

# 1 Gaze doesn't always lead steering

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24 **Abstract**

25

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

29

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

36

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

44

45 **Highlights:**

46

- 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.

47

48

49

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

51

# 52 1. Introduction

53 Most of the time drivers' gaze is directed towards the road ahead. They look approximately two  
54 seconds ahead in curves; steering is closely coupled to gaze direction, with the gaze direction  
55 anticipating vehicle rotation with a lead time of approximately one second (Land, 1992; Land & Lee,  
56 1994; Lappi, Lehtonen, Pekkanen, & Itkonen, 2013; Lehtonen, Lappi, Koirikivi, & Summala, 2014;  
57 Wilson, Chattington, & Marple-Horvat, 2008). These gaze behaviours are known as *guiding fixations*,  
58 which are important for steering and make up the majority of fixations in normal driving (Lappi et al.,  
59 2013; Lappi, Rinkkala, & Pekkanen, 2017).

60  
61 However, drivers do not keep their eyes on the road at all times. Often the close correlation  
62 between gaze and steering is deliberately broken, for example when performing anticipatory look-  
63 ahead fixations at a curve many seconds before any steering action is required (Lehtonen, Lappi,  
64 Kotkanen, & Summala, 2013), scanning for potential hazards in intersections (Räsänen & Summala,  
65 2000), or performing an eyes-off-road task while driving (Stutts et al., 2005). This time-sharing  
66 between the primary task of steering and other visual tasks—i.e. the *intermittency* of visual  
67 sampling—is a fundamental characteristic of natural driving behavior.

68  
69 Eyes-off-road tasks have been extensively studied from the perspective of driver distraction. Their  
70 execution compromises lane-keeping and decreases driving speeds (Engström, Johansson, &  
71 Östlund, 2005). Eyes-off-road glances increase the crash risk (Dingus et al., 2016) by delaying  
72 reactions in, for example, critical rear-end situations (Lamble, Laakso, & Summala, 1999)—where  
73 looking on or off the road often determines if a near-crash becomes a crash (Bärgman, Lisovskaja,  
74 Victor, Flannagan, & Dozza, 2015). Increasing driving automation may increase engagement in  
75 secondary tasks (Naujoks, Purucker, & Neukum, 2016). Therefore, in the future it will be even more  
76 important to understand how drivers self-regulate their gaze behavior.

77  
78 In this study, we investigated how on- and off-road glances are coordinated with steering  
79 corrections. The study had three objectives.

80  
81 1) The first objective was to investigate if drivers use a *gaze-leads-steering* strategy, in which the  
82 gaze returns from off-road to the road ahead to glean guiding information for steering actions just  
83 before they are to be performed. This is a 'just-in-time' strategy; gaze is directed at the task-relevant  
84 regions at the last moment, to minimize reliance on short-term memory (Ballard, Hayhoe, & Pelz,  
85 1995; Land, 2009; Lappi, 2014). If drivers use this strategy, we should observe that gaze returns to  
86 the road ahead and a steering correction is made with a rather fixed latency (the visuomotor lag  
87 from processing the visual input). On the other hand, previous studies have shown that drivers can  
88 use peripheral vision to keep the car within the lane, even for tens of seconds, without looking back  
89 at the road (Bhise & Rockwell, 1971; Summala, Nieminen, & Punto, 1996). This suggests that steering  
90 correction would not have to be temporally coupled to road-ahead glances at all; that is, drivers  
91 would not necessarily use the gaze-leads-steering strategy.

92  
93 2) The second objective was to investigate whether the availability of peripheral visual information  
94 from the road ahead influences the use of the gaze-leads-steering strategy. The availability of  
95 peripheral visual information depends primarily on gaze *eccentricity*, the visual angle between the

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

101

102 In addition to eccentricity, asymmetry in the spatial resolution of human vision also influences the  
103 ability to use peripheral vision. Spatial resolution of human vision is more acute in the lower versus  
104 upper peripheral visual field, a phenomenon called ‘vertical meridian asymmetry’ (Talgar & Carrasco,  
105 2002). Therefore, it may be that more peripheral visual information enters from the road when a  
106 target is at the level of the windscreen instead of down at the dashboard—because the road ahead  
107 is visible only in the upper visual field. Thus, targets that are equally eccentric in terms of the visual  
108 angle between the target and the road may still differ in the amount of visual information that is  
109 available peripherally, if one of the targets is lower down, at the dashboard level.

