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Title: On the Difference Between Necessary and Unnecessary Glances Away From the Forward Roadway : An Occlusion Study on the Motorway

Year: 2020

Version: Accepted version (Final draft)

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Please cite the original version:

Kircher, K., Kujala, T., & Ahlström, C. (2020). On the Difference Between Necessary and Unnecessary Glances Away From the Forward Roadway : An Occlusion Study on the Motorway. *Human Factors*, 62(7), 1117-1131. <https://doi.org/10.1177/0018720819866946>

1 Topic: Cognition

2 On the Difference between Necessary and Unnecessary 3 Glances away from the Forward Roadway: An Occlusion 4 Study on the Motorway 5

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12

13 Précis

14 Using self-paced visual occlusion in an on-road setting, the impact of situational information on spare
15 attentional capacity and necessary glances away from the forward roadway was investigated. Glancing
16 away for driving purposes qualitatively differs from glancing away for other purposes, and neither is
17 necessarily related to distraction.

18

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20

21 Running head: Necessary and Unnecessary Glances

22 Manuscript Type: Research Article

23 Word Count: 4530

24

25 Acknowledgements

26 We are grateful to the Danish Road Directorate for financing a large part of the study. We gratefully
27 acknowledge Olle Sjöblom for his contributions to the radar analyses and Jonas Ihlström for the
28 proximity and manoeuvre encodings.

29

31 Abstract

32 **Objective:** The present study strove to distinguish traffic-related glances away from the forward
33 roadway from non-traffic-related glances while assessing the minimum amount of visual information
34 intake necessary for safe driving in particular scenarios.

35 **Background:** Published gaze-based distraction detection algorithms and guidelines for distraction
36 prevention essentially measure the time spent looking away from the forward roadway, without
37 incorporating situation-based attentional requirements. Incorporating situation-based attentional
38 requirements would entail an approach that not only considers the time spent looking elsewhere, but
39 also checks whether all necessary information has been sampled.

40 **Method:** We assess the visual sampling requirements for the forward view based on 25 experienced
41 drivers' self-paced visual occlusion in real motorway traffic, dependent on a combination of
42 situational factors, and compare these with their corresponding glance behaviour in baseline driving.

43 **Results:** Occlusion durations were on average three times longer than glances away from the forward
44 roadway, and they varied substantially depending on particular manoeuvres and on the proximity of
45 other traffic, showing that interactions with nearby traffic increase perceived uncertainty. The
46 frequency of glances away from the forward roadway was relatively stable across proximity levels and
47 manoeuvres, being very similar to what has been found in naturalistic driving.

48 **Conclusion:** Glances away from the forward roadway proved qualitatively different from occlusions
49 in both their duration and when they occur. Our findings indicate that glancing away from the forward
50 roadway for driving purposes is not the same as glancing away for other purposes, and that neither is
51 necessarily equivalent to distraction.

52 **Keywords:** driver behaviour, attention, distraction, occlusion, glance behaviour

53

54 1 Introduction

55 Our eyes face the forward roadway approximately 80% of the time while driving (Fitch et al., 2013;
56 Victor et al., 2015). As we have to monitor surrounding road users, possibly with intersecting
57 trajectories, we also have to sample information from the sides and even from behind. This requires
58 that we look away from the forward roadway long enough to sample the necessary information, but
59 not too long, as we might then swerve out of our lane or hit what is in front of us. Not looking forward
60 is therefore an essential aspect of safe driving, provided the timing is right (Hirsch, 1995).

61 Proper timing depends on the predictability of the current situation, which is determined by external
62 factors such as the proximity of obstacles and other road users – their speeds, trajectories, and degrees
63 of freedom of movement – in the context of infrastructural information, in combination with one’s
64 ability to assess these factors (Endsley, 1995; Gibson & Crooks, 1938; Kircher & Ahlstrom, 2017;
65 Lee, 2014). One’s own speed may affect one’s assessment ability by altering the time available to
66 update one’s mental model, adjust the relevant predictions, and act and react accordingly. In any given
67 situation, these factors are combined in different ways, such that predictability varies within and
68 between trips. Here, predictability is defined as the probability of correctly anticipating what is going
69 to happen in the near future in relation to one’s own travel path.

70 The predictability of the upcoming traffic situation determines the need to sample external
71 information. High predictability diminishes the need for frequent sampling, and possibly also reduces
72 the time needed to acquire and process the required information, which might mean shorter sampling
73 durations. If the observed prediction error is small and possibly only an error in quantity, it is easier to
74 identify its source and correct it than if the error is in quality, which may require more information
75 sampling and processing to rectify (Clark, 2013). For example, detecting and processing a deviation in
76 predicted headway may take less time than understanding why the lead car is braking unexpectedly in
77 an intersection despite its assumed right to proceed first. With high probability, the latter would
78 require glancing away from the forward roadway (e.g., to check for crossing vehicles or missed traffic
79 signs).

