Drivers anticipate lead-vehicle conflicts during automated longitudinal control: sensory cues capture driver attention and promote appropriate and timely responses

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Abstract Adaptive Cruise Control (ACC) has been shown to reduce the exposure to critical situations by maintaining a safe speed and headway. It has also been shown that drivers adapt their visual behavior in response to the driving task demand with ACC, anticipating an impending lead vehicle conflict by directing their eyes to the forward path before a situation becomes critical. The purpose of this paper is to identify the causes related to this anticipatory mechanism, by investigating drivers' visual behavior while driving with ACC when a potential critical situation is encountered, identified as a forward collision warning (FCW) onset (including false positive warnings). This paper discusses how sensory cues capture attention to the forward path in anticipation of the FCW onset. The analysis used the naturalistic database EuroFOT to examine visual behavior with respect to two manually-coded metrics, glance location and glance eccentricity, and then related the findings to vehicle data (such as speed, acceleration, and radar information). Three sensory cues (longitudinal deceleration, looming, and brake lights) were found to be relevant for capturing driver attention and increase glances to the forward path in anticipation of the threat; the deceleration cue seems to be dominant. The results also show that the FCW acts as an effective attention-orienting mechanism when no threat anticipation is present. These findings, relevant to the study of automation, provide additional information about drivers' response to potential lead-vehicle conflicts when longitudinal control is automated. Moreover, these results suggest that sensory cues are important for alerting drivers to an impending critical situation, allowing for a prompt reaction.

Keywords: naturalistic driving, glance analysis, automation, driver behavior, forward collision warning, adaptive cruise control.

1 INTRODUCTION

Adaptive cruise control (ACC) is an advanced driver assistance system (ADAS) that automates the longitudinal control of the vehicle. This system, classified as level 1 automation (NHTSA, 2015; SAE, 2014), maintains speed and time headway according to chosen settings. The driver activates and sets the ACC system by pressing buttons on the steering wheel. When a lead vehicle is detected, the speed is automatically controlled to keep the selected headway. However, ACC's braking capacity is limited to a level sufficient for normal headway maintenance situations, not extreme braking situations. The allowed deceleration varies among implementations, but the ACC maximum braking authority is usually about 0.3g, as suggested in the standards ISO 15622:2010 and ISO 22179:2009. When the driving situation exceeds the braking capacity of the ACC, because of a highly decelerating lead vehicle, for example, a frontal collision warning (FCW) is issued. The FCW's role is to redirect the driver's attention to the forward road and elicit a driver braking response in critical situations, by means of visual and auditory signals. ACC has primarily been seen as a system supporting normal driving situations, for comfort. However, by maintaining a safe speed and headway, ACC and FCW have been shown to improve safety-related measures, reducing the exposure to critical situations (Malta et al., 2011; NHTSA, 2005).

Based on the hierarchical structure proposed by Michon (1985), ACC primarily supports the driver at the *control* level (i.e. accelerating and braking) and the *maneuvering* level (i.e. speed selection, gap acceptance and obstacle avoidance); it does not perform the entire dynamic driving task. The driver must monitor the system and take over when required, either by the system itself (e.g., when a FCW is issued) or when ACC does not react to a lead vehicle due to system limitations, such as the radar's field-of-view. Several studies questioned the ability of a driver to reclaim control in an effective and safe manner after a system failure. They raised concerns about the harmful effect of ACC (and, by extension, of higher levels of automation) due to the degradation of *situation awareness* and a slower response to critical events (for example); for a review see de Winter et al. (2014). Situation awareness is defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1988, p. 792). The review by de Winter et al. (2014) shows that results for situation awareness vary between studies. ACC use can result in deteriorated situation awareness when drivers engage in secondary tasks, but improves situation awareness if they are attending to the driving task. Similarly, a number of experiments have found that ACC drivers can be slower to respond to critical events compared to manual drivers, while many studies have shown faster reactions to artificial visual stimuli (de Winter et al., 2014). A more nuanced examination of the response processes in critical events when using ACC is clearly needed.