110

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

116

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

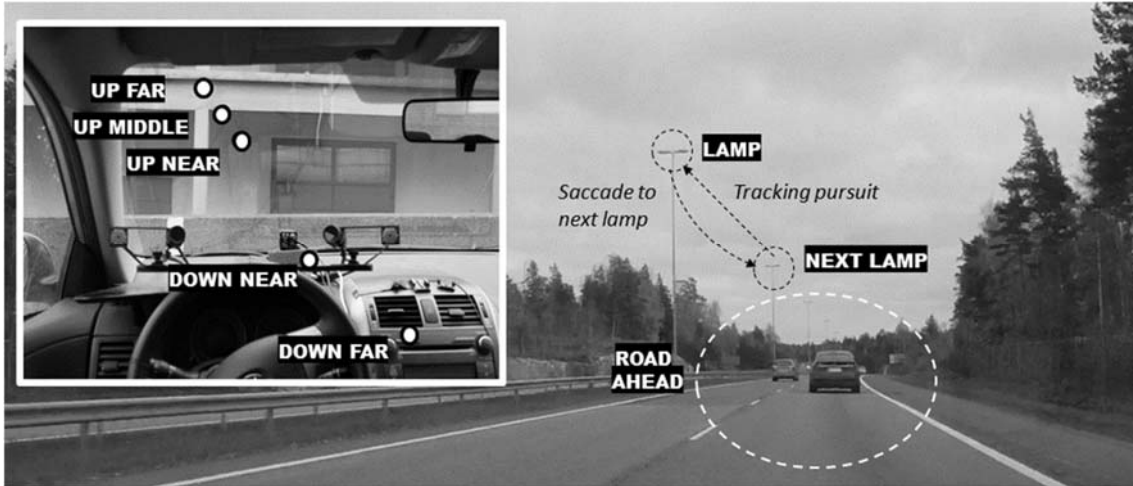
## 129 2. Methods

### 130 2.1. Task

131

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

137  
138 Participants were instructed to look at the designated target as much as possible, but always while  
139 prioritizing safe driving—including the maintenance of lane position and monitoring of other  
140 vehicles. They were also told to drive in the right lane of the motorway at a speed of 90 km/h  
141 (according to the speedometer), but to always keep a reasonable safety margin (a distance of two  
142 lamp posts) when there was another car in front of them. An accompanying researcher, who had  
143 access to the eye-tracking data in real time, monitored participants' compliance with all instructions.  
144  
145 In total, six different trials were performed. Five of them were '*Fixation*' trials, and the sixth was a  
146 '*Pursuit*' trial, which used a series of targets outside the vehicle (see Figure 1 for target locations).  
147 Each Fixation target remained stable in egocentric coordinates in the vehicle frame of reference. In  
148 contrast, the outside targets remained stationary in the environment, thus drivers had to pursue  
149 them with their gaze.  
150  
151 All participants drove the test route (Figure 2) six times, once for each trial. The trial order was  
152 varied between participants. The first participant made the trips with the targets in this order:  
153 Down-Far, Down-Near, Up-Near, Up-Middle, Up-Far, and Pursuit (Figure 1, inset). For the second the  
154 order was reversed. The third started from the Down-Near target and ended with Down-Far, and the  
155 fourth reversed the sequence of the third one, etc.  
156  
157 The drivers' capability to acquire information from the road via peripheral vision was manipulated by  
158 varying the vertical and horizontal eccentricity of the Fixation targets: Three of the targets were up  
159 on the windscreen and two down on the dashboard. We included a Pursuit trial, with a series of  
160 targets outside the vehicle, to explore the potential effect of inside vs. outside targets. Consecutive  
161 street lamps in the median barrier of the motorway, appearing at regular intervals, were the outside  
162 targets (Figure 1). Drivers were asked to track the top of a lamp post with their gaze as it  
163 approached. When the lamp post became occluded by the roof of the car, or was considered too  
164 eccentric, they were instructed to switch their gaze to the next lamp post.  
165  
166 Each Fixation target was a black, circular, 3-cm diameter sticker with the white numbers "6983"  
167 (Times New Roman, 18pt) in the middle. The participants were asked to look at the target "so that  
168 they could read the numbers", because we wanted to encourage all the participants to use the same  
169 strategy. (It is possible to look at a close target without focusing on it, holding the gaze direction on  
170 the target but binocularly converging elsewhere—on the scene behind, or infinity).  
171  
172 The windscreen targets' locations were chosen to approximate the location of the Pursuit targets in  
173 the driver's visual field. Since the Fixation targets were fixed in the car, their exact position in the  
174 driver's field of view and eccentricity relative to the road ahead varied somewhat with each driver  
175 (Table 1), even though the seat was adjusted so that the drivers' heads would (as far as possible)  
176 always be at the same height.  
177



178

179 **Figure 1. Main picture: Schematic depiction of the Road Ahead region of interest, demonstrating**  
 180 **how the driver is to track successive street lamps in the Pursuit trial. Inset: Positioning of the**  
 181 **Fixation targets inside the car. ‘Up’ targets are on the windshield while ‘Down’ targets are on**  
 182 **the dashboard. Note that the Up-Near, Up-Middle, and Up-Far Fixation targets are located 9 cm,**  
 183 **16 cm, and 24 cm from the edge of the windshield along an imaginary line; they are placed so**  
 184 **that they would occupy the same part of the driver’s visual field as the Pursuit targets.**

185

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

191

192 Target	Mean (deg)	SD
194 Pursuit	14.0	1.9
195 Up-Far	17.5	4.0
196 Up-Middle	11.8	2.7
197 Up-Near	6.5	1.8
198 Down-Near	14.1	1.8
199 Down-Far	35.4	3.1

## 200 2.2. Participants

201 Participants were recruited via university email lists and from the researchers’ personal contacts.  
 202 Seventeen drivers participated in the experiment. Data from three participants were excluded due  
 203 to poor eye tracking signals. Of the 14 resulting participants, eight were females. Nine of the  
 204 participants had driven cars for more than 30,000 km (and had held a valid driving license for two to  
 205 14 years); five had driven less than 30,000 km (and had held a valid license for one to two years at  
 206 the time of the experiment). All participants reported normal vision, and none of them reported  
 207 strabismus or any neurological diseases that could affect their driving ability or eye movements.  
 208 Participants’ ages ranged from 18–33 years. Informed consent was obtained from all participants in

209 the study. Ethical recommendations in the 1964 Declaration of Helsinki were followed, and the study  
210 settings were approved by the ethical review board of the University of Helsinki.

## 211 2.3. Equipment

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

## 221 2.4. Route

222 The test route was a section of Porvoonväylä motorway between the interchanges of Sipoonlahti  
223 and Östersundom in Finland (Figure 2). Each driver started from the petrol station (upper-right  
224 corner). The task was performed while driving from A to B and then returning from B to A. The  
225 distance between A and B was approximately seven km. There were two lanes (each 3.75 m wide) in  
226 both directions. In Finland, the traffic runs on the right-hand side of the road, and in this experiment  
227 the rightmost lanes were used.  
228



229  
230 **Figure 2. A map of the test route. Data was collected between points A (N60.281637, E25.325432)**  
231 **and B (N60.271168, E25.223723) driven in both directions. Map information Google (c) 2016.**

232  
233

## 234 2.5. Procedure

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

238

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

244

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

250

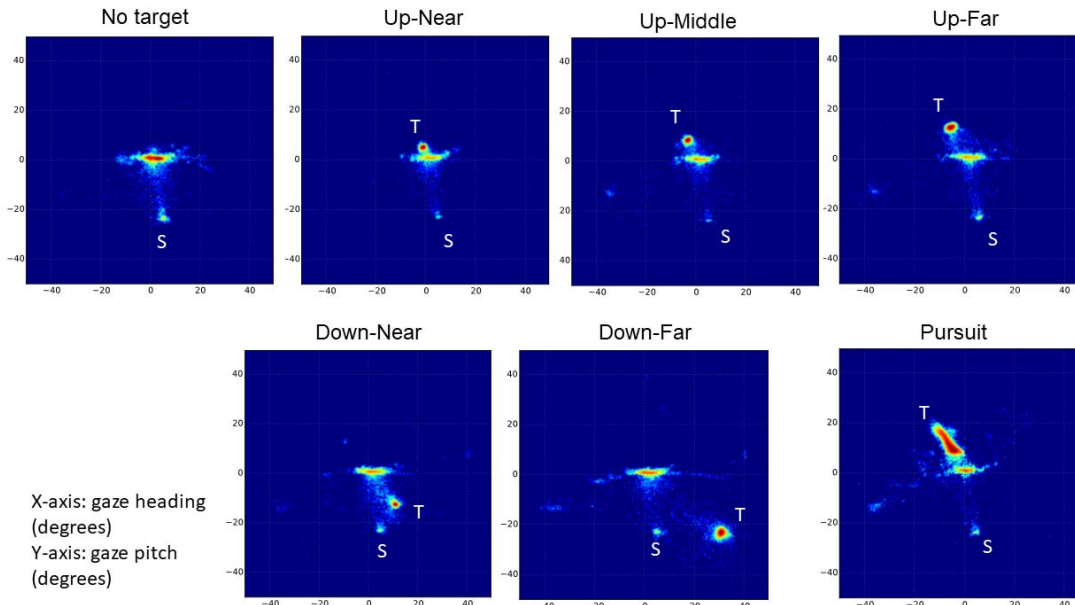
251 First, participants drove the car to a service station in Sipoonlahti, which was about 20 km away from  
252 the campus. On a motorway leading to the test route, they briefly practiced the secondary task. As  
253 they approached the start point, they actually drove the test route without performing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