80 It would be too easy to say that any looking away from the forward roadway equals distraction, as
81 some glances towards other targets are strictly necessary and other glances do not necessarily impede
82 taking in all relevant information. Moreover, not sampling the relevant targets off the forward roadway
83 should also be identified as distraction. Despite this, published gaze-based real-time distraction
84 detection algorithms essentially measure the time spent looking away from the forward roadway
85 without considering situation-based attentional requirements at all (e.g. Donmez, Boyle, & Lee, 2008;
86 Fernández, Usamentiaga, Carús, & Casado, 2016; Klauer, Dingus, Neale, Sudweeks, & Ramsey,
87 2006; Victor, 2005), or not more than in a rudimentary way, as in the AttenD algorithm, which has a
88 built-in mechanism for acknowledging the necessity of mirror and speedometer glances (Kircher &
89 Ahlstrom, 2013). However, it does not evaluate whether such a glance was necessary in a given
90 situation, but just assumes that is the case for any glance at the mirror or speedometer. Incorporating
91 informed situation-based attentional requirements would entail an approach that does not focus only
92 on the time spent looking elsewhere, but also checks whether all necessary information has been
93 sampled (Kircher & Ahlstrom, 2017). This approach would allow drivers to self-regulate, influencing
94 both the information requirements and the available time to meet them (see also Clark, 2016). The
95 drawback is obviously that it is difficult to define the minimum requirements for attentive driving.
96 Requirements which are related to the infrastructure can typically be established based on rules and
97 regulations in combination with infrastructural and environmental constraints. For example, when
98 approaching an intersection on a feeder road, one must ensure that the main road is clear for passage,
99 and this must be done within a certain time frame, starting when the line of sight becomes
100 unobstructed and ending just before entering the intersection. Preliminary attempts have been made to
101 operationalize such requirements on real roads (Nygårdhs, Ahlström, Ihlström, & Kircher, 2018) and
102 in simulators (Kujala, Mäkelä, Kotilainen, & Tokkonen, 2016). Requirements which are related to
103 other road users and to one's own movements in relation to the road ahead, do not have such clear
104 boundaries. How often information must be sampled to maintain an up-to-date mental representation
105 varies with several factors. These include proximity and speed relative to other vehicles, traffic rules,

106 infrastructure, features inherent to the road user or other dynamic target in question, and one's own
107 manoeuvring intentions (Kircher & Ahlstrom, 2018).

108 The occlusion technique is a method that can be used to assess what forward glances are necessary,
109 and thus to estimate the dynamic requirement to look at the forward roadway. The principle is that
110 occluded periods indicate when a driver does not need to sample additional visual information. Visual
111 occlusion has mainly been used in simulators (Andersen, Cisneros, Atchley, & Saidpour, 1999;
112 Kircher, Ahlstrom, Nylin, & Mengist, 2018; Kujala, Mäkelä, et al., 2016; Pekkanen, Lappi, Itkonen, &
113 Summala, 2017; Saffarian, de Winter, & Senders, 2015; Samuel & Fisher, 2015; Tsimhoni & Green,
114 1999, 2001), but also on real roads (Kircher & Ahlstrom, 2018; Senders, Kristofferson, Levison,
115 Dietrich, & Ward, 1967) and on test tracks or closed roads (Blaauw, Godthelp, & Milgram, 1984;
116 Godthelp, 1986; Godthelp, Milgram, & Blaauw, 1984; Pekkanen et al., 2018). Occlusion frequency
117 and duration have been used as proxies for perceived uncertainty (Kircher & Ahlstrom, 2018; Kujala,
118 Mäkelä, et al., 2016; Pekkanen et al., 2017; Pekkanen et al., 2018; Senders et al., 1967), which can be
119 interpreted as the inverse of the experienced predictability of events in the near future (Chen &
120 Milgram, 2011). The time spent viewing the forward roadway between occlusions has been found to
121 be relevant to hazard detection (Samuel & Fisher, 2015).

122 It can be assumed that when driving without executing additional tasks and without occlusion (i.e.,
123 "baseline" driving), alert expert drivers perform all necessary glances away from the forward roadway,
124 as well as some extra "stray" glances towards objects that need not be sampled for safe driving. By
125 "necessary", we mean glances that are needed to sample information required in order to stay in one's
126 lane, maintain one's safety margins relative to other traffic, navigate to one's goal, etc. – in short, to
127 achieve the goals of the driving task. This situation can be compared to a setting where drivers are
128 encouraged to occlude their vision whenever possible. Here, all necessary forward viewing should
129 remain, together with all necessary glances away from the forward roadway. The occluded periods
130 will then provide an estimate of when and for how long the driver feels that visual information
131 sampling is not necessary for successful task performance. A comparison of baseline driving and

132 driving with occlusion should therefore show which glances away from the forward roadway are
133 necessary as well as how much forward viewing is necessary.

134 In this paper, we assess the visual sampling requirements for the forward view based on experienced
135 drivers' self-paced visual occlusion in real traffic, dependent on the driver's speed and intended
136 manoeuvres, proximity to other traffic, headway distance and speed relative to the lead car, and the
137 number of vehicles ahead, and compare these with the corresponding glance behaviour in baseline
138 driving. A motorway scenario was chosen to keep the infrastructure and traffic situation rather
139 constant, while still obtaining naturalistic traffic scenarios. Assuming that there is a qualitative
140 difference between necessary traffic-related glances away from the forward roadway (henceforth, "off-
141 forward glances") and occlusions (i.e., off-forward glances not related to driving), we hypothesize that
142 the frequency and duration of off-forward glances and occlusions differ in situations with varying
143 predictability, or more specifically, that:

- 144 1. Situations with more vehicles in close proximity, larger speed differences, smaller headways,
145 and interactions with other traffic are associated with decreased predictability and therefore
146 lead to diminished occlusions.
- 147 2. Less predictable situations require longer unoccluded durations between occlusions.
- 148 3. Off-forward glances are qualitatively different from occlusions, such that
 - 149 a. occlusions vary more in frequency with changes in task-relevant situational
150 parameters than glances do;
 - 151 b. occlusion duration is sensitive to the predictability of the upcoming situation, while
152 glance duration is rather constant; and
 - 153 c. occlusions and glances are "additive" in that occlusions will not reduce the number of
154 necessary glances.

