Topic: Cognition

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

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Précis

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

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Abstract

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

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

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

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

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

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

1 Introduction

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

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

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

It would be too easy to say that any looking away from the forward roadway equals distraction, as some glances towards other targets are strictly necessary and other glances do not necessarily impede taking in all relevant information. Moreover, not sampling the relevant targets off the forward roadway should also be identified as distraction. Despite this, published gaze-based real-time distraction detection algorithms essentially measure the time spent looking away from the forward roadway without considering situation-based attentional requirements at all (e.g. Donmez, Boyle, & Lee, 2008; Fernández, Usamentiaga, Carús, & Casado, 2016; Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006; Victor, 2005), or not more than in a rudimentary way, as in the AttenD algorithm, which has a built-in mechanism for acknowledging the necessity of mirror and speedometer glances (Kircher & Ahlstrom, 2013). However, it does not evaluate whether such a glance was necessary in a given situation, but just assumes that is the case for any glance at the mirror or speedometer. Incorporating informed situation-based attentional requirements would entail an approach that does not focus only on the time spent looking elsewhere, but also checks whether all necessary information has been sampled (Kircher & Ahlstrom, 2017). This approach would allow drivers to self-regulate, influencing both the information requirements and the available time to meet them (see also Clark, 2016). The drawback is obviously that it is difficult to define the minimum requirements for attentive driving.

Requirements which are related to the infrastructure can typically be established based on rules and regulations in combination with infrastructural and environmental constraints. For example, when approaching an intersection on a feeder road, one must ensure that the main road is clear for passage, and this must be done within a certain time frame, starting when the line of sight becomes unobstructed and ending just before entering the intersection. Preliminary attempts have been made to operationalize such requirements on real roads (Nygårdhs, Ahlström, Ihlström, & Kircher, 2018) and in simulators (Kujala, Mäkelä, Kotilainen, & Tokkonen, 2016). Requirements which are related to other road users and to one’s own movements in relation to the road ahead, do not have such clear boundaries. How often information must be sampled to maintain an up-to-date mental representation varies with several factors. These include proximity and speed relative to other vehicles, traffic rules, infrastructure, features inherent to the road user or other dynamic target in question, and one's own manoeuvring intentions (Kircher & Ahlstrom, 2018).

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

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

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

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

2 Method

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

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

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

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

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

2.1 Procedure

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

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

2.2 Data reduction and pre-processing

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

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

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	

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

2.3 Statistical modelling

To determine the sampling requirements for the forward view based on changes in task-relevant situational parameters, two multilevel regression models were created. The dependent variables for the models were occlusion duration and time between occlusions. All predictor variables (i.e., vehicle speed, manoeuvre, proximity of other traffic, relative speed and headway distance to a lead car in the same lane, and number of lead cars) were entered in the models in the first phase. Non-significant predictors with an alpha level <.05 were then removed individually to find a model that explained as much as possible of the variance in the dependent variable. To be included in the model, a predictor had to improve the model fit significantly according to the χ^2 test, as measured by the –2 log likelihood (–2LL, the smaller the better). Participant was included as a random effect. The restricted maximum likelihood estimation method was used in the multilevel regression analyses.

3 Results

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

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

Time Spent (%)	BL	Slow Lane	Fast Lane	Fast to Slow	Slow to Fast	Total	OCC	Slow Lane	Fast Lane	Fast to Slow	Slow to Fast	Total
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

3.1 Off-forward glance behaviour

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

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

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

The mean glance duration was comparable across proximity levels and manoeuvres at 0.60 s (SD = 0.11 s) in BL versus 0.56 s (SD = 0.13 s) in OCC. The average time spent looking forward before the 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 measured since the last glance or occlusion, whichever was closest.

3.2 Occlusion behaviour

Occlusion frequency and duration varied substantially with proximity level and manoeuvre (TABLE 3). In general, with increasing proximity, the occlusion frequency decreased. When driving in or changing back into the slow lane, the occlusion frequency was higher than when driving in the fast lane. Drivers were least likely to occlude when changing from the slow lane to the fast lane. The average time between occlusions was 8.9 s (SD = 12.8 s), ranging from 3.2 s when changing back into the slow lane at proximity level 1 to 23.2 s when changing into the fast lane at proximity level 3.

