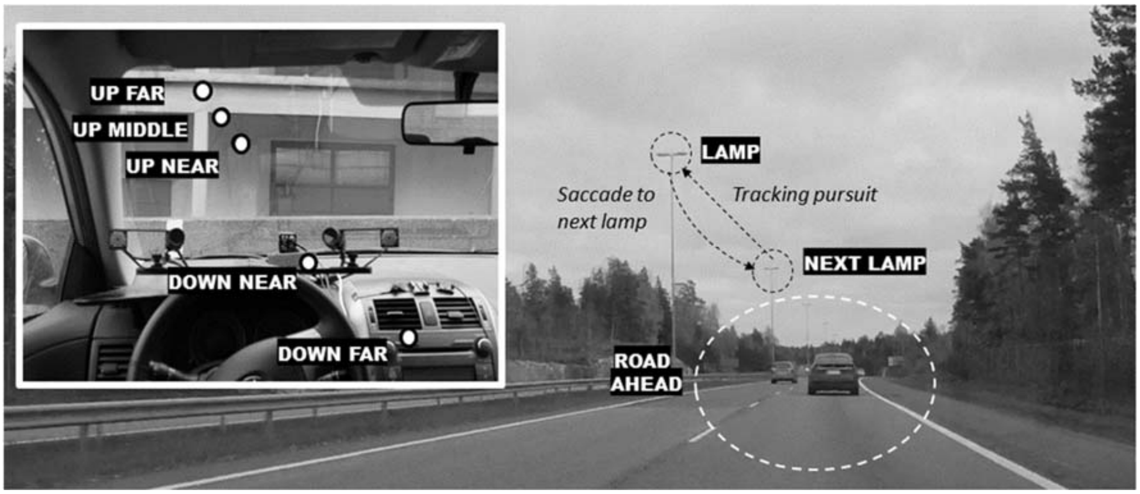

Figure 1. Main picture: Schematic depiction of the Road Ahead region of interest, demonstrating how the driver is to track successive street lamps in the Pursuit trial. Inset: Positioning of the Fixation targets inside the car. 'Up' targets are on the windscreen while 'Down' targets are on the dashboard. Note that the Up-Near, Up-Middle, and Up-Far Fixation targets are located 9 cm, 16 cm, and 24 cm from the edge of the windscreen along an imaginary line; they are placed so that they would occupy the same part of the driver's visual field as the Pursuit targets.

Table 1. The eccentricity of the targets relative to the direction of the road ahead (see 2.6.1). Eccentricities were calculated from the eye-tracking data by averaging the eccentricity of detected target glances. Because the participants had different body dimensions, the average eccentricity varied somewhat between the participants. In the following, the standard deviation characterizes the between-participant variability.

Target	Mean (deg)	SD
Pursuit	14.0	1.9
Up-Far	17.5	4.0
Up-Middle	11.8	2.7
Up-Near	6.5	1.8
Down-Near	14.1	1.8
Down-Far	35.4	3.1

2.2. Participants

Participants were recruited via university email lists and from the researchers' personal contacts. Seventeen drivers participated in the experiment. Data from three participants were excluded due to poor eye tracking signals. Of the 14 resulting participants, eight were females. Nine of the participants had driven cars for more than 30,000 km (and had held a valid driving license for two to 14 years); five had driven less than 30,000 km (and had held a valid license for one to two years at the time of the experiment). All participants reported normal vision, and none of them reported strabismus or any neurological diseases that could affect their driving ability or eye movements. Participants' ages ranged from 18−33 years. Informed consent was obtained from all participants in the study. Ethical recommendations in the 1964 Declaration of Helsinki were followed, and the study settings were approved by the ethical review board of the University of Helsinki.

2.3. Equipment

The instrumented car was a Toyota Corolla 1.6 compact sedan (MY 2007) with a manual transmission (Toyota Motor Corporation, Toyota, Aichi, Japan). A two-camera video-based remote eye tracker Smart Eye Pro version 5.7 (www.smarteye.se) with a sampling rate of 60 Hz was used to measure the gaze direction. The road scene was filmed with a forward-looking VGA scene camera (5 fps). The eye tracker and the scene camera were mounted on the dashboard. The GPS position was recorded at 1 Hz. The steering wheel signal, reverse-engineered from the vehicle CAN bus, had a rotational resolution of three degrees; it was recorded at 100 Hz and subsequently down-sampled to synchronize with the eye tracker. A computer running custom software synchronized and timestamped the data during the procedure.

2.4. Route

The test route was a section of Porvoonväylä motorway between the interchanges of Sipoonlahti and Östersundom in Finland (Figure 2). Each driver started from the petrol station (upper-right corner). The task was performed while driving from A to B and then returning from B to A. The distance between A and B was approximately seven km. There were two lanes (each 3.75 m wide) in both directions. In Finland, the traffic runs on the right-hand side of the road, and in this experiment the rightmost lanes were used.

Figure 2. A map of the test route. Data was collected between points A (N60.281637, E25.325432) and B (N60.271168, E25.223723) driven in both directions. Map information Google (c) 2016.

2.5. Procedure

The experiment started at the campus of the University of Helsinki. The starting time was either in the morning (~ 9.00 am) or in the afternoon (~ 12.30 pm). The experiment took about 3.5 hours in its entirety for each participant. The participants were compensated with two movie vouchers.

The participant filled out the informed consent form and a background questionnaire. The driver-seat height was adjusted so that all participants' eyes were at approximately the same, prespecified height, and then the eye tracker was calibrated for each individual. The seat backrest was set as upright as possible to minimize forward-backward head movements during the experiment, which could reduce the quality of the eye-tracker signal.

The driver was always accompanied by a professional driving instructor, who monitored the traffic situation during the experiment and had an extra set of clutch and brake pedals in the passenger footwell. He also told the driver where/whether to turn at junctions, and when to start and stop the task. In some sessions, there was also a third person in the vehicle assisting in the conduction of the experiment.

First, participants drove the car to a service station in Sipoonlahti, which was about 20 km away from the campus. On a motorway leading to the test route, they briefly practiced the secondary task. As they approached the start point, they actually drove the test route without performing any secondary task. Then, each participant drove the test route (Figure 2) six times, once for each target, starting and ending the drive at the service station. Afterwards they drove the test route again as they returned to campus. The first and last trips furnished data for the control trial with a target. During these control drives, the participants were also asked to keep to the inside lane at 90 km/h.

2.6. Data analysis

2.6.1. Glance detection

The direction of the road ahead was identified using a 2D gaze histogram created from the gaze data in the control drives. Bin sizes of 0.5 degrees were created, and the bin with the highest value was used (Figure 3). The locations of the Fixation targets and the speedometer were similarly identified, by manually selecting the midpoint of the corresponding gaze concentration in the 2D gaze histograms. Identification of the road ahead and target locations was done individually for each participant because the slight variations in seating position affected the gaze angles (heading and pitch) reported by the eye tracker.