155 2 Method

156 Twenty-five experienced drivers (six female) participated in the study. Selection criteria were high
157 familiarity with the test route and normal vision or vision corrected to normal via contact lenses;

158 glasses had been found to interfere with the eye tracker and were therefore not allowed. The
159 participants' mean age was 39 years (SD = 13 years, range 24–72 years). On average they had 18
160 years of driving experience (SD = 12 years, range 6–53 years) and were very familiar with the route
161 driven. This research complied with the American Psychological Association Code of Ethics and was
162 approved by the regional ethics committee in Linköping (Dnr 2014/0177-8.2). All participants signed
163 two separate informed consent forms before each driving condition. A separate form was used in the
164 treatment phase, when the occlusion glasses were mentioned for the first time, to prevent drawing the
165 participants' attention to their visual sampling behaviour during baseline driving.

166 The test route comprised a 14-km section of a dual-lane motorway outside the city of Linköping,
167 Sweden. The posted speed limit was 110 km/h on the whole section, and the annual average daily
168 traffic for this road section is about 13,000 vehicles. The experiment used a within-subject design with
169 two conditions, baseline (BL) and occlusion (OCC). To ensure unaffected glance behaviour, the
170 participants were unaware of the purpose of the study in the BL condition. Each participant drove the
171 14-km motorway section three times consecutively per condition, BL first, followed by the OCC
172 condition. The participant was free to decide when to overtake other traffic.

173 The test vehicle was a Volvo V70 with manual transmission and six gears. It was equipped with a
174 five-camera eye tracker (SmartEye Pro 6.1, Smart Eye AB, Gothenburg, Sweden), front radar (UMRR
175 Type 29, Smart Microwave Sensors GmbH, Braunschweig, Germany), a CAN data logger (CTAG,
176 Porriño, Spain), and video cameras (GoPro Inc., San Mateo, CA, USA) filming the driver, forward
177 roadway, and rear view. Mechanical occlusion glasses, custom made for the study, were operated by
178 the participant via a microswitch attached to the left index finger. Pressing the switch to a surface (e.g.,
179 the steering wheel or one's thumb) closed the occlusion glasses and releasing the switch opened them
180 again. The black plastic material (Figure 1) was transparent to infrared light to prevent loss of eye
181 tracking data.

182 The vehicle had dual command and the driver was accompanied by an experienced safety driver. A
183 test leader was seated in the back seat, giving directions and monitoring the logging equipment.

184 **2.1 Procedure**

185 After the BL run, the participant was informed of the purpose of the treatment run and equipped with
186 the occlusion glasses. The participant had the opportunity to practice closing and opening the glasses,
187 first when standing still and then on a 7.5-km road stretch while driving to the test route. When the
188 participant felt confident in handling the equipment, which in all cases took less than a minute while
189 standing still, he or she drove the test route with the instruction to occlude his or her vision as often as
190 possible without jeopardizing traffic safety. It was stressed that this was not a competition, but that we
191 were interested in learning when information was and was not needed in a given situation. The
192 participants were told that they were responsible for their driving, and that they should not view the
193 safety driver as a fall-back. When the test was completed, the participant drove back to VTI, all
194 equipment was removed, and the participant completed a short questionnaire about his or her
195 experience with the occlusion glasses.



196

197 *Figure 1. A driver occluding her vision during the practice period.*



198 **2.2 Data reduction and pre-processing**

199 Data from three participants were removed from the analyses, because two participants did not occlude
200 their vision at all and the third encountered technical problems. The analyses are based on data from
201 22 participants.

202 Driving manoeuvres were manually annotated as “driving in slow lane”, “driving in fast lane”, “lane
203 change from fast to slow”, and “lane change from slow to fast”. The lane change manoeuvre from the

204 slow to fast lane was always coded as starting 5 s before the line crossing to include the preparation
 205 for the manoeuvre. The proximity of surrounding traffic was manually scored on a scale of 1–4 based
 206 on the recorded forward view videos (TABLE 1). The rating scale is loosely based on the anchored
 207 workload estimation scale suggested by Schweitzer and Green (2007). To avoid inter-rater variability,
 208 all ratings were made by one person.

209 TABLE 1: Proximity Scoring of the Prevailing Traffic Situation (THW = Time Headway).

Level	Description
1	Driving in slow lane: traffic far from own vehicle, but visible
	
2	Driving in slow or fast lane: traffic nearby but no nearer than a THW of approximately 5 s
	
3	Driving in slow or fast lane: traffic present at THWs of 3–5 s



4 Driving in slow or fast lane: traffic nearer than a THW of 3 s; includes changing lanes for overtaking



210

211 The time onset and duration of each occlusion was extracted from the data log, along with the
212 corresponding proximity level, manoeuvre, vehicle speed, time since last occlusion, number of
213 vehicles ahead, relative speed, and headway distance. The latter variables were all derived from radar
214 data, which is why the number of vehicles ahead is an underestimate limited by what was visible to the
215 radar. The different variables were extracted at the moment when the occlusion started.

216 [2.3 Statistical modelling](#)

217 To determine the sampling requirements for the forward view based on changes in task-relevant
218 situational parameters, two multilevel regression models were created. The dependent variables for the
219 models were occlusion duration and time between occlusions. All predictor variables (i.e., vehicle
220 speed, manoeuvre, proximity of other traffic, relative speed and headway distance to a lead car in the
221 same lane, and number of lead cars) were entered in the models in the first phase. Non-significant
222 predictors with an alpha level $<.05$ were then removed individually to find a model that explained as

223 much as possible of the variance in the dependent variable. To be included in the model, a predictor
 224 had to improve the model fit significantly according to the χ^2 test, as measured by the $-2 \log$ likelihood
 225 ($-2LL$, the smaller the better). Participant was included as a random effect. The restricted maximum
 226 likelihood estimation method was used in the multilevel regression analyses.