## 258 2.6. Data analysis

### 259 2.6.1. Glance detection

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



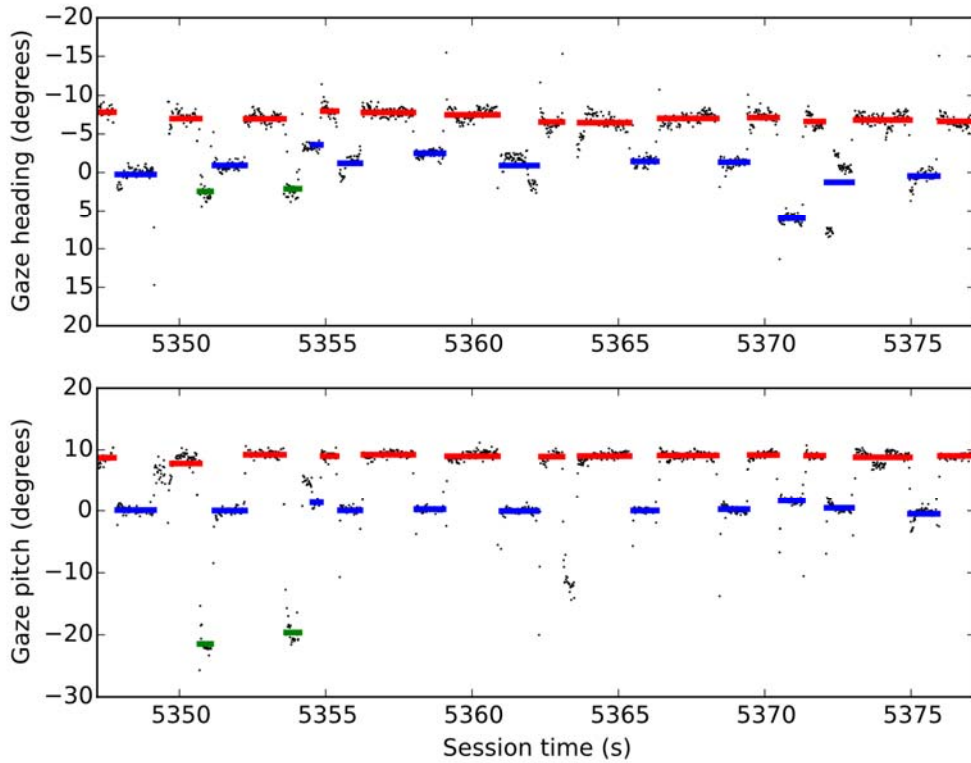


267  
 268 **Figure 3. 2D histograms illustrated with heat maps identify the road ahead and target**  
 269 **locations. Data are from a single participant. Gaze heading on x-axis and pitch on y-axis, in**  
 270 **degrees relative to the system coordinates (before centering to the road ahead). The road**  
 271 **ahead is clearly visible in the middle of the figures as a red-yellow area. Another red-yellow**  
 272 **area (T) corresponds to the location of the target, if present. The speedometer location (S) is**  
 273 **also clearly visible.**

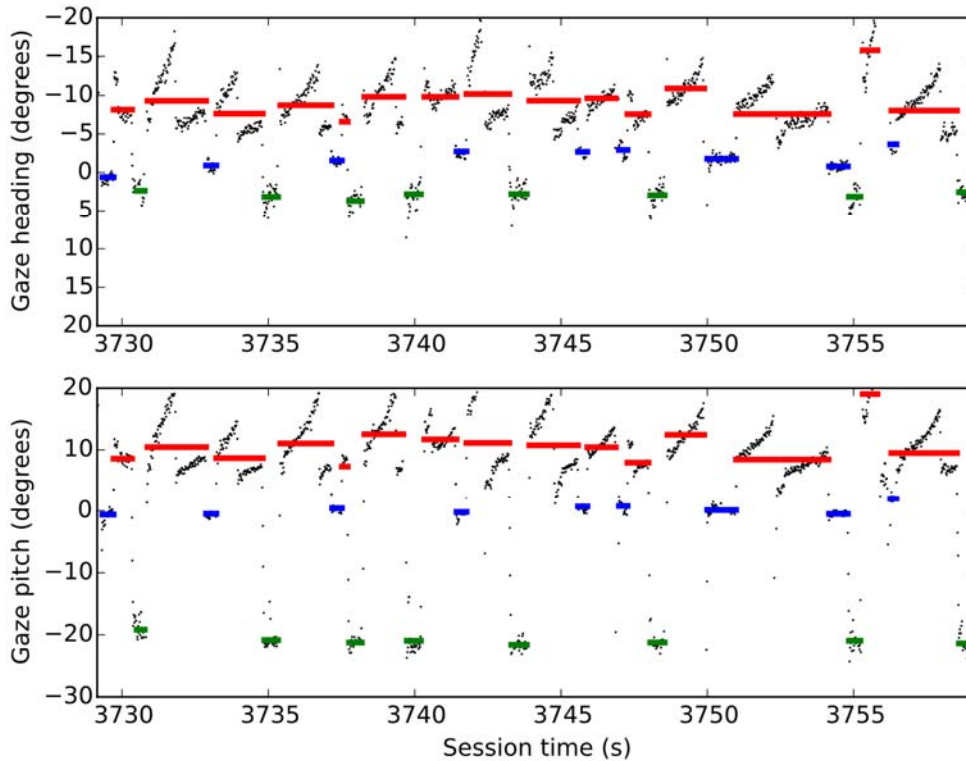
274  
 275 After the road ahead, target, and speedometer were located, glances were defined using the area-  
 276 of-interest (AOI) method. In short, for the purpose of this method, a glance refers to the period of  
 277 time when the gaze is within the defined area. A glance is defined as starting when the gaze enters  
 278 an AOI and ending when it exits the AOI. A maximum of 200 ms of deviations/missing data were  
 279 allowed within a glance if the gaze returned to the AOI within that time; Otherwise, signal noise and  
 280 missed frames would have artificially split the glance (as determined by an inspection of the raw  
 281 glance data). Finally, glances shorter than 100 ms were removed.

282  
 283 AOIs were defined relative to the manually identified road ahead and target locations.  
 284 AOI dimensions were based on a visual comparison of the raw signal against the detected glances  
 285 and were the same for all the participants.

286  
 287 The road-ahead AOI spanned -8 to 8 degrees horizontally and -2.5 to 2.5 degrees vertically from the  
 288 road ahead direction. All Fixation-target AOIs covered a circle around the identified locations with an  
 289 AOI radius of two degrees, except at the Down-Far location; a radius of four degrees was used since  
 290 the eye-tracker data were noisier. In order to avoid confusing speedometer glances with downward  
 291 target glances, the speedometer location was also determined. Its AOI was also a circle with a radius  
 292 of four degrees. For the Pursuit trial, the lower end of the mass of the gaze was identified, and the  
 293 Pursuit targets' AOI was defined as containing all the gaze data which was up and left from the lower  
 294 end within a two-degree margin. The output of the glance detection algorithm for a segment of data  
 295 is illustrated in Figures 4 and 5.