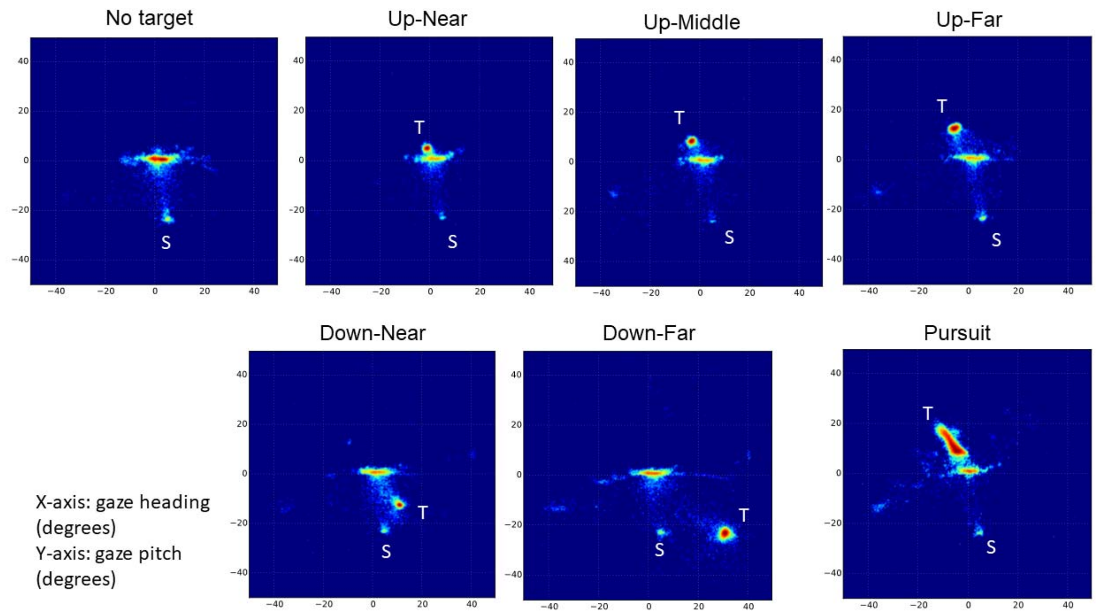

Figure 3. 2D histograms illustrated with heat maps identify the road ahead and target locations. Data are from a single participant. Gaze heading on x-axis and pitch on y-axis, in degrees relative to the system coordinates (before centering to the road ahead). The road ahead is clearly visible in the middle of the figures as a red-yellow area. Another red-yellow area (T) corresponds to the location of the target, if present. The speedometer location (S) is also clearly visible.

After the road ahead, target, and speedometer were located, glances were defined using the area-of-interest (AOI) method. In short, for the purpose of this method, a glance refers to the period of time when the gaze is within the defined area. A glance is defined as starting when the gaze enters an AOI and ending when it exits the AOI. A maximum of 200 ms of deviations/missing data were allowed within a glance if the gaze returned to the AOI within that time; Otherwise, signal noise and missed frames would have artificially split the glance (as determined by an inspection of the raw glance data). Finally, glances shorter than 100 ms were removed.

AOIs were defined relative to the manually identified road ahead and target locations. AOI dimensions were based on a visual comparison of the raw signal against the detected glances and were the same for all the participants.

The road-ahead AOI spanned -8 to 8 degrees horizontally and -2.5 to 2.5 degrees vertically from the road ahead direction. All Fixation-target AOIs covered a circle around the identified locations with an AOI radius of two degrees, except at the Down-Far location; a radius of four degrees was used since the eye-tracker data were noisier. In order to avoid confusing speedometer glances with downward target glances, the speedometer location was also determined. Its AOI was also a circle with a radius of four degrees. For the Pursuit trial, the lower end of the mass of the gaze was identified, and the Pursuit targets' AOI was defined as containing all the gaze data which was up and left from the lower end within a two-degree margin. The output of the glance detection algorithm for a segment of data is illustrated in Figures 4 and 5.

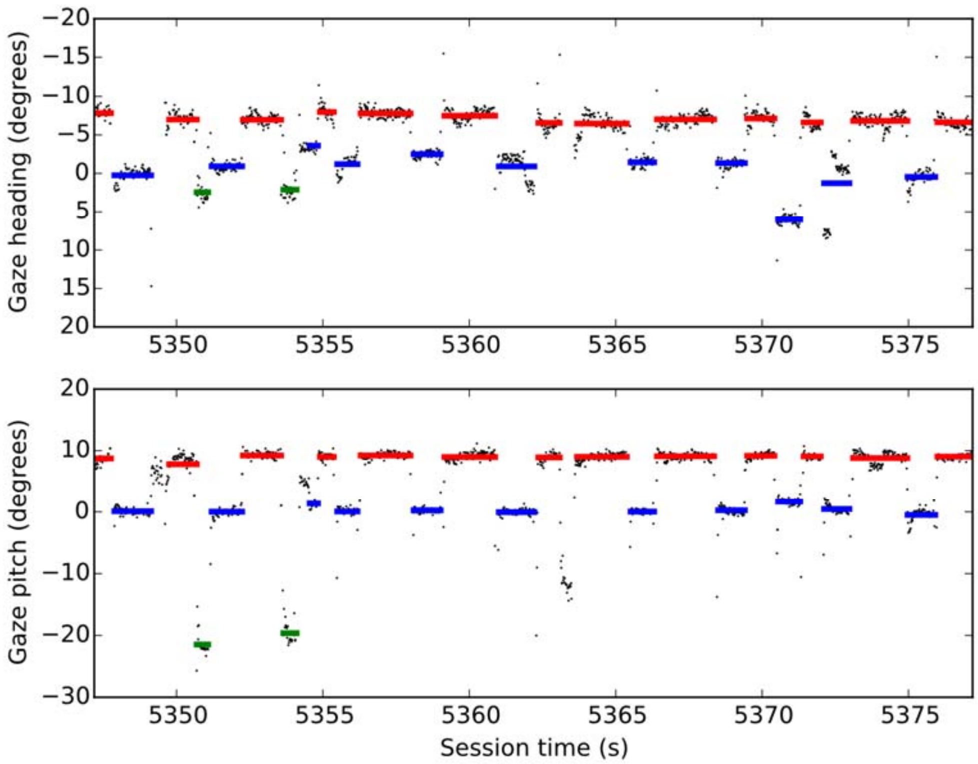

Figure 4. Illustration of glance detection for the Up-Middle target. Time from the beginning of the recording on x-axis (s). Raw gaze heading and pitch coordinates (y-axis) shown as black dots (degrees). Target glances illustrated as red lines, drawn from the beginning of a glance until its end. Road-ahead glances shown in blue and speedometer glances in green.

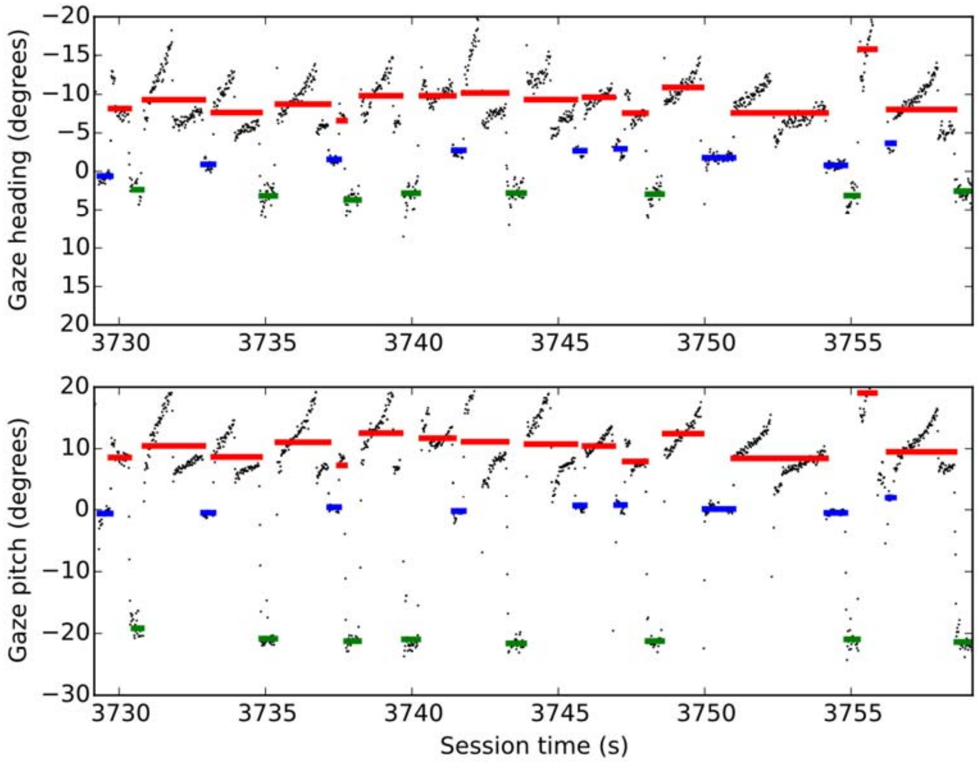

Figure 5. Illustration of the glance detection for Pursuit targets. Time from the beginning of the recording on x-axis (s). Raw gaze heading and pitch coordinates (y-axis) shown as black dots (degrees). Target glances illustrated as red lines, drawn from the beginning of a glance until its end. Road-ahead glances shown in blue and speedometer glances in green.