227 3 Results

228 Altogether, 16.1 h of driving were analysed (7.7 h in the BL condition and 8.4 h in the OCC
 229 condition), resulting in 4234 occlusions (192 ± 116 per participant), 11,700 off-forward glances in
 230 OCC (488 ± 193 per participant), and 11,443 off-forward glances in BL (510 ± 244 per participant).
 231 TABLE 2 shows how much time was spent in each manoeuvre at each proximity level in each driving
 232 condition. Driving in the slow lane was most common, and proximity levels 2 and 4 were more
 233 frequent than were levels 1 and 3. Typically, other traffic was nearby when changing lanes and when
 234 driving in the fast lane. The mean speed in BL was 106.4 km/h ($SD = 8.0$ km/h) and in OCC was
 235 106.0 km/h ($SD = 8.4$ km/h).

236 **TABLE 2:** Percentage of Time Spent in Each Manoeuvre for Each Proximity Level (Prox) in the BL versus OCC Conditions

	Time Spent (%)	BL					OCC					
		BL	Slow Lane	Fast Lane	Fast to Slow	Slow to Fast	Total	OCC	Slow Lane	Fast Lane	Fast to Slow	Slow to Fast
Prox	1	12.5	0.0	0.0	0.2	12.8	1	15.5	0.0	0.1	0.1	15.8
	2	28.9	0.2	0.1	1.4	30.7	2	37.6	0.2	0.1	2.1	40.1
	3	11.7	0.9	0.1	1.6	14.3	3	5.7	0.1	0.1	1.1	7.1
	4	6.3	25.1	5.2	5.6	42.2	4	2.3	22.2	5.3	7.3	37.1
	Total	59.4	26.3	5.5	8.9	100.0	Total	61.2	22.6	5.6	10.6	100.0

237

238 3.1 Off-forward glance behaviour

239 TABLE 3 provides an overview of the percentage of time glancing away from the forward roadway
240 and occluding one's vision, respectively, per condition, manoeuvre, and proximity level. Some of the
241 results are presented in the following text.

242 In the BL condition, participants looked away from the forward roadway 24.9% of the driving time,
243 with the highest percentage in low traffic (proximity level 1). When driving in the fast lane, glancing
244 away was slightly less frequent than in the other three manoeuvres. The cumulative proportion of time
245 looking away from forward was 21.7% in OCC. The variability of the overall proportion of time
246 looking away from forward across proximity levels and manoeuvres was low, i.e., $SD = 4.7\%$ in BL
247 and 7.3% in OCC.

248 The percentage of time spent glancing away from the forward roadway was similar in BL and OCC,
249 with 3.2% more time spent glancing away in BL. The largest difference between the two conditions
250 was found for proximity level 1. When driving in the slow lane and when changing lanes back into the
251 slow lane, the glance frequency away from forward was about 10% lower in OCC than in BL, whereas
252 the contrary was found when changing lanes into the fast lane, with a 9.6% higher glance frequency
253 away from forward in OCC.

254 The mean glance duration was comparable across proximity levels and manoeuvres at 0.60 s ($SD =$
255 0.11 s) in BL versus 0.56 s ($SD = 0.13$ s) in OCC. The average time spent looking forward before the
256 next glance was 1.8 s in BL ($SD = 2.5$ s) and 1.4 s in OCC ($SD = 1.7$ s); in the latter case, the time was
257 measured since the last glance or occlusion, whichever was closest.

258 3.2 Occlusion behaviour

259 Occlusion frequency and duration varied substantially with proximity level and manoeuvre (TABLE
260 3). In general, with increasing proximity, the occlusion frequency decreased. When driving in or
261 changing back into the slow lane, the occlusion frequency was higher than when driving in the fast
262 lane. Drivers were least likely to occlude when changing from the slow lane to the fast lane. The

263 average time between occlusions was 8.9 s (SD = 12.8 s), ranging from 3.2 s when changing back into
 264 the slow lane at proximity level 1 to 23.2 s when changing into the fast lane at proximity level 3.

265 **TABLE 3:** Percentage Off-forward Glance Time in BL versus OCC in Each Manoeuvre at Each Proximity Level (Top Row),
 266 Percentage Time Occluding (Lower Left), and Total Percentage Time Occluding or Glancing Off-forward (Lower Right)

		Total Off-forward Glance Time (%), BL					Total Off-forward Glance Time (%), OCC					
		Slow	Fast	Fast	Slow	Total	Slow	Fast	Fast to	Slow	Total	
		Lane	Lane	to	to		Lane	Lane	Slow	to		
				Slow	Fast					Fast		
Prox	1	31.9			17.5	31.7	1	20.6		15.3	27.1	20.6
	2	25.2	28.6	28.8	26.8	25.3	2	22.7	27.5	33.2	32.3	23.2
	3	23.5	18.9		28.2	23.7	3	20.2			26.9	20.9
	4	26.5	19.8	29.2	26.6	22.9	4	20.6	20.8	21.0	19.7	20.6
	Total	26.4	19.8	29.2	26.7	24.9	Total	21.8	20.8	21.0	23.1	21.7
		Total Occlusion Time (%), OCC					Total Occlusion + Glance Time (%), OCC					
		Slow	Fast	Fast	Slow	Total	Slow	Fast	Fast to	Slow	Total	
		Lane	Lane	to	to		Lane	Lane	Slow	to		
				Slow	Fast					Fast		
Prox	1	37.7				37.7	1	52.6		58.3	95.7	58.3
	2	31.8	27.8		9.3	30.6	2	52.1	41.6	54.5	55.3	53.8
	3	18.0			3.0	15.2	3	17.9			11.2	36.1
	4	18.9	12.2	19.7	5.7	12.4	4	40.7	25.4	39.4	32.9	33.0
	Total	31.5	12.4	19.9	6.3	23.9	Total	40.8	29.3	53.4	33.1	45.5

267 *Note.* Percentages corresponding to manoeuvre/proximity combinations with fewer than 10 data points
 268 have been removed from the table.