297  
 298 **Figure 4. Illustration of glance detection for the Up-Middle target. Time from the beginning of**  
 299 **the recording on x-axis (s). Raw gaze heading and pitch coordinates (y-axis) shown as black**  
 300 **dots (degrees). Target glances illustrated as red lines, drawn from the beginning of a glance**  
 301 **until its end. Road-ahead glances shown in blue and speedometer glances in green.**



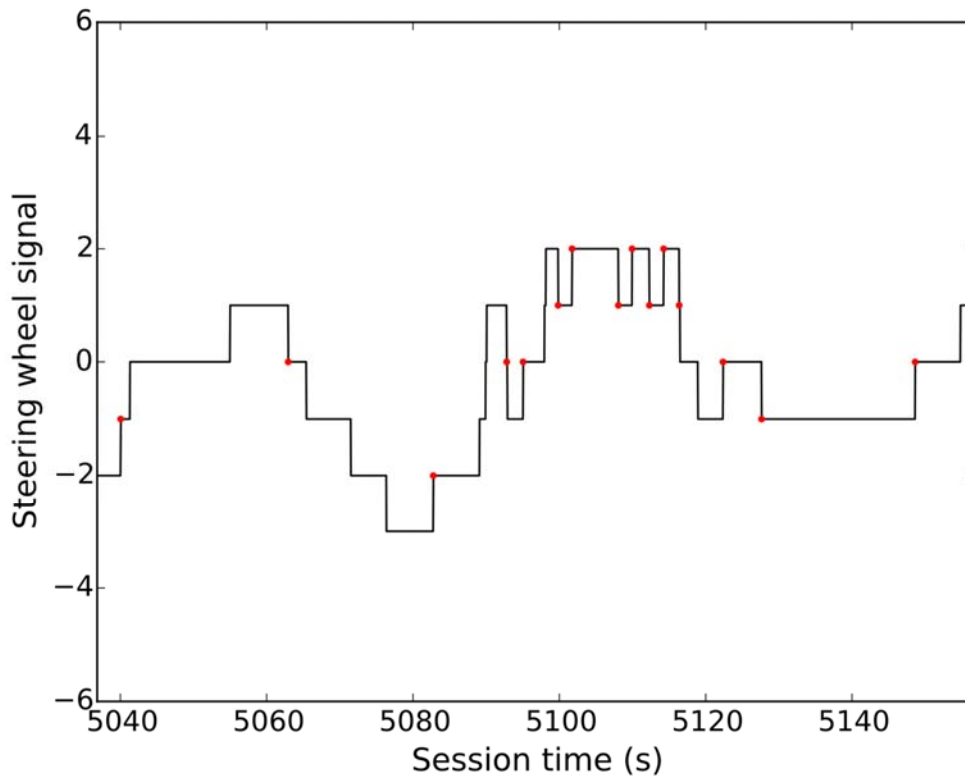
302 **Figure 5. Illustration of the glance detection for Pursuit targets. Time from the beginning of the**  
 303 **recording on x-axis (s). Raw gaze heading and pitch coordinates (y-axis) shown as black dots**  
 304 **(degrees). Target glances illustrated as red lines, drawn from the beginning of a glance until its**  
 305 **end. Road-ahead glances shown in blue and speedometer glances in green.**  
 306

307  
 308 As noted, three participants out of 17 were excluded due to insufficient eye-tracking data quality. In  
 309 addition, the Down-Far and Down-Near trials were excluded for two participants, and one of the  
 310 Control trips from one participant, for the same reason. In order to include all the available data,  
 311 mixed-effect models were used for the statistical analysis instead of the more traditional repeated-  
 312 measures ANOVA. In the models 'Participant' was included as a random factor.

### 313 2.6.2. Steering corrections

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

317 the opposite direction of the previous change (Figure 6).



318  
319 **Figure 6. Illustration of steering wheel reversal (SWR) detection. Black line is the steering**  
320 **wheel signal captured from the CAN bus. Steering wheel reversals are marked with red dots.**

### 321 3. Results

#### 322 3.1. Gaze-leads-steering strategy

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

<sup>1</sup> 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.

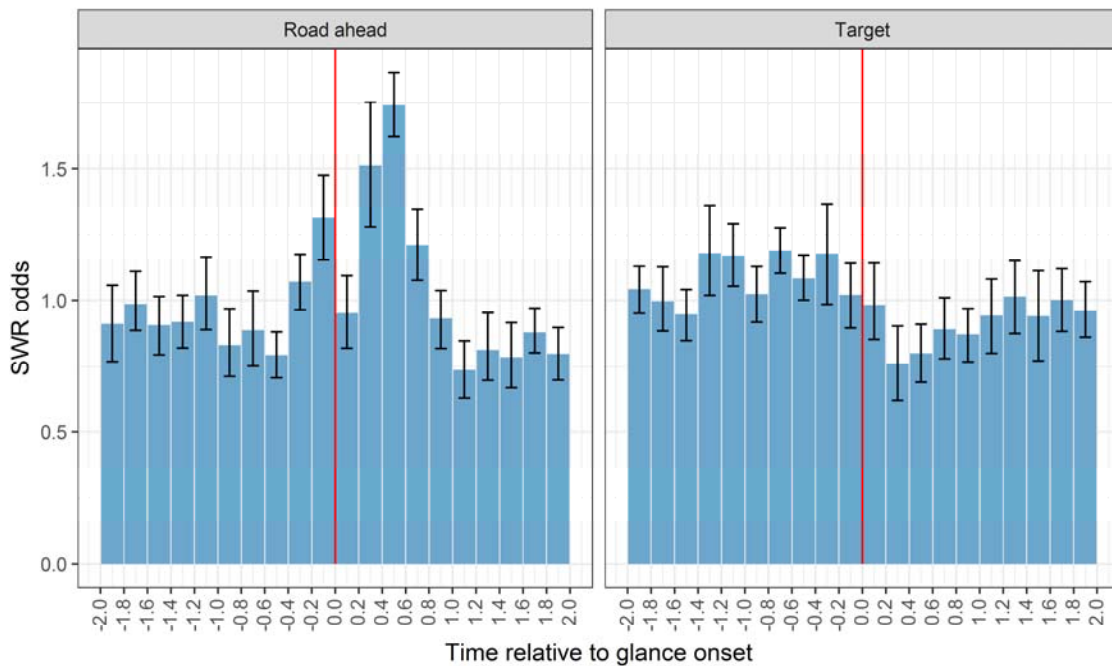
334 the odds of an SWR occurrence in each 200-ms interval, relative to the overall SWRs occurrences of  
335 that participant in that trial.

336

337 When the SWR odds were averaged over the trials and participants, it was seen that SWRs were  
338 especially common around road-ahead glance onsets, both 0-400 ms before (*Before* segments) and  
339 200-600 ms after (*After* segments) (Figure 7). The SWR odds were calculated for both intervals, and  
340 found to be higher than 1.0 (before:  $t(13)=3.431$ ,  $p<.01$ ,  $M=1.19$ , 95 % CI [1.07, 1.32]; after:  
341  $t(13)=7.636$ ,  $p<.001$ ,  $M=1.63$ , 95 % CI [1.45, 1.80]).