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

Total Off-forward Glance Time (%), BL

		Slow Lane	Fast Lane	Fast to Slow	Slow to Fast	Total
Prox	1	31.9			17.5	31.7
	2	25.2	28.6	28.8	26.8	25.3
	3	23.5	18.9		28.2	23.7
	4	26.5	19.8	29.2	26.6	22.9
	Total	26.4	19.8	29.2	26.7	24.9

Total Off-forward Glance Time (%), OCC

		Slow Lane	Fast Lane	Fast to Slow	Slow to Fast	Total
Prox	1	20.6		15.3	27.1	20.6
	2	22.7	27.5	33.2	32.3	23.2
	3	20.2			26.9	20.9
	4	20.6	20.8	21.0	19.7	20.6
	Total	21.8	20.8	21.0	23.1	21.7

Total Occlusion Time (%), OCC

		Slow Lane	Fast Lane	Fast to Slow	Slow to Fast	Total
Prox	1	37.7				37.7
	2	31.8	27.8		9.3	30.6
	3	18.0			3.0	15.2
	4	18.9	12.2	19.7	5.7	12.4
	Total	31.5	12.4	19.9	6.3	23.9

Total Occlusion + Glance Time (%), OCC

		Slow Lane	Fast Lane	Fast to Slow	Slow to Fast	Total
Prox	1	52.6		58.3	95.7	58.3
	2	52.1	41.6	54.5	55.3	53.8
	3	17.9			11.2	36.1
	4	40.7	25.4	39.4	32.9	33.0
	Total	40.8	29.3	53.4	33.1	45.5

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

Occlusion durations became shorter with increasing proximity. Within each manoeuvre, the longest occlusion durations were found at proximity level 1. The relationships between off-forward glance durations and occlusion durations per manoeuvre and proximity level are illustrated in Figure 2. Note that almost 50% of all occlusions at proximity level 1 were 2 s or longer, and that driving in the slow lane generally led to the longest occlusions. Overall, around one third of occlusions were longer than 2 s. The longest ones lasted up to 3.5–4 s; however, these long occlusions were rare (2% above 3.5 s), almost always occurring when driving in the slow lane without any traffic nearby.

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

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

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

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

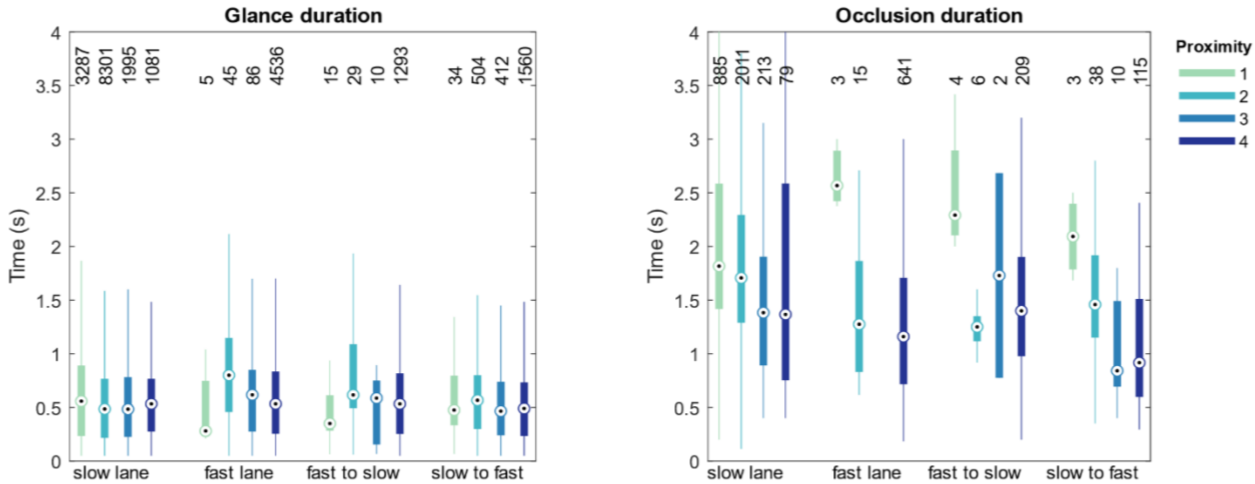

Figure 2. Boxplots showing off-forward glance durations (data from BL and OCC) and occlusion durations per manoeuvre and proximity level. The number of observations is presented above each box.