269 Occlusion durations became shorter with increasing proximity. Within each manoeuvre, the longest
 270 occlusion durations were found at proximity level 1. The relationships between off-forward glance

271 durations and occlusion durations per manoeuvre and proximity level are illustrated in Figure 2. Note
 272 that almost 50% of all occlusions at proximity level 1 were 2 s or longer, and that driving in the slow
 273 lane generally led to the longest occlusions. Overall, around one third of occlusions were longer than 2
 274 s. The longest ones lasted up to 3.5–4 s; however, these long occlusions were rare (2% above 3.5 s),
 275 almost always occurring when driving in the slow lane without any traffic nearby.

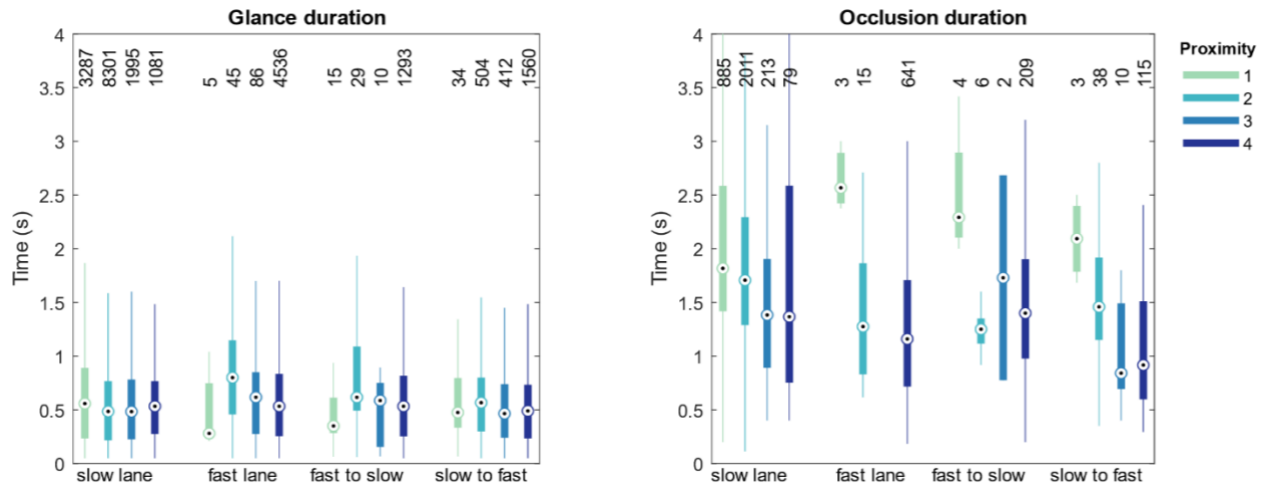
276 The ratio between off-forward glances and occlusions was calculated to investigate the frequency of
 277 occlusions versus the frequency of glances (TABLE 4). This ratio was calculated by first normalizing
 278 the absolute occlusion distribution and the absolute glance distribution by their respective grand sums;
 279 the resulting percentages for occlusion were then divided by the corresponding percentages for
 280 glancing away from the forward roadway.

281 As expected, changing into the fast lane was glance intensive, leaving less time for occlusions.
 282 Situations with nearby traffic were also generally more glance intensive, leaving less time for
 283 occlusions. Driving in the slow lane was generally the least glance intensive, leaving more time for
 284 occlusions, especially in the more predictable situations with no other traffic nearby, in which
 285 occlusions were more frequent than glances.

286 **TABLE 4:** Ratio between Percentage of Time Occluded and Percentage of Time Glancing Away

	Occlusion/Glance Ratio	Slow Lane	Fast Lane	Fast to Slow	Slow to Fast	Total
Prox	1	1.8				1.8
	2	1.4	1.0		0.3	1.3
	3	0.9			0.1	0.7
	4	0.9	0.6	0.9	0.3	0.6
	Total	1.4	0.6	0.9	0.3	1.1

287 *Note.* A value >1 indicates that occlusion was more frequent, while <1 indicates that off-forward
 288 glancing was more frequent. Ratios in which either the numerator or denominator was <10 are
 289 excluded.



290

291 *Figure 2.* Boxplots showing off-forward glance durations (data from BL and OCC) and occlusion durations per manoeuvre
 292 and proximity level. The number of observations is presented above each box.

293 Based on the multilevel regression model, the predicted grand mean for occlusion duration is 1532 ms.
 294 Headway distance, proximity level, and manoeuvre were found to be significant predictors of
 295 occlusion duration when controlling for individual differences (Table 5).

296 The effect of headway distance is rather small. As the distance to the lead vehicle in the same lane
 297 increases by 1 m, the occlusion duration increases by 3.48 ms. The corresponding increase in
 298 occlusion duration when the headway distance increases by 50 m is 174 ms. Note that this relationship
 299 between occlusion duration and headway distance is only applicable to the present dataset, and that
 300 there is likely an upper limit to headway distance after which this relationship does not apply.
 301 Furthermore, the participants chose not to occlude themselves in conditions with very short headway
 302 distances, meaning that there might also be a lower limit for the model.

303 There is a predicted decrease in occlusion duration with increasing proximity levels (Figure 2). An
 304 increase in time headway (THW) to traffic ahead from proximity level 4 (THW < 3 s) to level 1 (i.e.,
 305 traffic far away) increases occlusion durations by 266 ms. Furthermore, occlusion durations decrease
 306 by 302 ms when driving in the fast rather than the slow lane. Occlusion durations are also 286 ms
 307 shorter when the driver is changing lanes from the slow lane to the fast lane, rather than when driving
 308 in the slow lane.