As noted, three participants out of 17 were excluded due to insufficient eye-tracking data quality. In addition, the Down-Far and Down-Near trials were excluded for two participants, and one of the Control trips from one participant, for the same reason. In order to include all the available data, mixed-effect models were used for the statistical analysis instead of the more traditional repeated-measures ANOVA. In the models ‘Participant’ was included as a random factor.

2.6.2. Steering corrections

Steering corrections were operationalized as steering wheel reversals (SWR). A steering wheel reversal was identified when the steering wheel signal captured from the vehicle CAN bus changed (corresponding to approximately 3 degrees of rotation in the steering wheel), if the change was in the opposite direction of the previous change (Figure 6).

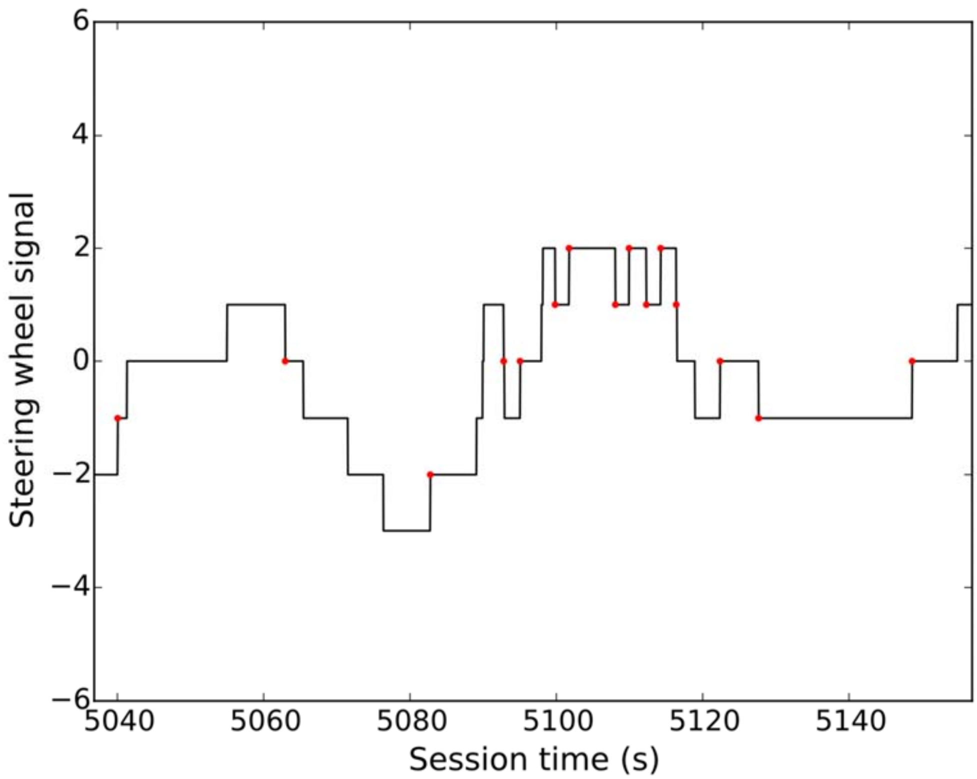

Figure 6. Illustration of steering wheel reversal (SWR) detection. Black line is the steering wheel signal captured from the CAN bus. Steering wheel reversals are marked with red dots.

3. Results

3.1. Gaze-leads-steering strategy

The first objective was to investigate whether drivers use the gaze-leads-steering strategy. The timing of SWRs relative to the road-ahead and Fixation/Pursuit target glances was investigated by comparing the SWR times to the glance onset times. For each glance, SWRs occurring two seconds before and two seconds after were identified. This four-second time window was divided into 200-ms windows[1], and the number of SWRs within each interval was counted across the glances for each participant and trial. This process was done separately for the road-ahead and target glances. The SWR frequency can be affected not only by the target placement (higher eccentricity means less available peripheral visual information), but also by individual driving speed (lower speed implies more time for glances) and individual visual strategies (differences in typical glance duration), so we divided the frequencies by the average frequency of the 200-ms windows in each participant/trial pair (i.e. each participant/target pair had its individual average). In other words, the results indicate

[1] With intervals of 200 ms the pattern was most clearly visible. Using intervals of 100 ms did not change the statistical significance of the tests.

the odds of an SWR occurrence in each 200-ms interval, relative to the overall SWRs occurrences of that participant in that trial.

When the SWR odds were averaged over the trials and participants, it was seen that SWRs were especially common around road-ahead glance onsets, both 0-400 ms before (*Before* segments) and 200-600 ms after (*After* segments) (Figure 7). The SWR odds were calculated for both intervals, and found to be higher than 1.0 (before: $t(13)=3.431$, $p<.01$, $M=1.19$, 95 % CI [1.07, 1.32]; after: $t(13)=7.636$, $p<.001$, $M=1.63$, 95 % CI [1.45, 1.80]).

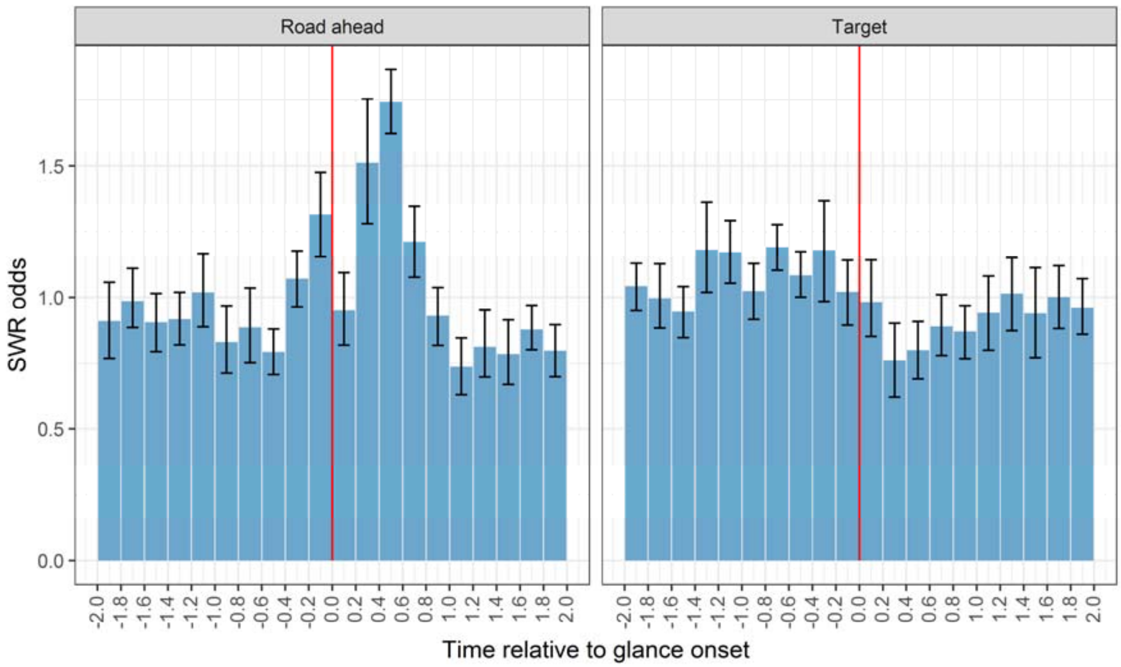

Figure 7. Odds of SWRs relative to road-ahead glance and target glance onsets (zero on the x-axis, highlighted with red vertical line). The average for all participants and its 95 % confidence intervals are shown, so that in effect 1.0 corresponds to the average SWR occurrence rate.