342

343



344

345

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

349

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

357

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

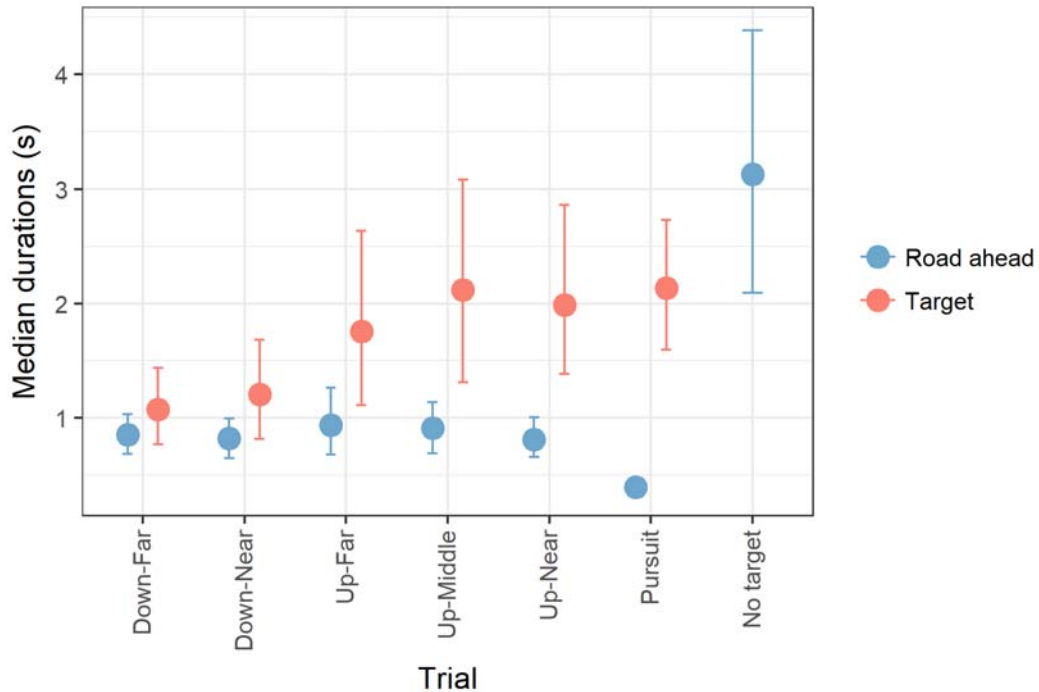
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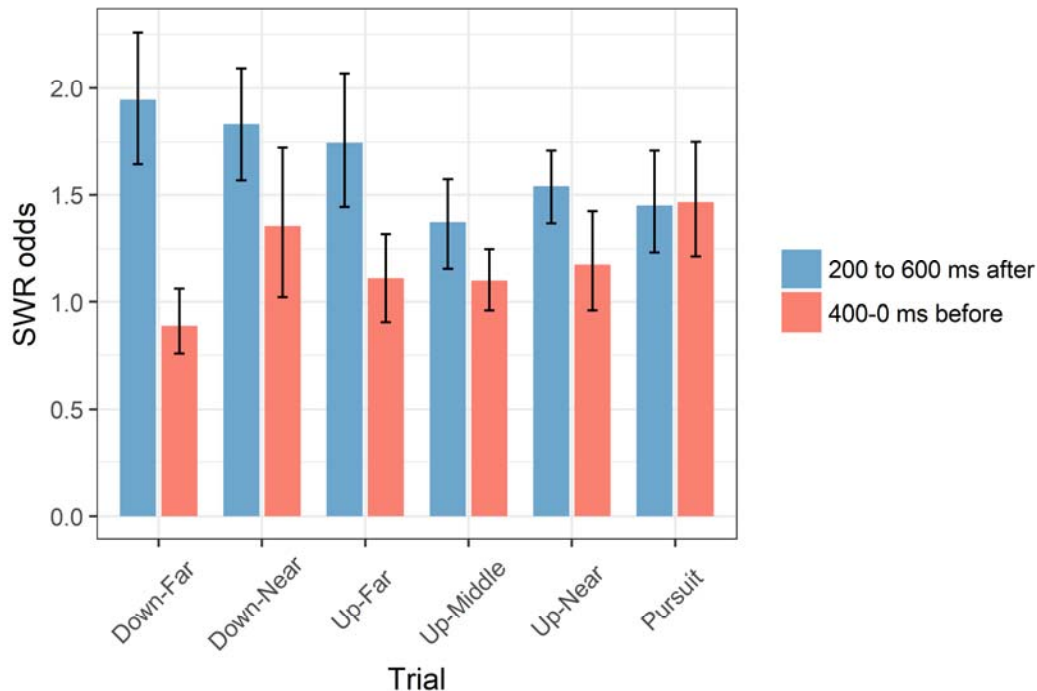


391 Down-Far, Down-Near, Up-Far, Up-Middle, and Up-Near, based on the availability of peripheral  
 392 visual information for guidance of steering. The results follow this order, with the exception of  
 393 Down-Near and Up-Far, which switch places.  
 394  
 395



396  
 397  
 398 **Figure 9. Grand average of median glance durations for the target and road-ahead AOIs with**  
 399 **each target and when driving without a target. 95 % CI are shown.**

400  
 401  
 402 The SWR odds were calculated for both Before and After segments by each target and participant.  
 403 The interaction of target and segment was significant ( $F(5, 135)=3.973, p = .002$ ) when tested with a  
 404 mixed-effects model. Polynomial contrasts indicated a quadratic increase in the difference between  
 405 the values from the Pursuit to Down-Far targets (Figure 10). Among the Fixation targets, this trend  
 406 roughly follows the availability of peripheral visual information for steering.



407  
408  
409  
410  
411  
412

**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.**

### 413 3.3. Glance strategies in the Pursuit trial

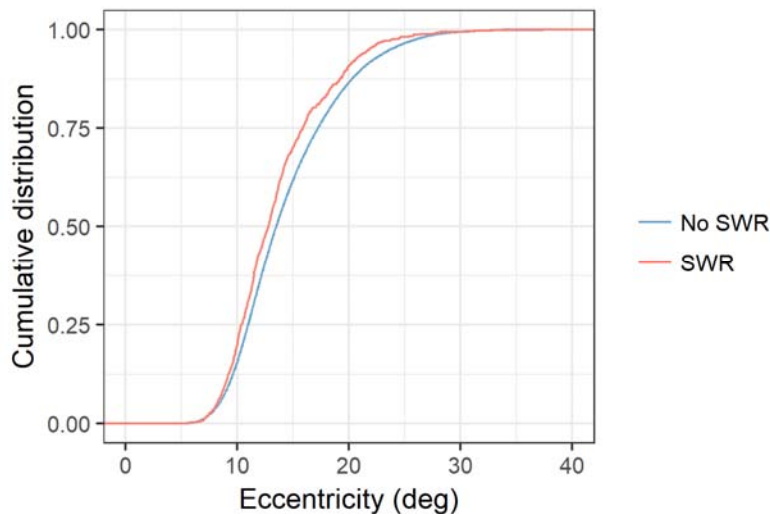
414 The third objective was to explore the differences between Fixation and Pursuit trials. The glance  
415 durations presented in Figure 9 were used. Targets were modelled as a six-level fixed-effect factor  
416 with participant as a random factor. The type of target had a significant main effect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

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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.