A possible explanation for degraded detection of and response to critical driving situations can be regarded as an unintended effect, also known as *behavioral adaptation* (OECD, 1990). For example, ACC decreases the visual demand of driving; as a consequence drivers use freed resources to engage in non-driving activities, which may reduce the attention allocated for monitoring the road ahead (Rudin-Brown & Parker, 2004). The widespread availability of in-vehicle infotainment systems and nomadic devices may further aggravate this effect (Lee et al., 2006). In their naturalistic study, Malta et al. (2011) found a general increase in secondary-task engagement while driving with ACC. A follow-up study by Tivesten et al. (2015) examined the drivers' visual attention in motorway car-following scenarios. In steady state driving, the analysis confirmed a lower attention level to the forward path with ACC than without (~77% mean eyes on path with ACC, compared to ~85% for manual driving without ACC). Tivesten et al (2015) also clarified that most of the glances away from the forward path were driving-related. Because driving relies heavily on vision (Shinar, 2007), diversion of visual attention from the forward road could lead to a collision there. However, Malta et al. (2011) pointed out that drivers kept their attention on the primary driving task in critical situations. Furthermore, Tivesten et al. (2015) showed a *threat anticipation* response: drivers anticipate the impending criticality by directing their eyes to the forward roadway before a situation becomes critical. This is evidence that allocation of attention away from the road is a function of the current driving situation demand (Ranney, 1994; Summala, 2007).

A simulator study by Lee et al. (2006) evaluated the effectiveness of warning modalities at reengaging drivers when the ACC capabilities are exceeded. Their results showed that if warned that an intervention is needed, drivers could effectively resume control even if distracted. However, other studies showed that drivers responded poorly to unexpected events or failures for which alerts are not provided—for example, sensor failures (Nilsson et al., 2013; Rudin-Brown & Parker, 2004; Stanton et al., 1997; Strand et al., 2014). Fortunately, in the real world these failures are rare, thanks to technology advances and sensor redundancy; even so, providing feedback on the system status and availability is recommended by the standard ISO 15622:2010. Therefore, the difficulties encountered by drivers may be overrepresented in studies when such feedback is not provided (Lee et al., 2006).

Although the FCW is intended to redirect the gaze of the driver towards the forward path and inform the driver that an avoidance maneuver is needed, the results in (Tivesten et al., 2015) suggested that there may be other cues that elicit a shift of visual attention in anticipation of a critical situation, even before an FCW is issued. However, the cause for this anticipatory mechanism was not clearly identified; hence the need for further investigation. Tivesten et al. (2015) showed that the average percent of eyes on path increased steadily over time, and they suggested that this increase was due to drivers' reactions to external stimuli (e.g., related to the approach toward the lead vehicle).

This study discusses three sensory cues which are considered relevant for prompting the drivers' visual attention towards the forward path in anticipation of a lead vehicle conflict. The first cue is the detection of the longitudinal acceleration of the driver vehicle by the vestibular system. As pointed out in (Lee et al., 2006; 2007), another benefit of the ACC is that the cue associated with the speed modulation (deceleration or braking) before the onset of the warning may be particularly effective at alerting drivers and making them resume control when needed. Subjective data from a field operational test of ACC (Fancher et al., 1998) indicated that drivers acknowledged the deceleration cue as beneficial for informing them of an evolving headway conflict. Lee et al. (2006) found the detection threshold to be between 0.15–0.20 m/s^2. However, this deceleration cue effect is often discounted in studies in fixed-base simulators, since they do not provide these deceleration cues.