There is a drop in the SWR odds approximately one second after the road-ahead glance onset, which corresponds closely with the median duration of road-ahead glances. Around this time, the drivers would, of course, typically initiate a target glance (see Supplementary Figure 1. In contrast, SWRs are not time-locked to target-glance onsets like they are to road-ahead glance onsets. Instead, there appears to be a decrease in the SWR odds 0–600 ms after the onset of a target glance. That is, drivers refrain from performing SWRs after the gaze has been switched toward a target (see also Supplementary Table 1).

Overall, the results suggest that drivers do use a gaze-leads-steering strategy, in which road-ahead glances precede SWRs. Unexpectedly, the figure suggests that a reverse strategy was also used.

3.2. Gaze-steering strategy as a function of target placement

The second objective was to investigate whether the availability of the peripheral visual information from the road ahead influences the gaze steering strategies. To do so, we needed to confirm that target eccentricity and the verticality (Up vs. Down factor) did, in fact, influence the target glance durations. Longer target glance durations can be taken to indicate that drivers were better able to use information from their peripheral vison for steering control.

It was expected that the eccentricity and the Up vs Down factor would determine how well the drivers were able to use peripheral vision to guide their steering. The effect of eccentricity on the median Fixation target glance durations was tested (Figure 8; see Supplementary Figure 2 for the distributions). Glance duration medians were first log10-transformed to control heteroscedasticity. Mixed effects models were used to test the effect of target location on the median Fixation-target glance durations. Eccentricity and the Up vs Down factor were fixed effects and participant was a random effect.

As expected, both the eccentricity (B=-0.0032, SE=0.0017, $F(1,50)=40.665$, $p<.001$) and the Up vs Down factor were significant (B=0.1786, SE=0.0361, $F(1,50)=24.419$, $p<.001$). (F-values were calculated sequentially, first controlling for eccentricity before evaluating Up vs Down). With the average eccentricity of 16.58 deg, the glances to the Down targets had a median duration of 1.01 s, 95 % CI [0.72, 1.41] and those to the Up targets had a median duration of 1.52 s, 95 % CI [1.10, 2.10].

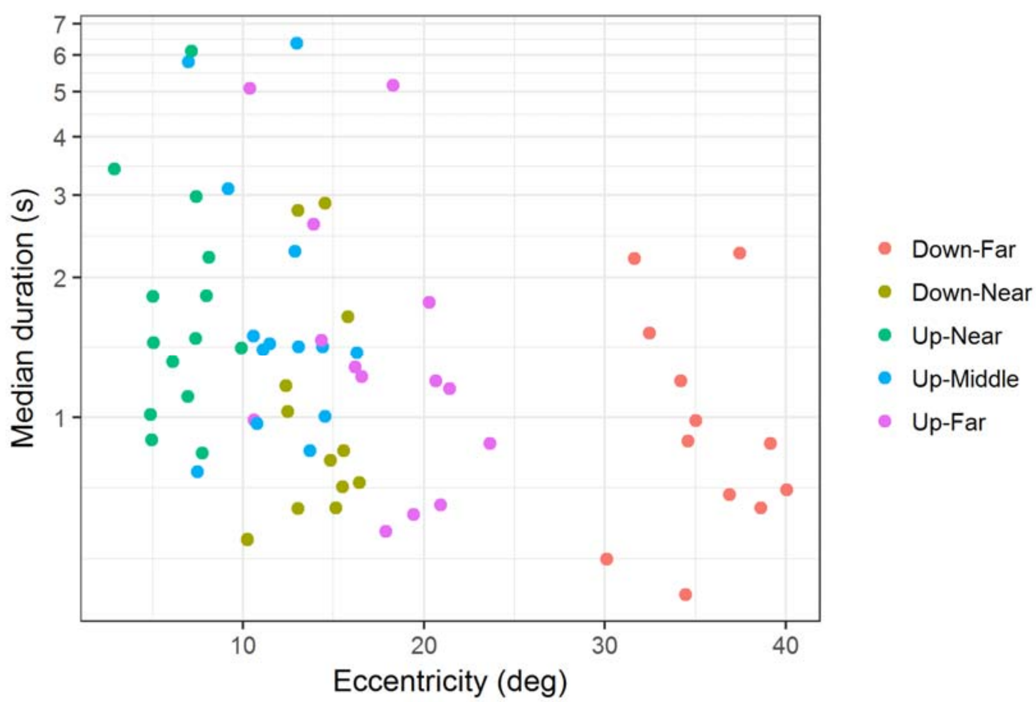

Figure 8. Median Fixation-target glance durations (y-axis) as a function of eccentricity (x-axis, log10 transformed).

Figure 9 shows the average of median glance durations for each trial, both for the target glances and for the road-ahead glances. It can be argued that the Fixation targets should be ranked in the order

Down-Far, Down-Near, Up-Far, Up-Middle, and Up-Near, based on the availability of peripheral visual information for guidance of steering. The results follow this order, with the exception of Down-Near and Up-Far, which switch places.

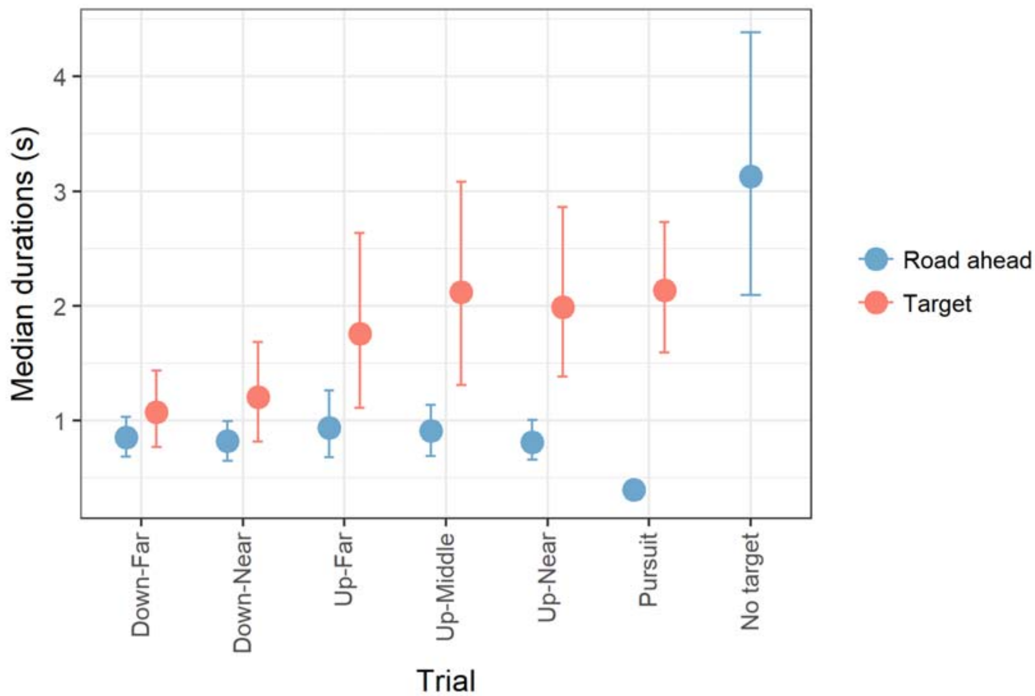

Figure 9. Grand average of median glance durations for the target and road-ahead AOIs with each target and when driving without a target. 95 % CI are shown.