432 The less eccentric a Fixation target was relative to the road ahead, the more often drivers performed  
433 SWRs during the target glances. Therefore, we wanted to see if the same were true of the Pursuit  
434 targets: Would drivers also be more willing to perform SWRs when the Pursuit target is less  
435 eccentric? To answer this question, we calculated the median eccentricity of raw gaze-data samples  
436 within the Pursuit-target glances as a function of SWR co-occurrence (Figure 11). The difference in  
437 the median eccentricity was 1.07 deg, 95 % CI [-0.70, 1.45]. It was greater when there was no SWR  
438 than when an SWR occurred;  $t(13)=6.127, p < .001$ . This result suggests that drivers did indeed  
439 perform SWRs more often when the gaze was less eccentric, but the difference of one degree is very  
440 small in practice.  
441



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

### 447 3.4. Driving performance

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

453

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

459

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462

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

464

465 Trial	466 SWRs per second		466 Speed (km/h)	
	466 M	466 SD	466 M	466 SD
467 No target	0.10	0.05	86.9	2.9
468 Down-Far	0.17	0.10	86.9	3.4
469 Down-Near	0.20	0.11	88.0	2.2
470 Up-Near	0.17	0.08	87.8	2.3
471 Up-Middle	0.15	0.06	87.6	2.3
472 Up-Far	0.16	0.07	88.4	2.4
473 Pursuit	0.20	0.08	85.0	3.6

474

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

478

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

483

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

487

## 488 4. Discussion

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

496  
497 This strategy was most evident when the Fixation target of the secondary task was very eccentric to  
498 the road ahead. Glance durations on the Fixation targets also shortened, and SWR rates during these  
499 glances decreased, with increasing eccentricity. This suggests that as the quality and/or quantity of  
500 peripheral information available from the road ahead decreases, drivers are less able to rely on it to  
501 make steering corrections and instead must make glances back to the road before steering (cf.  
502 Summala et al., 1996).

503  
504 In contrast, with low-eccentricity targets, drivers steered first and then looked back to the road  
505 ahead. In this steering-leads-gaze strategy, the drivers apparently used their peripheral vision to  
506 guide their steering actions.

507  
508 The current results suggest that, in addition to eccentricity, the vertical position may also affect the  
509 availability of peripheral visual information from the road ahead. Glances to Fixation targets down  
510 on the dashboard were half a second shorter than glances to targets on the windscreen—when  
511 eccentricity was controlled.

512  
513 Glance durations to the Pursuit targets were not significantly different from glance durations to the  
514 Fixation targets (which were positioned so that they would approximately coincide with the location  
515 of the Pursuit targets in the visual field). In both cases the median glance durations averaged  
516 approximately two seconds, suggesting that drivers did not glean useful information for visual  
517 guidance of steering from the Pursuit targets, which were stationary in the environment—in spite of  
518 the fact that their egocentric motion in the visual field is potentially directly useful for steering. If the  
519 Pursuit targets had provided useful control information, we would have expected to see longer  
520 glance durations towards the Pursuit targets.

521  
522 However, it is noteworthy that the road-ahead glances were shorter in the Pursuit trial than in any of  
523 the Fixation target trials. Although peripheral glances to the street lamps might not have provided  
524 sufficient information to completely obviate the need to make occasional road-ahead glances, they  
525 may have provided some information, so shorter road-ahead glances were required. Buttressing this  
526 interpretation, the median gaze eccentricity during the Pursuit glances was slightly less eccentric  
527 during SWR occurrences.

528  
529 Overall, drivers had a higher SWR rate while performing the peripheral viewing task than during the  
530 control task. This result indicates that the visual task imposed higher task demands, since visually  
531 demanding secondary tasks have been shown to increase the lane position variability, which means

532 more SWRs (Engström et al., 2005; Jamson & Merat, 2005; Liang & Lee, 2010; Tsimhoni, Smith, &  
533 Green, 2004). These tasks have also been linked to reductions in driving speed (Engström et al.,  
534 2005; Jamson & Merat, 2005), but in the current experiment a reduction in speed was only  
535 demonstrated in the Pursuit trial compared to the Fixation trials. Drivers may have self-regulated  
536 their engagement with the viewing task as a function of their ability to use peripheral visual  
537 information by adjusting their glance durations (cf. Pekkanen, Lappi, Itkonen, & Summala, 2017).  
538 This ability can be affected by driving experience. Our sample consisted of drivers with different  
539 levels of experience, but due to the small sample size it is was not reasonable to analyze the effect of  
540 experience. Summala et al. (1996) found that experienced drivers (> 30,000 km in their lifetime)  
541 were better able to utilize peripheral vision for steering. Thus it can be hypothesized that novice  
542 drivers would use the gaze-leads-steering strategy more often than experienced drivers.

#### 543 4.1 Implications for steering models

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

549  
550 The present results suggest that a more comprehensive steering model should take into account the  
551 fact that human drivers use *peripheral visual information* (Lamble, Summala, & Hyvärinen, 2002;  
552 Summala et al., 1996) as well as *continuous extraretinal input* (sensory input not coming from the  
553 eyes: vestibular sensations, somatosensation, proprioception, hearing). Driving under visual  
554 occlusion or with eyes off the road is sometimes called open-loop driving (Godthelp, 1986), but it is  
555 only open-loop *visually*, because during these eyes-off-road periods, steering control is at least  
556 partly accomplished using memory (specifically, stored visual information and/or precalculated  
557 motor programs). Visual information from the previous guiding fixations may be retained in a short-  
558 term memory ‘image’ or visual buffer (Cavallo, Brun-Dei, Laya, & Neboit, 1988; Kujala, Mäkelä,  
559 Kotilainen, & Tokkonen, 2016; Land & Furneaux, 1997; Senders, Kristofferson, Levison, Dietrich, &  
560 Ward, 1967). Alternatively, a ‘precognitive motor program’ may be generated during the previous  
561 eyes-on-the-road episode and launched at its end (Godthelp, 1986; McRuer, Allen, Weir, & Klein,  
562 1977).

563  
564 The present results show that when looking at an off-road target, drivers feel compelled to return  
565 their gaze to the road ahead after some seconds (cf. Summala et al., 1996). This urge might be due  
566 to some peripherally observed or extraretinal cue, or simply to cumulative time or cumulative  
567 uncertainty over the current vehicle trajectory in the absence of (focal) visual information (Godthelp,  
568 1986; Johnson, Sullivan, Hayhoe, & Ballard, 2014; Kujala et al., 2016; Senders et al., 1967; Summala  
569 et al., 1996). When the available information is less accurate (such as when looking at a more  
570 eccentric fixation target), the accumulated uncertainty of memory/prediction could reach an  
571 uncertainty threshold sooner (Johnson et al., 2014; Kujala et al., 2016; Senders et al., 1967), leading  
572 to the shorter eyes-off-road glances observed.

573  
574 Sampling the road ahead can be understood as serving anticipatory processes as well; that is,  
575 processes that predict the current or future state based on past observation history. In control-

576 theoretical terms, this is forward inference (Miall & Wolpert, 1996; Wolpert, Diedrichsen, &  
577 Flanagan, 2011; Wolpert, Ghahramani, & Flanagan, 2001). The role of prediction has been  
578 emphasized in many hypotheses which are applicable in the current context, such as maintaining  
579 and updating an ‘image’ (Senders et al., 1967), ‘expectancy’ (Näätänen & Summala, 1976), or  
580 ‘situational awareness’ (Endsley, 1995).