309 The proportion of observed variance in occlusion duration between participants is approximately 58%
 310 (intraclass correlation, ICC). A post-hoc analysis of the between-participant variation indicated that
 311 the individual differences could to some extent be explained by age, which displayed a moderate
 312 correlation with occlusion duration ($r = .458, p < .05$), explaining 22% of the variance. There were no
 313 significant differences between men and women in any of the investigated variables.

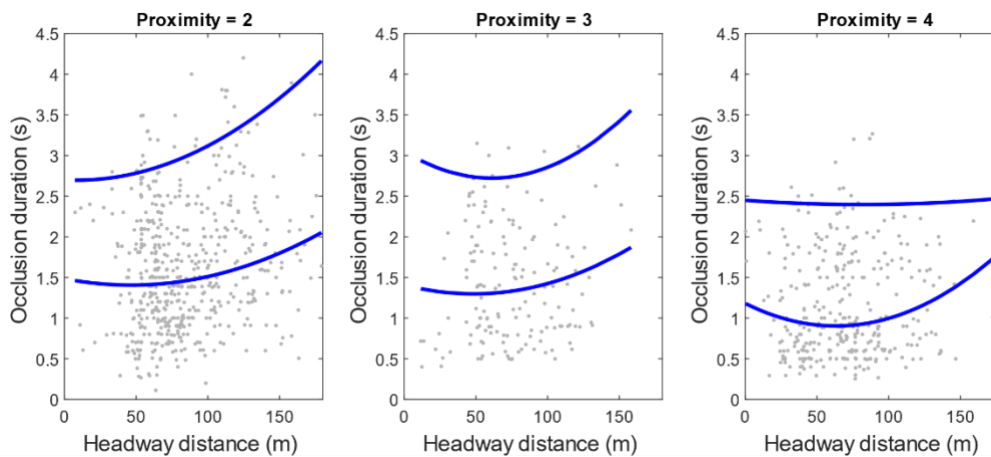
314 **Table 5:** Multilevel Regression Model of Occlusion Duration, Milliseconds

Fixed Effects	<i>B</i>	<i>s.e.</i>	<i>p</i>
Intercept	1531.52	175.13	<.0001
Headway distance (m)	3.48	0.52	<.0001
Proximity 4	-265.97	132.69	.045
Proximity 3	-212.19	119.66	.076
Proximity 2	-27.95	110.86	.801
Proximity 1	0		.
Slow to Fast	-285.70	87.84	.001
Fast to Slow	-183.07	99.37	.066
Fast Lane	-301.77	81.79	<.0001
Slow Lane	0		.
Random Effects	σ^2	<i>s.e.</i>	<i>p</i>
Intercept (Participant)	325,605.60	105,941.60	.002
Residual	235,096.10	10,380.80	<.0001
Intraclass Correlation (ICC)			

Participant	.581
Model Fit (-2LL)	16,041.375

315 *Note.* The beta coefficients for proximity and manoeuvre are values relative to the assumedly most
316 predictable conditions (i.e., proximity 1 and driving in slow lane).

317 As shown in the model, mean occlusion duration increased with increasing headway distance. Figure 3
318 shows that this pattern also holds for the 95th percentile, but that there is an interaction with proximity.
319 The higher the level of proximity, the less the influence of the distance to the vehicle in front, mainly
320 as a result of avoiding very long occlusions in denser traffic.



321
322 *Figure 3.* Scatter plots of headway distance versus occlusion duration per proximity level (level 1 was excluded, because
323 there were so few objects within sight of the radar). The lines are determined by the median and 95th-percentile quantile
324 regressions.

325 Based on the other multilevel model, the grand mean of time since last occlusion is 13.4 s. Similar to
326 occlusion duration, time since last occlusion is affected by headway distance and manoeuvre, but not
327 by proximity level (Table 6). Increasing the headway distance by 1 m results in a predicted 40-s
328 decrease in time since last occlusion. For example, with a 50-m increase in headway distance, the
329 predicted decrease in the unoccluded period between occlusions is 2 s. Compared with driving in the
330 slow lane, changing into the fast lane increases the time since last occlusion by 5.2 s, while changing
331 from the fast to slow lane increases it by 8.0 s. The proportion of observed variance in time since last
332 occlusion between participants is approximately 56% (ICC).

333 **Table 6:** Multilevel Regression Model of Time since Last Occlusion (i.e., Unoccluded Period between Occlusions), Seconds

Fixed Effects	B	s.e.	p
Intercept	13.37	2.16	<.0001
Headway Distance (m)	-0.04	0.01	<.0001
Slow to Fast	5.16	1.12	<.0001
Fast to Slow	7.99	1.45	<.0001
Fast Lane	1.20	0.61	.050
Slow Lane	0		.
Random Effects	σ^2	s.e.	p
Intercept (Participant)	67.62	23.25	.004
Residual	53.62	2.40	<.0001
Intraclass Correlation (ICC)			
Participant	.558		
Model Fit (-2LL)	7090.058		

334 *Note.* The beta coefficients for manoeuvres are relative to the assumedly most predictable condition
 335 (i.e., driving in the slow lane).

336 3.3 Subjective answers

337 On average, the participants estimated to have used approximately 80% (SD = 11%) of the available
 338 occlusion occasions, meaning that the estimated possible occlusion percentage could have been around
 339 30% of the total time. Reported strategies for occluding mainly concerned the closeness of other road
 340 users and the ability to continue in one's own lane without disturbances. Drivers reported feeling more
 341 aware of non-visual input during the occlusion phase. Opinions varied as to the anxiety felt during
 342 occlusion. Most participants did not experience their driving as more dangerous during occlusion, with

343 some reporting that they were more focused in general, which might even have had a beneficial effect.
344 Several participants reported heightened alertness.