The SWR odds were calculated for both Before and After segments by each target and participant. The interaction of target and segment was significant ($F(5, 135)=3.973$, p = .002) when tested with a mixed-effects model. Polynomial contrasts indicated a quadratic increase in the difference between the values from the Pursuit to Down-Far targets (Figure 10). Among the Fixation targets, this trend roughly follows the availability of peripheral visual information for steering.

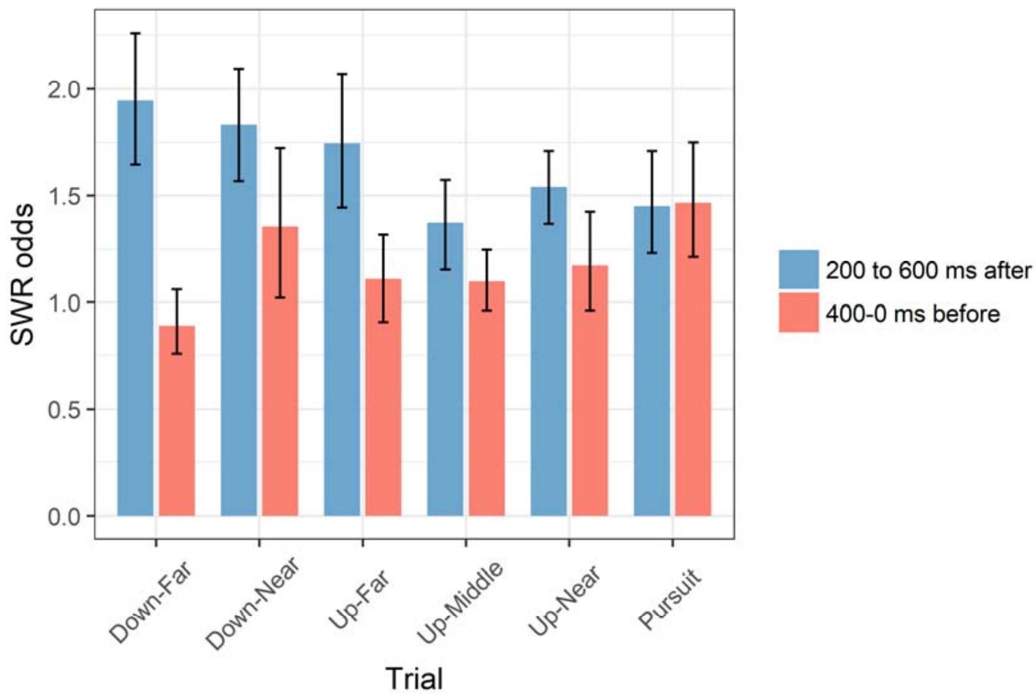

Figure 10. Odds of SWRs for After segments (200-600 ms after: gaze-leads-steering) and Before segments (0-400 ms before: steering-leads-gaze) relative to road-ahead glance onset by target.

3.3. Glance strategies in the Pursuit trial

The third objective was to explore the differences between Fixation and Pursuit trials. The glance durations presented in Figure 9 were used. Targets were modelled as a six-level fixed-effect factor with participant as a random factor. The type of target had a significant main effect on median glance durations ($F(5, 61)=16.384$, $p < .001$). Pairwise comparisons with Holm adjustment showed that the target glance durations in the Pursuit trial were significantly ($p < .01$) longer than in the Down-Far, Down-Near, and Up-Far trials, but the durations were not statistically different from the Up-Middle and Up-Near trials. The same analysis was done with the road-ahead glance durations: trial had a significant effect on duration ($F(5, 61)=31.946$, $p < .001$). Holm-adjusted pairwise comparisons showed that the road-ahead glances were significantly shorter in the Pursuit trial than in all other trials (all $p < .001$).

The Pursuit target required drivers to move their eyes while looking at the target, continually changing the eccentricity of the road ahead. Individual gaze data revealed that some participants could at times keep their eyes on the street lamps for very long durations, shifting to the next street lamp only when the pursued lamp disappeared behind the top of the car. These drivers experienced a systematic (and predictable) variation in the eccentricity of the road ahead during the Pursuit target glances, which contained both visual pursuits of the lampposts and saccades towards (but not all the way to) the road-ahead region.

The less eccentric a Fixation target was relative to the road ahead, the more often drivers performed SWRs during the target glances. Therefore, we wanted to see if the same were true of the Pursuit targets: Would drivers also be more willing to perform SWRs when the Pursuit target is less eccentric? To answer this question, we calculated the median eccentricity of raw gaze-data samples within the Pursuit-target glances as a function of SWR co-occurrence (Figure 11). The difference in the median eccentricity was 1.07 deg, 95 % CI [-070, 1.45]. It was greater when there was no SWR than when an SWR occurred; t(13)=6.127, $p < .001$). This result suggests that drivers did indeed perform SWRs more often when the gaze was less eccentric, but the difference of one degree is very small in practice.

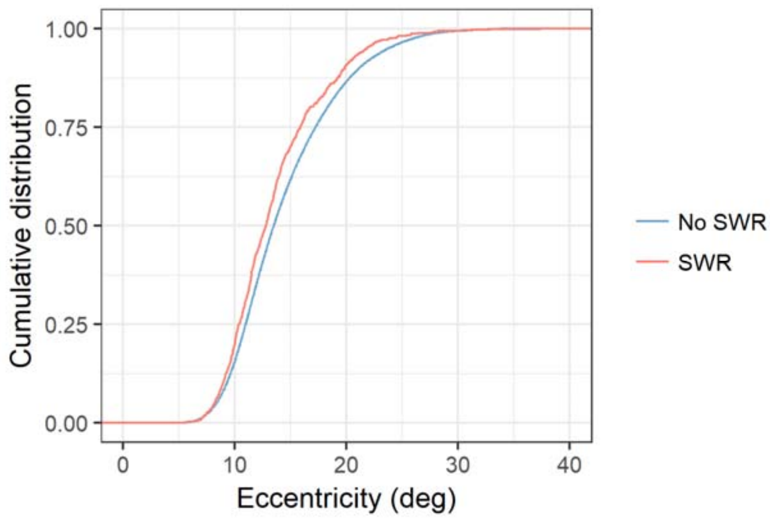

Figure 11. Cumulative density of gaze eccentricity during Pursuit glances as a function of SWR co-occurrence.

3.4. Driving performance

Qualitatively speaking, all the participants were able to control their lane position, speed, and distance to lead vehicle while performing the secondary task. Only a couple of times did the safety driver have to instruct participants to keep to their own lane, if the vehicle was drifting to the left (toward the adjacent lane) and there was another car approaching from behind in that lane. Otherwise, the participants kept to their own lane without intervention.

To rule out the possibility that the differences in glance-steering coordination could be explained by differences in steering activity or driving speed, driving performance was analyzed quantitatively by comparing SWR and average speed in the seven different trials (No target, five Fixation targets, and one Pursuit target). Mixed-effect models with trial as a fixed effect and participant as a random effect were used.

Table 3. Average steering wheel reversal (SWR) rates and average speed per trial.

Trial	SWRs per second		Speed (km/h)	
	M	SD	M	SD
No target	0.10	0.05	86.9	2.9
Down-Far	0.17	0.10	86.9	3.4
Down-Near	0.20	0.11	88.0	2.2
Up-Near	0.17	0.08	87.8	2.3
Up-Middle	0.15	0.06	87.6	2.3
Up-Far	0.16	0.07	88.4	2.4
Pursuit	0.20	0.08	85.0	3.6

Trial had a significant effect on the overall SWR rate ($F(6, 68)=6.974$, $p < .001$). Pairwise comparisons were performed and *p* values adjusted using Holm's method. The SWR rate was found to be lower in the No target trial than in all target trials ($p < .005$), except for the Up-Middle trial ($p = .058$).