581

582 In the predictive processing framework (Clark, 2013; Engström et al., 2017), actions are understood  
583 as a way to reduce *prediction error*, minimizing the mismatch between the predicted and observed  
584 sensory input. In driving, this means that a steering correction would be executed when the sensory  
585 input does not match the expectancies formed from the previous sensory states and the actions  
586 taken. However, sometimes the uncertainty regarding the relevant received sensory input is very  
587 high—for example, when driving and looking away from the road ahead for an extended period. In  
588 this case, more information needs to be sampled to accumulate sufficient *sensory evidence* before a  
589 steering action can be performed. This leads to the *gaze-leads-steering* strategy observed in the  
590 current study, where gaze precedes the task just before the initiation of the action (Hayhoe et al.,  
591 2003; Land et al., 1999; Land, 2009).

592

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

## 600 4.2. Limitations

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

609

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

615

616 With the current eye tracker, it was not possible to accurately estimate vergence. The Pursuit targets  
617 were at a comparable *depth distance* to where gaze would normally land on the road. Looking at  
618 them would be less likely to produce diplopia (double vision) of the road than looking at the Fixation

619 targets. Thus, while the participants were instructed to look at the Fixation targets in such a way that  
620 they would be able to read the text printed on them, some of them might still have not converged at  
621 the target distance, but at the more typical guiding fixation distance or even infinity (“staring  
622 through” the target). In a 3D VR set-up, the Fixation targets could be placed at the same distance as  
623 the Pursuit targets.

## 624 5. Conclusions

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

631  
632 First, the results are in line with the observation that drivers use peripheral visual information to  
633 guide their steering actions when it is readily available. When it is less available, there is more  
634 uncertainty regarding the present state, and thus road ahead glances need to be performed more  
635 often. Second, the use of the opposite strategy suggests that steering actions themselves create  
636 uncertainty which must be resolved by glancing back to the road.

637  
638 These observations pave the way for a more complete understanding of the strategic interplay of  
639 gaze and steering in natural driving, and the way the brain copes with the intermittency of visual  
640 input in complex multitasking environments.

641

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646  
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648  
649 **Data availability:** All data analyzed during this study and the analysis code written in R with R  
650 Markdown format are available from figshare repository  
651 <https://figshare.com/s/c53c24441d9925a2fe7e> (doi: 10.6084/m9.figshare.5572636). Raw gaze  
652 tracking and vehicle data is available from the corresponding author on reasonable request.

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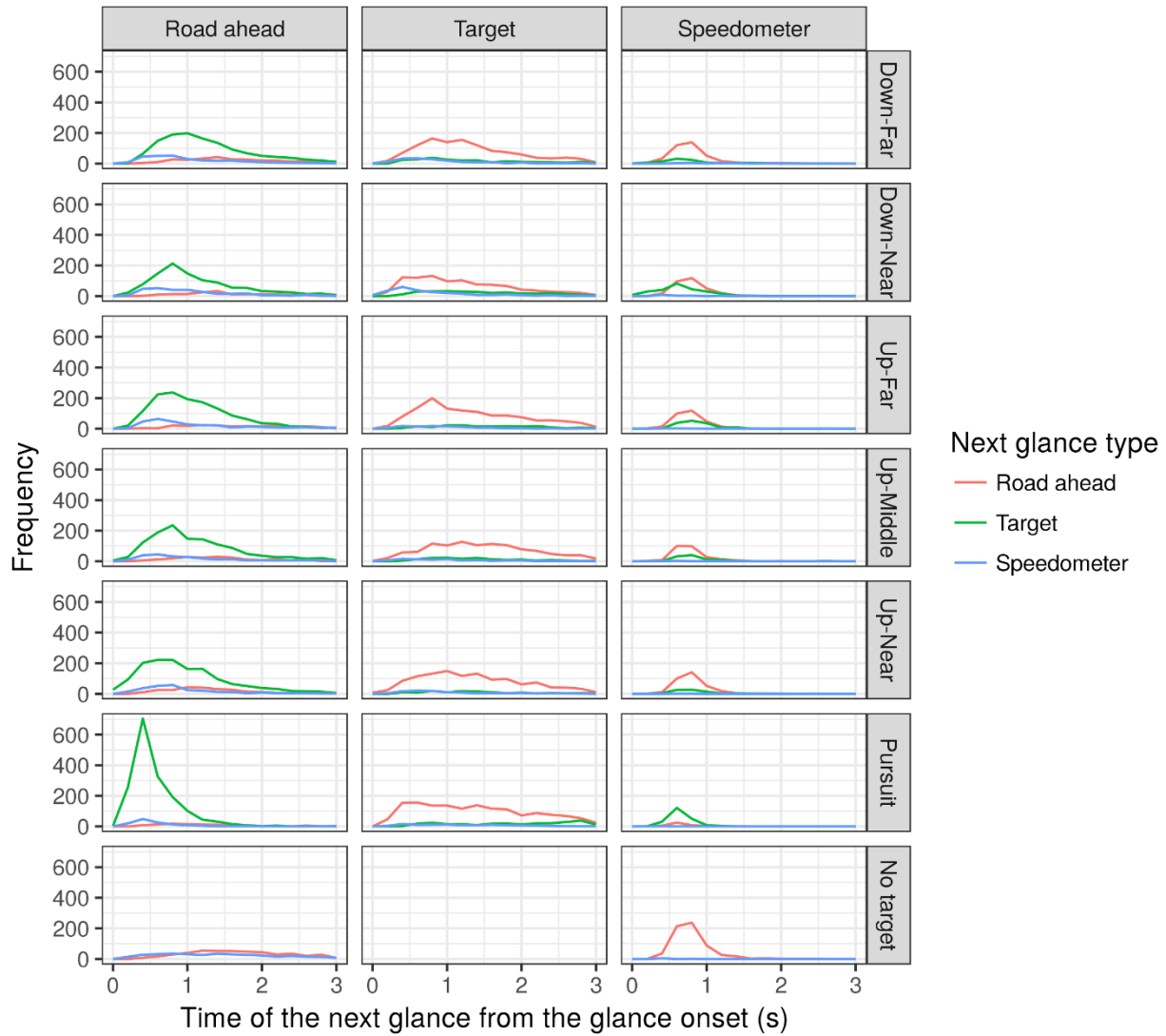
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# Supplementary Material