The second cue is visual looming, the optical expansion of the lead vehicle in the eye of the driver. Visual cues have been shown to be particularly relevant in car-following scenarios. Previous studies have argued that the driver could detect changes in relative velocity and control the evasive maneuvers (e.g., braking) based solely on information like the visual angle subtended by the lead vehicle (θ), the rate of change ($\dot{\theta}$), or the combination thereof (τ) (See, for example, Hoffmann, 1968; Hoffmann & Mortimer, 1994a; Lee, 1976; Mortimer, 1990). More details on these measures are given in section 2.5. Visual detection performance generally deteriorates towards the retinal periphery, therefore the further the driver diverts the eyes away from the forward path the worse the ability to detect threats and objects on the road (Victor et al., 2008). However, results from laboratory experiments show that certain salient stimuli (e.g., moving and looming targets) induce automatic and reflexive reactions. When one of these stimuli occurs, the attention is shifted to the stimulus, especially when it is not expected (Jonides, 1981; Klein et al., 1992; Regan & Vincent, 1995). The salient stimuli expected to elicit an attention shift are associated with behavioral urgency. For example, given stimuli of the same magnitude, looming objects indicate an impending collision and would trigger a reflexive response, whereas receding objects should not elicit the same response, being neither potentially urgent nor threatening (behavioral urgency hypothesis in Franconeri & Simons, 2003; Lin et al., 2008). In on-road studies, drivers could detect a closing car even when visual attention was diverted away from the road, but with increasing eccentricity the threshold for detection increased (Lamble et al., 1999; Summala et al., 1998). (The table in Appendix B provides a compilation of the results from these two studies.) When looking along the line of motion, the perceptual threshold of $\dot{\theta}$ for discriminating the closure of the lead vehicle was around 0.0036 rad/s (with a minimum value of 0.0022 rad/s), regardless of the test conditions (initial headway, speed, and deceleration). This threshold is higher than, yet comparable to, the value of about 0.0030 rad/s, which was proposed by studies from experiments in which the participants were required to watch film clips, and from reviews of previous findings (Hoffmann & Mortimer, 1994a; Hoffmann & Mortimer, 1994b; Mortimer, 1990). With increasing eccentricity, the detection threshold for $\dot{\theta}$ increases linearly. However, there is little agreement on the results for τ^{-1} since, unlike $\dot{\theta}$, this variable may be quite sensitive to the different experimental conditions.

The third cue is the brake light onset. The brake light onset signals that the lead vehicle started braking, but its predictive value is limited and it does not give information about the criticality of the situation, e.g., whether/how hard one must brake (Lee, 1976). In their study of naturalistic crashes and near-crashes, Victor et al. (2015) concluded that brake lights had a limited impact on driver behavior in rear-end situations. In fact, the brake light onsets which occurred while the driver was looking forward were generally ignored (i.e. the drivers were willing to take their eyes off path while the brake lights were still illuminated) and do not seem to have notably influenced the driver reaction. One explanation is that, in real world driving, drivers may be exposed to brake light onsets which are not associated to any threat, leading to a cry-wolf effect (Victor et al., 2015). Furthermore, Markkula et al. (2016) and Victor et al. (2015) showed that reaction times in real crashes and near-crashes are influenced by lead-vehicle looming, and not by brake light onsets as reported, for example, by Young and Stanton (2007). Assuming that the brake lights are salient enough to be detected while looking ahead (consider, for example, the difficulty encountered in strong sunlight), Summala et al. (1998) found that detection was significantly impaired in the periphery, even at a low level of eccentricity[1]. However, for night driving, the stimulus would be more salient and might be more easily detected, making the change in angular separation of the car's brake lights the prominent cue in the detection of relative speed (Janssen (1974).

There are a multitude of other attentional capture cues that were not taken into account in this study. Such cues might be related to the road infrastructure (e.g., road signs), to the surrounding traffic (e.g., behavior of other vehicles), to other visual properties (e.g., color, luminance, and contrast), and to cognitive and motivational factors (e.g., experience).

In summary, the present study investigates visual behavior when potentially critical situations (identified as FCW onsets) are encountered while driving with ACC and identifies possible reasons for the anticipatory response. The main hypothesis was that visual and vestibular/somatosensory cues were responsible for orienting the drivers' visual attention towards the forward path in anticipation of the FCW onset.