Trial also had a significant effect on the average speed ($F(6, 74)=3.29$, $p = .006$). Pairwise comparisons with Holm-adjusted *p* values showed that average speed was lower during the Pursuit task than during Up-Near, Up-Far, and Down-Near ($p < .05$). There were no statistically significant differences in speed between the No target and Fixation trials

In summary, the SWR rates were higher during all peripheral viewing tasks than during 'free' driving (the No target trial), but SWR rates for the different target trials were similar. Drivers slowed down slightly while performing the Pursuit target task, but otherwise speeds were not affected.

4. Discussion

Previous naturalistic research into visual tasks involving multiple targets and extended sequences of saccades has established that gaze often precedes manual actions with a small, constant lead time (Ballard et al., 1995; Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Land, Mennie, & Rusted, 1999). In driving this is manifested as the gaze-leads-steering strategy. The present study shows that this strategy applies when drivers are time-sharing between visual control of steering and a visual secondary task. That is, drivers often glance back to the road ahead before performing a steering correction.

This strategy was most evident when the Fixation target of the secondary task was very eccentric to the road ahead. Glance durations on the Fixation targets also shortened, and SWR rates during these glances decreased, with increasing eccentricity. This suggests that as the quality and/or quantity of peripheral information available from the road ahead decreases, drivers are less able to rely on it to make steering corrections and instead must make glances back to the road before steering (cf. Summala et al., 1996).

In contrast, with low-eccentricity targets, drivers steered first and then looked back to the road ahead. In this steering-leads-gaze strategy, the drivers apparently used their peripheral vision to guide their steering actions.

The current results suggest that, in addition to eccentricity, the vertical position may also affect the availability of peripheral visual information from the road ahead. Glances to Fixation targets down on the dashboard were half a second shorter than glances to targets on the windscreen—when eccentricity was controlled.

Glance durations to the Pursuit targets were not significantly different from glance durations to the Fixation targets (which were positioned so that they would approximately coincide with the location of the Pursuit targets in the visual field). In both cases the median glance durations averaged approximately two seconds, suggesting that drivers did not glean useful information for visual guidance of steering from the Pursuit targets, which were stationary in the environment—in spite of the fact that their egocentric motion in the visual field is potentially directly useful for steering. If the Pursuit targets had provided useful control information, we would have expected to see longer glance durations towards the Pursuit targets.

However, it is noteworthy that the road-ahead glances were shorter in the Pursuit trial than in any of the Fixation target trials. Although peripheral glances to the street lamps might not have provided sufficient information to completely obviate the need to make occasional road-ahead glances, they may have provided some information, so shorter road-ahead glances were required. Buttressing this interpretation, the median gaze eccentricity during the Pursuit glances was slightly less eccentric during SWR occurrences.

Overall, drivers had a higher SWR rate while performing the peripheral viewing task than during the control task. This result indicates that the visual task imposed higher task demands, since visually demanding secondary tasks have been shown to increase the lane position variability, which means more SWRs (Engström et al., 2005; Jamson & Merat, 2005; Liang & Lee, 2010; Tsimhoni, Smith, & Green, 2004). These tasks have also been linked to reductions in driving speed (Engström et al., 2005; Jamson & Merat, 2005), but in the current experiment a reduction in speed was only demonstrated in the Pursuit trial compared to the Fixation trials. Drivers may have self-regulated their engagement with the viewing task as a function of their ability to use peripheral visual information by adjusting their glance durations (cf. Pekkanen, Lappi, Itkonen, & Summala, 2017). This ability can be affected by driving experience. Our sample consisted of drivers with different levels of experience, but due to the small sample size it is was not reasonable to analyze the effect of experience. Summala et al. (1996) found that experienced drivers (> 30,000 km in their lifetime) were better able to utilize peripheral vision for steering. Thus it can be hypothesized that novice drivers would use the gaze-leads-steering strategy more often than experienced drivers.

4.1 Implications for steering models

Most existing steering models with a psychological perspective represent the driver as receiving continuous visual feedback that is instantaneously translated into steering actions (Donges, 1978; Land, 1998; Lappi, 2014; Salvucci & Gray, 2004). The models do not consider intermittent sampling and its effect on control. The role of memory, focal vs. peripheral visual input, or anticipatory processes is not well described by such models, either.

The present results suggest that a more comprehensive steering model should take into account the fact that human drivers use *peripheral visual information* (Lamble, Summala, & Hyvärinen, 2002; Summala et al., 1996) as well as *continuous extraretinal input* (sensory input not coming from the eyes: vestibular sensations, somatosensation, proprioception, hearing). Driving under visual occlusion or with eyes off the road is sometimes called open-loop driving (Godthelp, 1986), but it is only open-loop *visually,* because during these eyes-off-road periods, steering control is at least partly accomplished using memory (specifically, stored visual information and/or precalculated motor programs). Visual information from the previous guiding fixations may be retained in a short-term memory 'image' or visual buffer (Cavallo, Brun-Dei, Laya, & Neboit, 1988; Kujala, Mäkelä, Kotilainen, & Tokkonen, 2016; Land & Furneaux, 1997; Senders, Kristofferson, Levison, Dietrich, & Ward, 1967). Alternatively, a 'precognitive motor program' may be generated during the previous eyes-on-the-road episode and launched at its end (Godthelp, 1986; McRuer, Allen, Weir, & Klein, 1977).

The present results show that when looking at an off-road target, drivers feel compelled to return their gaze to the road ahead after some seconds (cf. Summala et al., 1996). This urge might be due to some peripherally observed or extraretinal cue, or simply to cumulative time or cumulative uncertainty over the current vehicle trajectory in the absence of (focal) visual information (Godthelp, 1986; Johnson, Sullivan, Hayhoe, & Ballard, 2014; Kujala et al., 2016; Senders et al., 1967; Summala et al., 1996). When the available information is less accurate (such as when looking at a more eccentric fixation target), the accumulated uncertainty of memory/prediction could reach an uncertainty threshold sooner (Johnson et al., 2014; Kujala et al., 2016; Senders et al., 1967), leading to the shorter eyes-off-road glances observed.

Sampling the road ahead can be understood as serving anticipatory processes as well; that is, processes that predict the current or future state based on past observation history. In control-theoretical terms, this is forward inference (Miall & Wolpert, 1996; Wolpert, Diedrichsen, & Flanagan, 2011; Wolpert, Ghahramani, & Flanagan, 2001). The role of prediction has been emphasized in many hypotheses which are applicable in the current context, such as maintaining and updating an 'image' (Senders et al., 1967), 'expectancy' (Näätänen & Summala, 1976), or 'situational awareness' (Endsley, 1995).

In the predictive processing framework (Clark, 2013; Engström et al., 2017), actions are understood as a way to reduce *prediction error*, minimizing the mismatch between the predicted and observed sensory input. In driving, this means that a steering correction would be executed when the sensory input does not match the expectancies formed from the previous sensory states and the actions taken. However, sometimes the uncertainty regarding the relevant received sensory input is very high—for example, when driving and looking away from the road ahead for an extended period. In this case, more information needs to be sampled to accumulate sufficient *sensory evidence* before a steering action can be performed. This leads to the *gaze-leads-steering* strategy observed in the current study, where gaze precedes to the task just before the initiation of the action (Hayhoe et al., 2003; Land et al., 1999; Land, 2009).

On the other hand, when drivers correct their steering without looking at the road ahead, the uncertainty caused by the steering correction itself may 'force' them to sample visual information. The uncertainty associated with the *action outcome*— caused by the steering action itself— might increase total uncertainty above an acceptance threshold. This may be what gives rise to the *steering-leads-gaze strategy,* where gaze is used to resolve the uncertainty *caused* by a steering correction. In support of this idea, we observed that the *steering-leads-gaze strategy* was used more when the eccentricity of the Fixation targets increased.