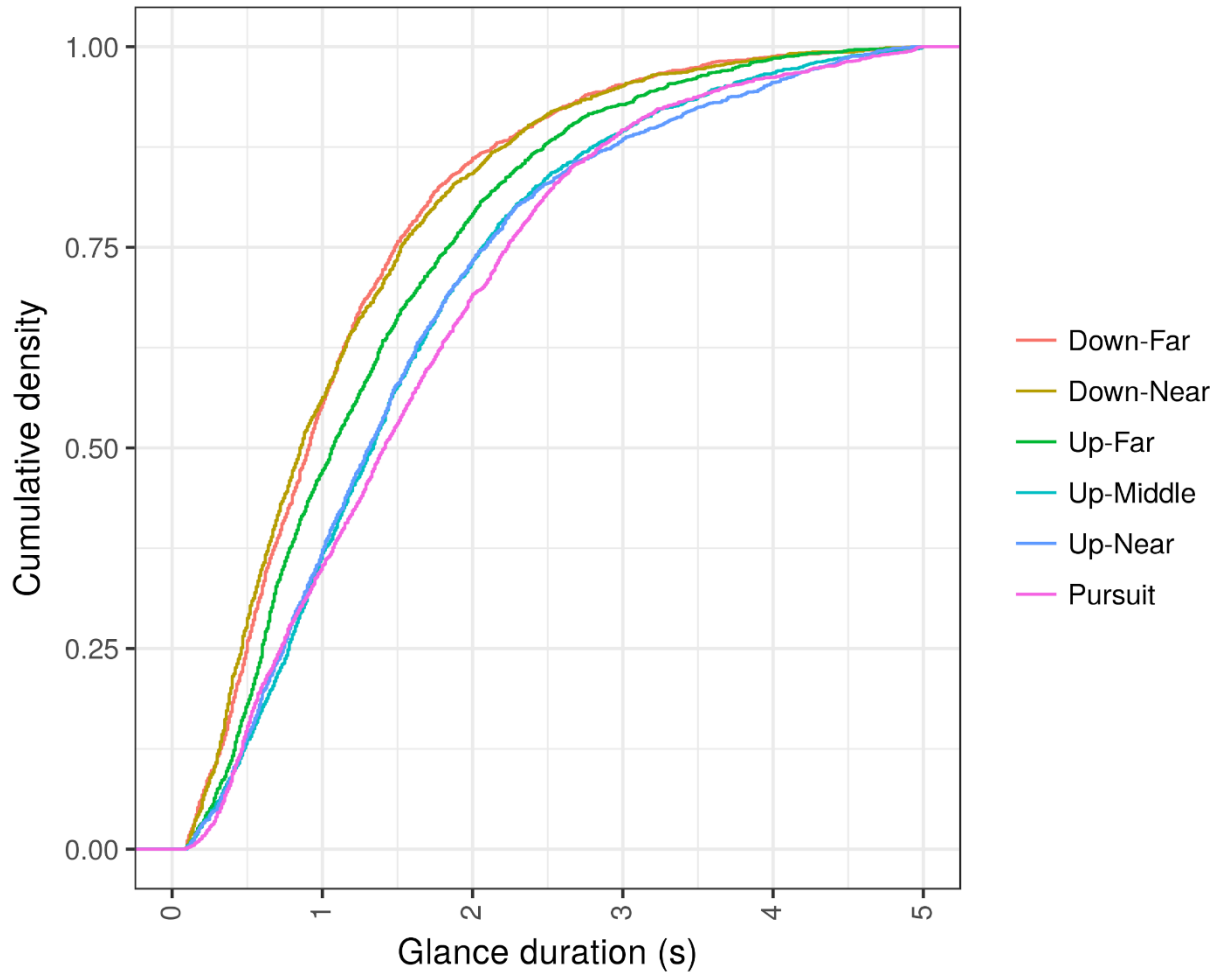
for 'Gaze doesn't always lead steering'

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

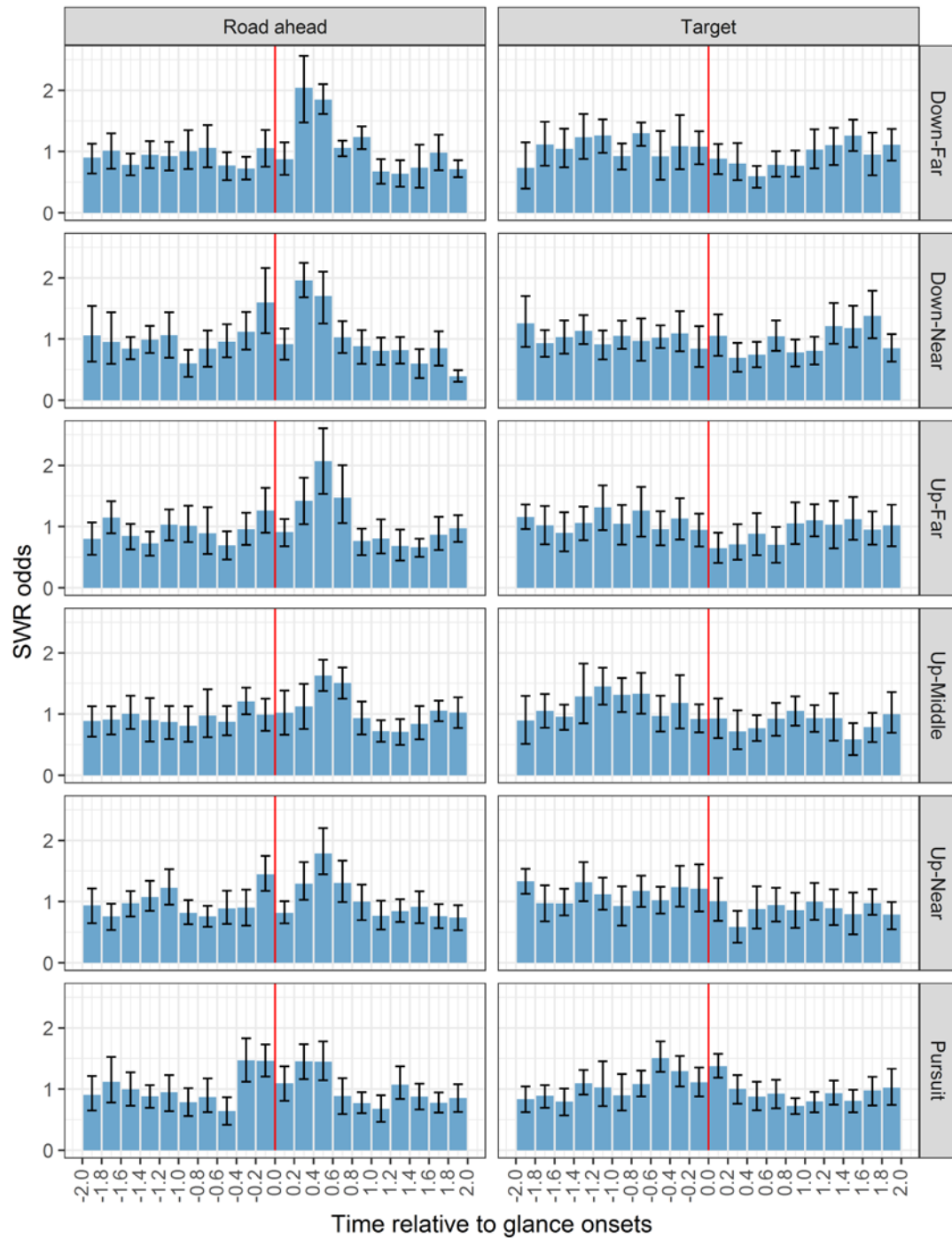
Trial	Road ahead		Target	
	M	SD	M	SD
No target	0.09	0.05	n/a	n/a
Down-Far	0.22	0.14	0.12	0.10
Down-Near	0.25	0.15	0.17	0.12
Up-Near	0.21	0.12	0.15	0.08
Up-Middle	0.18	0.08	0.14	0.06
Up-Far	0.20	0.09	0.13	0.06
Pursuit	0.26	0.14	0.18	0.08



*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.