2 METHODS

2.1 Data source

The data used in this study are from the Swedish subset of the EuroFOT database, collected from 100 Volvo cars (2009–2010 V70 and XC70 models) in the region of Västra Götaland over the period 2010–2011. EuroFOT (Kessler et al., 2012) was a Field Operational Test sponsored by the European Community to evaluate the impact of ADAS on routine driving in real traffic. Among the ADAS tested, the ones of particular interest for this study were the ACC and the FCW. All 263 drivers who participated in the project were Volvo employees who volunteered to participate in the study and drove their own cars.

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[1] In (Summala et al., 1998) an old compact car was used (1988 Lada Samara), and it is not clear if it was equipped with a center high-mount stop lamp (CHMSL) which could have improved the detection of the brake light onset.

Data were continuously collected from the controller area network (CAN) bus, from extra sensors (e.g., accelerometer, GPS), and from cameras mounted in the cars, sampled at 10 Hz. The collection began when the engine was started, and it was interrupted when the ignition was turned off. The driver inputs were gathered both from the CAN bus (i.e. pedals and steering wheel activity) and a camera recording foot movement. Other cameras were used to record the forward and backward view of the vehicle and the face of the driver. All CAN signals were pre-processed (e.g., decoded, synchronized, filtered) and stored in a relational database.

2.2 Event dataset

Initially, 280 critical events were extracted from the database. A critical event occurred any time a FCW was issued while driving with ACC. A critical event consisted of 20 s of driving, centered at the FCW onset (i.e. 10 s before and after the warning). General inclusion criteria were that before and at the onset of FCW, the ACC and FCW were active (the ACC was active at speeds above 30 km/h and disengaged when the driver pressed the brake pedal) and the alert modality of the FCW was visual and audio (according to the specifications described in Coelingh et al., 2007). The events were reviewed, and discarded if the video sources were not available or the driver's eyes were not clearly visible. Events were also rejected if, in the 5 s interval before the FCW, the driver changed the ACC or the FCW settings (e.g. ACC set speed, FCW sensitivity, etc.), changed lanes or overtook another vehicle, or overrode the ACC by accelerating (i.e. the driver intentionally pursued a small forward headway to the lead vehicle, making the warning predictable). Finally, events were also discarded if a lane departure warning (LDW) was triggered prior to the onset of FCW; otherwise the LDW may have confounded the effect of the FCW.

In the end, 125 events fulfilled the inclusion criteria and were included in the analysis. The dataset included 43 unique drivers (36 males and 7 females) between the ages of 18 and 61 (Mean = 47.76 years, standard deviation = 9.13).

2.3 Annotated variables

2.3.1 Event classification

Each event was categorized as either rear-end FCW or random FCW. An event was classified as *rear-end FCW* if the FCW was due to an imminent collision with a lead vehicle (from now on referred as principal other vehicle, POV). An event was classified as *random FCW* if a FCW was issued but no POV (or other threat) was present. A random FCW was probably the consequence of limitations in processing the radar information or in detection. A total of 87 rear-end FCW and 38 random FCW were analyzed.

2.3.2 Glance coding

In order to study the drivers' visual behavior two metrics were used: *glance location* and *glance eccentricity*. Glance location is the area of interest (AOI) the eyes are directed to. This metric identifies where the drivers were looking, in order to quantify how they allocated their visual attention; looking towards the road center is primary to safe maneuvering of the vehicle, although they also performed secondary visual tasks. Secondary tasks can be either driving-related (e.g. reading road signs, checking speedometer) or not (e.g. phone-related, reaching for objects). The glance location was manually coded frame by frame, based on the forward and driver videos (recorded at 10 frames per second), with the support of the MATLAB-based program FOTware (Dozza et al., 2010). The coding was in line with the work performed in (Tivesten et al., 2015; Victor et al., 2015). The main AOIs are illustrated in Figure 1 and a more complete description is given in Table A.1. Glance eccentricity is defined as the radial angle between the forward path and the glance location. Inspired by the work done in (Klauer et al., 2006, p. 107), the annotated AOIs were grouped into four levels based on the average angle away from the forward path (see Table A.2 for further details).