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

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

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

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

Table 5: Multilevel Regression Model of Occlusion Duration, Milliseconds

Fixed Effects	***B***	**s.e.**	***p***
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	□2	**s.e.**	***p***
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

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

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

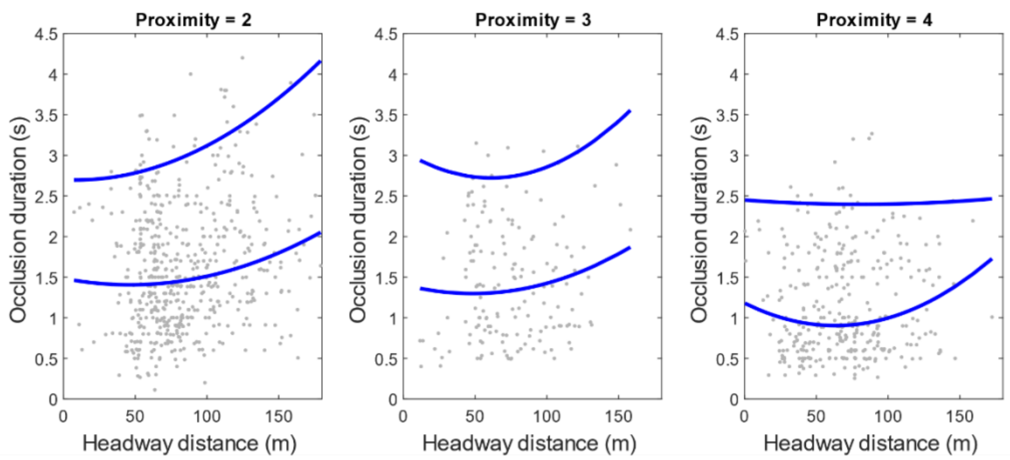

Figure 3. Scatter plots of headway distance versus occlusion duration per proximity level (level 1 was excluded, because there were so few objects within sight of the radar). The lines are determined by the median and 95th-percentile quantile regressions.

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

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	□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		

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

3.3 Subjective answers

On average, the participants estimated to have used approximately 80% (SD = 11%) of the available occlusion occasions, meaning that the estimated possible occlusion percentage could have been around 30% of the total time. Reported strategies for occluding mainly concerned the closeness of other road users and the ability to continue in one's own lane without disturbances. Drivers reported feeling more aware of non-visual input during the occlusion phase. Opinions varied as to the anxiety felt during occlusion. Most participants did not experience their driving as more dangerous during occlusion, with some reporting that they were more focused in general, which might even have had a beneficial effect. Several participants reported heightened alertness.

4 Discussion

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

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

4.1 Qualitative differences between off-forward glances and occlusion

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

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

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

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

Distraction detection algorithms (Donmez et al., 2008; Fernández et al., 2016; Kircher & Ahlstrom, 2013; Lee et al., 2013; Victor, 2005) and guidelines for distraction prevention (Liang, Lee, & Yekhshatyan, 2012; National Highway Traffic Safety Administration, 2012, 2016) typically emphasize the duration of glances away from the road, either for single glances or over a certain period of time. However, our results indicate that the occlusion duration experienced as acceptable depends on the situation; it can range from shorter durations than the 2 s that are often used as the maximum acceptable off-forward glance duration; (e.g. National Highway Traffic Safety Administration, 2012, 2016) to durations exceeding that. Increasing connectivity and instrumentation should allow for an adaptive distraction detection algorithm that takes the infrastructure and the surrounding traffic into account. Drivers are more likely to trust and accept contextually adaptive distraction warnings than warnings with static glance thresholds (Kujala, Karvonen, & Mäkelä, 2016; Sathyanarayana, Boyraz, & Hansen, 2011), which, based on our data, would be experienced as false alarms in many situations. This means that the warnings of such algorithms could potentially be more effective.

4.2 Predictors of uncertainty

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

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

The models suggest that the predictability of task-relevant event states determines the required information sampling rate. However, as seen in the significant individual variability in the occlusion measures, there is no single predictability value that could be assigned to an event state. Rather, for each person, it is determined by the combination of the event state's variability and one's ability to predict this variability. In line with this and earlier on-road studies (Falkmer & Gregersen, 2001; Mourant & Rockwell, 1972; Underwood, 2007), age had a moderate correlation with occlusion duration in this study, suggesting that more experience increased predictability for the driver. However, these relationships merit further study in a better controlled design.

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

4.3 Limitations

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

In normal driving, non-traffic-related off-forward glances are typically connected to some additional task. This may lead to a faster deterioration of the mental model, because the secondary task requires cognitive effort (Samuel & Fisher, 2015). In this study, no additional task was executed during occlusion, partly for ethical reasons, but also to avoid introducing confounding variables. Similarly, in the current experimental setting no in-car bottom-up stimuli captured the drivers' attention. This could otherwise have led to unnecessary off-forward glances replacing an occlusion, or worse, to missing necessary information, that is, a distraction.

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

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

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

5 Conclusions and practical implications

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

6 Key Points

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

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