345 4 Discussion

346 As mentioned earlier, glancing away from the forward roadway is a frequent behaviour that is
347 necessary for situational awareness (Victor et al., 2015). Our findings indicate that glancing away from
348 the forward view for driving purposes is not the same as glancing away for other purposes, and that
349 neither of the two is necessarily equivalent to distraction. This is because awareness of some targets
350 off the forward roadway is strictly necessary for driving, such that the corresponding information
351 sampling should not be classified as “distraction”. Assuming that the study participants followed the
352 instructions and occluded when they did not need any additional visual input for the time being, they
353 should be assumed to be attentive during the test drives. This is congruent with Kircher and Ahlstrom
354 (2017) definition of distraction.

355 The present study strove to separate traffic-related from non-traffic-related glances while assessing
356 drivers’ evaluation of the minimum visual information intake necessary for safe driving in particular
357 scenarios.

358 4.1 Qualitative differences between off-forward glances and occlusion

359 As predicted in Hypotheses 1 and 2, occlusion duration decreased and the time between occlusions
360 increased in situations involving more interaction with other vehicles. Drivers occluded less often
361 when driving with shorter headways and, if they did occlude, the occlusions were shorter; also, the
362 longest occlusions become much shorter in this situation. In addition, occlusion behaviour changed
363 depending on the manoeuvres carried out by the drivers. For example, the driver’s need for
364 information to predict the situation was greater when changing into the fast lane than when changing
365 back into the slow lane, which is reflected by the reduced occlusion frequency.

366 In accordance with Hypothesis 3, off-forward glances proved to be qualitatively different from
367 occlusions both in their duration and timing. In line with previous research (Birrell & Fowkes, 2014;
368 Rockwell, 1988; Taoka, 1990; Tijerina, Barickman, & Mazzae, 2004; Wierwille, Antin, Dingus, &

369 Hulse, 1988), the duration of traffic-related off-forward glances was rather stable. Occlusion durations
370 were on average three times longer than these glances, and they varied substantially with proximity
371 and manoeuvre type, showing that nearby traffic increases perceived uncertainty. Also, the frequency
372 of off-forward glances was relatively stable across manoeuvres and proximity levels and very similar
373 to what has been found in naturalistic driving (Fitch et al., 2013; Victor et al., 2015). This indicates
374 that drivers glanced around neither more (e.g., to monitor traffic) nor less (e.g., to ensure that they stay
375 in their lane) when traffic became more intense. Occlusion frequency, on the other hand, decreased
376 with increasing proximity and varied between manoeuvres, such that it seems to reflect the available
377 spare attentional capacity in different situations.

378 Overall, occlusions did not decrease the percentage of off-forward glances, except in very low traffic.
379 The decrease in these glances in OCC when driving in the slow lane indicates that some of the BL
380 glances were “stray” glances not strictly necessary for driving. It has to be noted that it is still possible
381 that there are remaining stray glances in both BL and OCC. The increase in percentage of glances in
382 OCC when changing into the fast lane may be a result of having lost some awareness while driving in
383 the slow lane, such that the drivers checked their mirrors and blind spots more intensively than in BL.
384 When traffic was closer, glance frequency was not affected by adding occlusions. This indicates that
385 not many stray glances were made at the higher proximity levels, and that, on average, at least around
386 one third of the time spent looking forward is redundant – and more so when other traffic is farther
387 away.

388 Distraction detection algorithms (Donmez et al., 2008; Fernández et al., 2016; Kircher & Ahlstrom,
389 2013; Lee et al., 2013; Victor, 2005) and guidelines for distraction prevention (Liang, Lee, &
390 Yekhshatyan, 2012; National Highway Traffic Safety Administration, 2012, 2016) typically
391 emphasize the duration of glances away from the road, either for single glances or over a certain
392 period of time. However, our results indicate that the occlusion duration experienced as acceptable
393 depends on the situation; it can range from shorter durations than the 2 s that are often used as the
394 maximum acceptable off-forward glance duration; (e.g. National Highway Traffic Safety
395 Administration, 2012, 2016) to durations exceeding that. Increasing connectivity and instrumentation

396 should allow for an adaptive distraction detection algorithm that takes the infrastructure and the
397 surrounding traffic into account. Drivers are more likely to trust and accept contextually adaptive
398 distraction warnings than warnings with static glance thresholds (Kujala, Karvonen, & Mäkelä, 2016;
399 Sathyanarayana, Boyraz, & Hansen, 2011), which, based on our data, would be experienced as false
400 alarms in many situations. This means that the warnings of such algorithms could potentially be more
401 effective.

402 4.2 Predictors of uncertainty

403 The multilevel regression models predicted that if other road users are farther away, occlusion
404 probability increases. Furthermore, if the driver is planning or executing a lane change manoeuvre,
405 occlusion probability decreases compared with driving in the slow lane. Against expectations, the
406 driver's speed, driver's speed relative to the lead car, and number of lead cars did not predict occlusion
407 duration or time between occlusions.

408 Visual sampling requirements for safe driving are likely based on a combination of external factors,
409 resulting in perceived uncertainty while occluded (Kujala, Mäkelä, et al., 2016; Senders et al., 1967).
410 However, this does not necessarily have to be a function of driving speed or the number of road users
411 present. It is probably more related to the predictability of the parts of the situation that are relevant to
412 the driver. A lead car can be assumed to be more relevant if it is being approached than if it is moving
413 farther away, though how fast the lead car is being approached or moving away may not be significant
414 for predictability. The predictability of events decreases with increasing lead car proximity, but the
415 increasing number of surrounding road users does not necessarily decrease predictability in a linear
416 fashion.