4.2. Limitations

The current study took the forced peripheral viewing task (Summala et al., 1996) one step closer to natural driving by performing the task on real roads at road speeds, and adding the Pursuit target trial. However, while more natural than a visual occlusion paradigm (Senders et al., 1967), a secondary viewing task is nevertheless an artificial way to instigate intermittent sampling. It is possible that the coupling of the gaze and steering would not be exactly similar when drivers are engaged in some other secondary task. Secondary tasks often impose substantial visual and/or cognitive loads on the driver which may fluctuate over time. For example, it is possible that when drivers are engaged in a more demanding secondary task they would not steer without looking first.

The upper Fixation targets where placed so that they would reside approximately in the same part of the visual field as the Pursuit targets. However, with the Pursuit targets the drivers had more freedom to adapt their gaze strategies. They could choose when to switch their gaze to the next lamp post. A simulator or augmented reality setup, where only one possible Pursuit target is presented at a time, could be used to address this.

With the current eye tracker, it was not possible to accurately estimate vergence. The Pursuit targets were at a comparable *depth distance* to where gaze would normally land on the road. Looking at them would be less likely to produce diplopia (double vision) of the road than looking at the Fixation targets. Thus, while the participants were instructed to look at the Fixation targets in such a way that they would be able to read the text printed on them, some of them might still have not converged at the target distance, but at the more typical guiding fixation distance or even infinity (“staring through” the target). In a 3D VR set-up, the Fixation targets could be placed at the same distance as the Pursuit targets.

5. Conclusions

The coordination of gaze and steering was studied using a ‘minimal’ visual secondary task, instructing participants to look at designated Fixation and Pursuit targets as much as they could while remaining comfortable and safe. The drivers often used the strategy of looking before they steered. However, an opposite strategy, steering before they looked, was also found, especially when the road ahead was not very eccentric to the Fixation target. Moreover, the eyes-off-road glance durations were longest with the Fixation targets.

First, the results are in line with the observation that drivers use peripheral visual information to guide their steering actions when it is readily available. When it is less available, there is more uncertainty regarding the present state, and thus road ahead glances need to be performed more often. Second, the use of the opposite strategy suggests that steering actions themselves create uncertainty which must be resolved by glancing back to the road.

These observations pave the way for a more complete understanding of the strategic interplay of gaze and steering in natural driving, and the way the brain copes with the intermittency of visual input in complex multitasking environments.

Acknowledgements: Heidi Honkanen and Anna Pakkanen participated in the data collection and preparation of the experiment. Tina Mayberry edited and proofread the manuscript.
This study was funded by The Academy of Finland (grant number 279905). The first author received also funding through Area of Advance Transport at the Chalmers University of Technology.

Conflict of Interest: The authors declare that they have no conflict of interest.

Data availability: All data analyzed during this study and the analysis code written in R with R Markdown format are available from figshare repository https://figshare.com/s/c53c24441d9925a2fe7e (doi: 10.6084/m9.figshare.5572636). Raw gaze tracking and vehicle data is available from the corresponding author on reasonable request.

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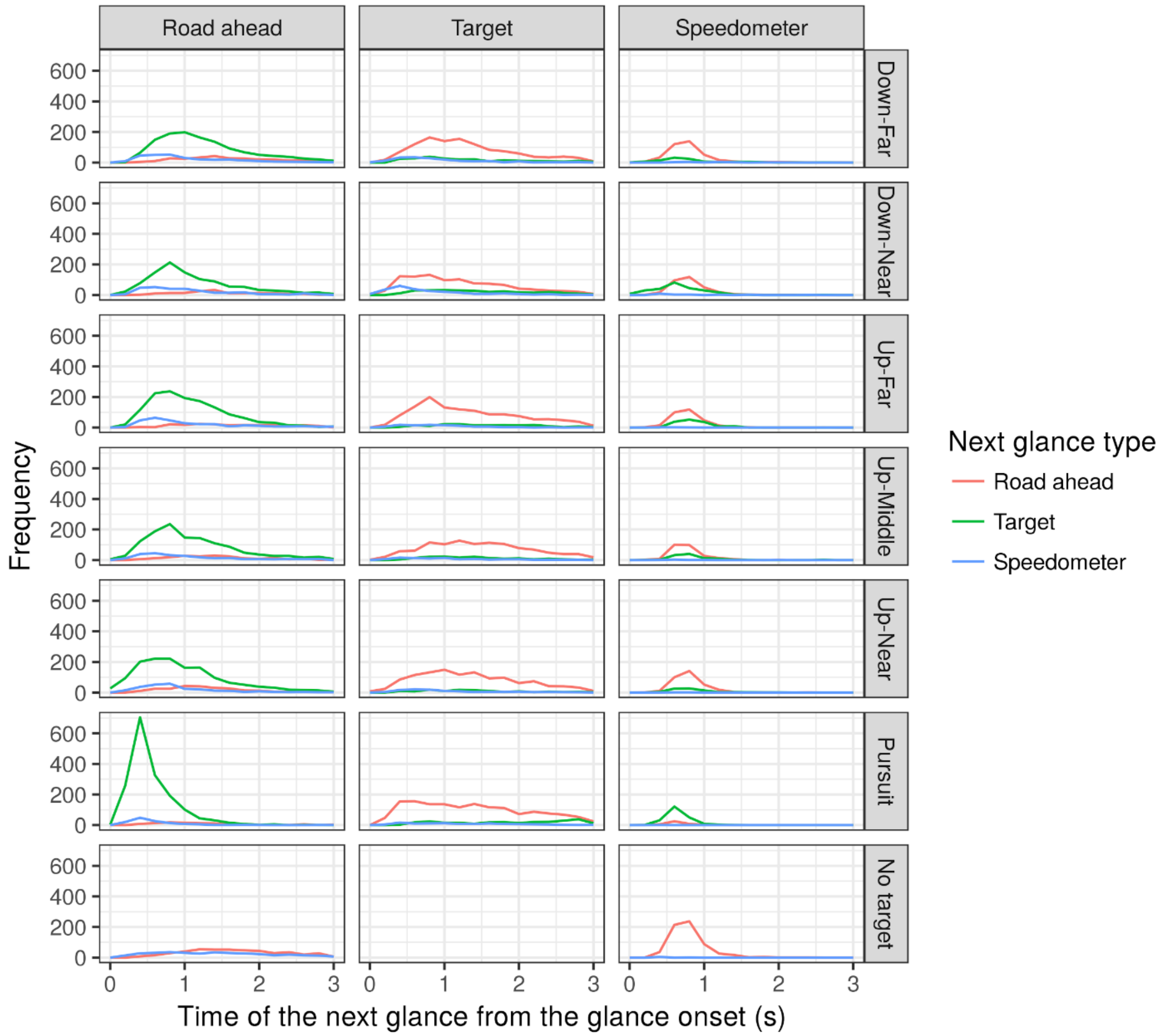
Supplementary Material