417 The models suggest that the predictability of task-relevant event states determines the required
418 information sampling rate. However, as seen in the significant individual variability in the occlusion
419 measures, there is no single predictability value that could be assigned to an event state. Rather, for
420 each person, it is determined by the combination of the event state's variability and one's ability to
421 predict this variability. In line with this and earlier on-road studies (Falkmer & Gregersen, 2001;
422 Mourant & Rockwell, 1972; Underwood, 2007), age had a moderate correlation with occlusion

423 duration in this study, suggesting that more experience increased predictability for the driver.

424 However, these relationships merit further study in a better controlled design.

425 The driver's own intentions and manoeuvres may also affect the predictability of upcoming events by
426 changing their perceived uncertainty. From the driver's point of view, the decision to overtake a
427 slower car and change to the fast lane already leads to different predictions and increased uncertainty
428 of the upcoming events than if the driver decides to continue in the slow lane (Clark, 2013).

429 4.3 Limitations

430 There is evidence that distance is a more appropriate unit than time for event-density-related occlusion
431 measurements, because distance incorporates the concept of self-regulation (Kujala, Mäkelä, et al.,
432 2016). This is especially relevant in situations without dynamic elements such as other traffic. If
433 occlusion is measured in time, the driver's speed determines how much information is "missed", as
434 two occluded seconds at high speed lead to more missed information than do two occluded seconds at
435 low speed. If occlusion length is measured in distance, speed is no longer part of the equation. As
436 shown by Kujala, Mäkelä, et al. (2016), in a situation without dynamic elements, drivers are more
437 consistent in the distance they choose to occlude (and thus in the amount of "missed" information)
438 than in the occlusion duration (which varies with speed). Therefore, in situations without dynamic
439 elements, we postulate that occlusion distance rather than time should be used. However, the situation
440 becomes more complicated when other moving agents have to be considered. Even if the driver
441 decides to self-regulate by reducing his or her speed, other traffic will still move independently of that,
442 making time a critical factor. With increasing closeness to and interaction with other traffic, time
443 becomes more important. For the present analyses, which include both situations without interacting
444 traffic (proximity level 1) and situations with nearby traffic (proximity levels 2–4), we therefore
445 decided to use occlusion time instead of distance.

446 In normal driving, non-traffic-related off-forward glances are typically connected to some additional
447 task. This may lead to a faster deterioration of the mental model, because the secondary task requires
448 cognitive effort (Samuel & Fisher, 2015). In this study, no additional task was executed during
449 occlusion, partly for ethical reasons, but also to avoid introducing confounding variables. Similarly, in

450 the current experimental setting no in-car bottom-up stimuli captured the drivers' attention. This could
451 otherwise have led to unnecessary off-forward glances replacing an occlusion, or worse, to missing
452 necessary information, that is, a distraction.

453 One aim of this study was to assess the minimum required information intake and to investigate
454 whether this was dependent on variables such as the distance to the lead car, relative speed, and
455 proximity of other traffic. However, given that the occlusion glasses were open by default (for ethical
456 reasons), in combination with the under-occluding reported by the participants, the results should
457 instead be interpreted as an assessment of minimum spare capacity. The study also revealed a dilemma
458 when attempting to produce reliable maximum occlusion values for small headways. In naturalistic
459 driving, these situations do not occur frequently, and if they do, drivers are unlikely to occlude their
460 vision. For a stringent assessment of minimum required information intake depending on headway and
461 relative speed, a controlled study in a simulator or on a test track would be more suitable than driving
462 in real traffic.

463 The recruited participants were a convenience sample with a broad age range. A more homogeneous
464 group of participants might have led to smaller variances in the observed variables.

465 The occlusion method provides subjective estimates of spare attentional capacity as experienced by the
466 individual. Even experienced drivers' ability to assess the minimum information intake required for
467 safe driving on a familiar road may vary, so the occlusion durations should not be taken as the
468 absolute times drivers can take their eyes off the road without compromising safety. The occlusion
469 method is the best available method for estimating the *experienced* predictability of traffic events, but
470 more objective measures for assessing the minimum required information intake dependent on
471 situational factors should be developed, such that the subjective assessment can be compared to
472 objective requirements.

473

474 5 Conclusions and practical implications

475 The National Highway Traffic Safety Administration driver distraction guidelines recommend that
476 devices be designed so that tasks can be completed by the driver while driving with individual glances
477 away from the roadway of 2 s or less and a cumulative time of 12 s or less per task spent looking away
478 from the roadway (National Highway Traffic Safety Administration, 2013). The clear differences
479 found in the present study between necessary traffic-related off-forward glances and occlusions
480 (representing stray glances and glances related to additional tasks) suggest that the concept of a fixed
481 glance duration as an indicator of distraction should be reconsidered. Fewer and shorter (or no) stray
482 glances are possible in less predictable situations, whereas longer and more frequent stray glances can
483 be acceptable in highly predictable situations. Situation-aware distraction detection algorithms should
484 therefore be able to achieve greater precision than using a fixed value, while false alarms can be
485 suppressed by using information about the glance target in combination with manoeuvre awareness.
486 Analogous studies with increasing levels of automated driving can provide insights into changes in the
487 driver's role and visual behaviour, such that driver monitoring algorithms can be adjusted to the level
488 of automation involved.

489 6 Key Points

- 490 • Driver distraction should be defined with reference to insufficient sampling of the necessary
491 driving-related targets in the forward or off-forward view.
- 492 • Self-paced visual occlusion in real-world driving was used to differentiate necessary glances
493 from spare attentional capacity.
- 494 • Off-forward glances differ qualitatively from occlusions both in their duration and in the
495 situations in which they occur.
- 496 • Not all off-forward glances are equivalent to driver distraction, and not all forward glances are
497 necessary.
- 498 • Incorporating situational information could improve distraction detection algorithms.

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