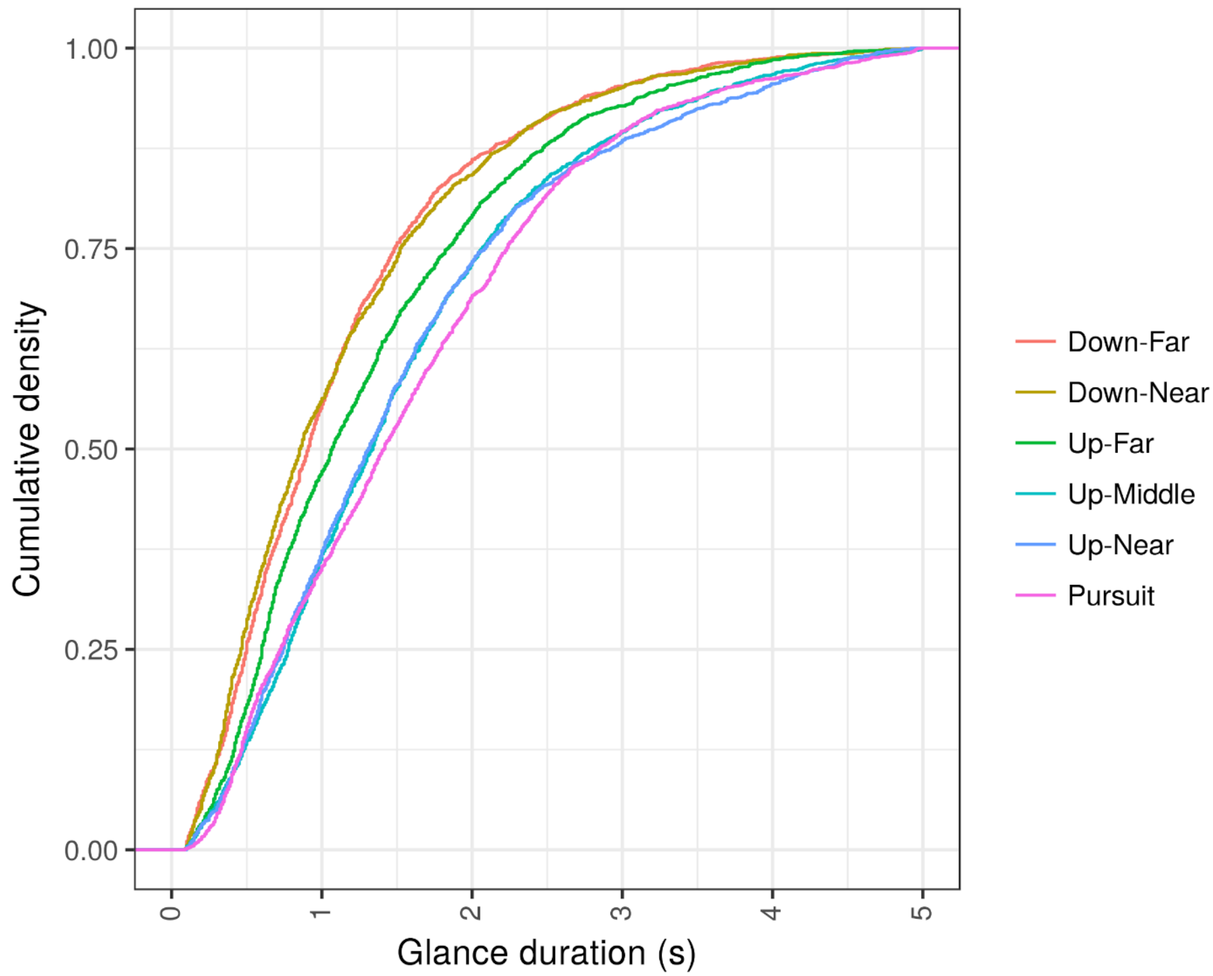
for ‘Gaze doesn’t always lead steering’

Supplementary Table 1. SWR rates for each trial during road ahead and target glances. Means and between-subject standard deviations in seconds.

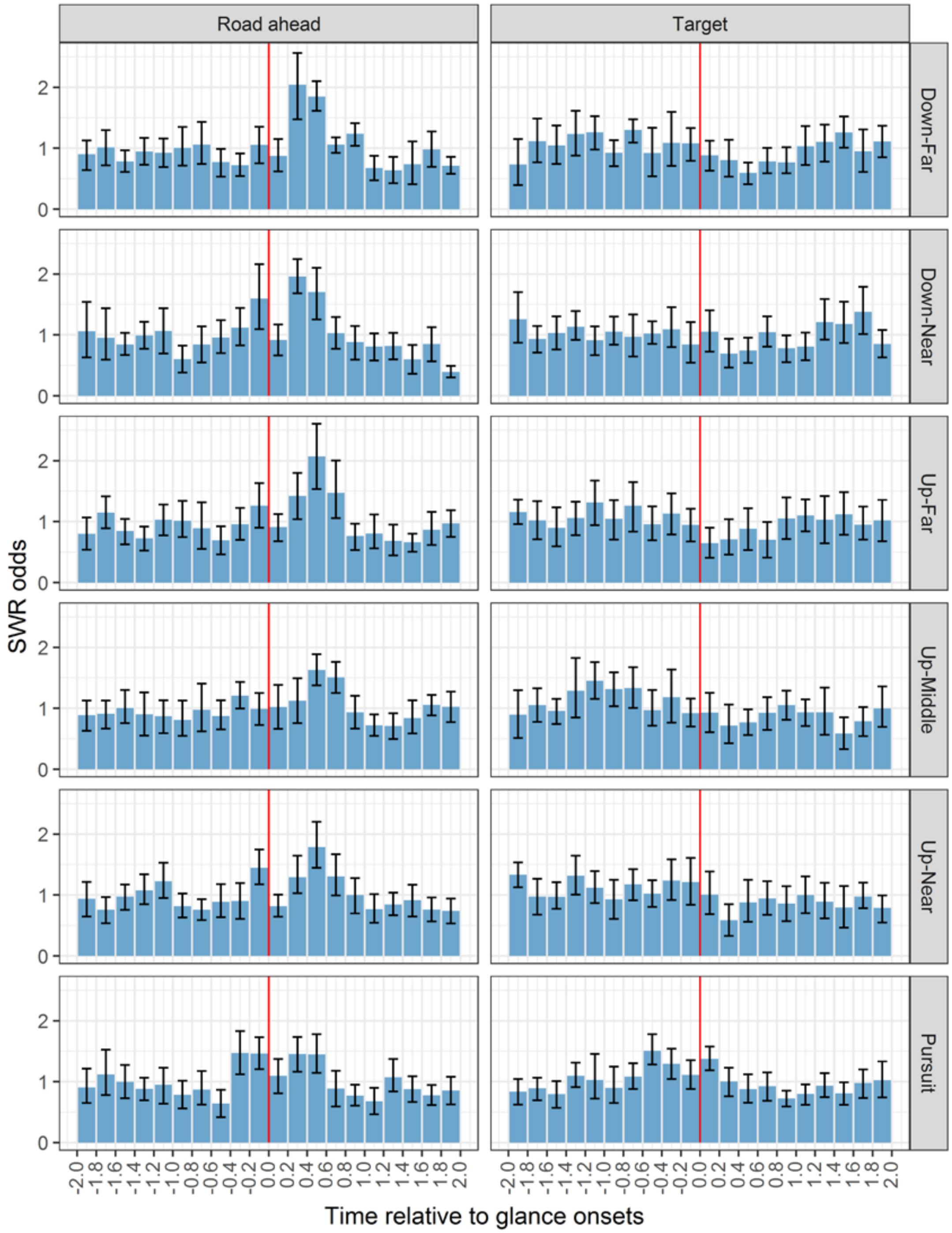
	Road ahead		Target	
Trial	M	SD	M	SD
No target	0.09	0.05	n/a	n/a
Down-Far	0.22	0.14	0.12	0.10
Down-Near	0.25	0.15	0.17	0.12
Up-Near	0.21	0.12	0.15	0.08
Up-Middle	0.18	0.08	0.14	0.06
Up-Far	0.20	0.09	0.13	0.06
Pursuit	0.26	0.14	0.18	0.08



Supplementary Figure 1. The time and type of the next glance to relative to the onset of a glance for each type of glance. Columns shows the type of the current glance. The consecutive glances are shown as a function of the onset time after the onset of the current glance. The glance detection ignored glances outside the designated areas or interests: Therefore, target to target and road ahead to road ahead glance sequences occur, if the driver has looked at the road environment outside the road ahead or to some non-target in-car location, for example. The dominating glance strategy is that road ahead glances were followed by a target glance, and target and speedometer glances were followed by a road ahead glance.



Supplementary Figure 2. Cumulative density functions for the target glance durations in each target trial.



Supplementary Figure 3. Odds of SWRs relative to road ahead glance and target glance onsets (= zero point of the x-axis highlighted with red vertical line) by trial. The average for the participants and its 95 % confidence intervals are shown so that in effect 1.0 corresponds the average SWR occurrence rate.