2.3.3 Other annotations

Relevant timestamps were annotated (i.e. the time of FCW onset and the time when the POV's brake lights turned on) as well as information about lighting, weather conditions, and road geometry (see Table

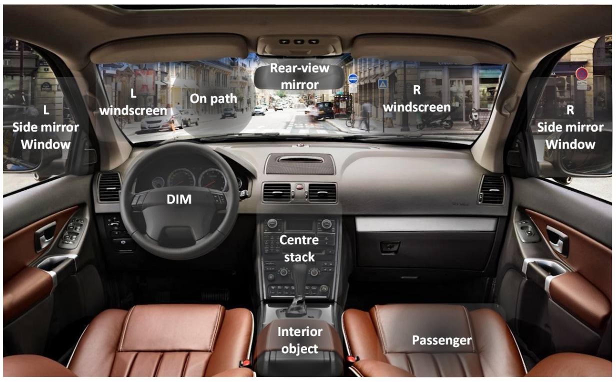

Figure 1. Location of the main AOIs. *Background photo: Volvo car.*

A.3 for a summary of the annotated environmental variables). Moreover, a narrative description of each event was written.

2.4 Vehicle measures

Among the signals collected from the CAN bus, the ones of particular interest for describing the vehicle dynamics and the driving situation (specifically the interaction with the POV) were the speed and the longitudinal acceleration of the driver vehicle, the distance (*Range*) and the relative speed (*Range rate*) to the POV, the time to collision (TTC), and the time headway (THW). The TTC and THW are two commonly used safety indicators. TTC is computed as the ratio between the distance and the relative speed to the POV; it expresses the severity of the impending collision. In this study the inverse of the TTC (TTC^{-1}) was used in order to have a measure that increases as the risk of colliding with the POV increases (Summala, 2000, defined it as urgency). THW is computed as the ratio between the distance to the POV and the speed of the driver vehicle. The THW, in steady-state car following, is a measure of the exposure to a potential threat. For example, if the leading vehicle brakes, a short THW would require a faster response than a longer THW in order to avoid the collision. It is important to remember that in the events under analysis, the drivers selected the desired THW to maintain in the ACC settings.

2.5 Optical variables

Three optically-defined variables were used: *theta* (θ), its time derivative *theta dot* ($\dot{\theta}$), and their ratio *tau* (τ). The angle θ is the optical angle (in rad) of the POV at the eyes of the driver[2] and it is calculated by

$$\theta = 2 \cdot \operatorname{atan} \frac{W}{2R}$$

where W is an estimation of the POV width (a standard value of 1.8 m was used, see also Victor et al., 2015, p. 28), and R is the distance to the POV (in m). The rate of change of the optical angle, $\dot{\theta}$ (in rad/s), is calculated by

$$\dot{\theta} = -\frac{4 W \dot{R}}{R^2 + 4 W^2}$$

where $\dot{R}$ is the relative speed of the driver vehicle (in m/s) and the POV. Finally, τ is given by the ratio of θ and $\dot{\theta}$, that is the rate of dilation of the retina image of the POV (in s) as proposed in (Lee, 1976). As in the case of TTC, in the analysis the inverse of τ (τ^{-1}) was used instead. It also turns out that τ is the optical approximation of the physical quantity TTC (Lee, 1976).

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[2] Properly speaking, the angle θ is estimated based on information from the front radar, therefore it is the optical angle at the bumper of the driver vehicle.

2.6 Data analysis framework

2.6.1 Response and explanatory variables

In the analysis framework of this study, the response variable is the time-course of the driver's visual behavior. In order to visualize it, a stacked histogram was used (see an example in Figure 2, and refer to Appendix A for the glance's color code). This graph is inspired by previous studies (Tivesten et al., 2015; Victor et al., 2015) and shows the proportion of various glances over time in the events under analysis. In addition, the curve for the mean percentage of eyes on path (*%EOPmean*) was used to better visualize the trend of the glances on path across the events (black curve in Figure 2). In line with the work done in (Tivesten et al., 2015), the curve was defined by chunking the glance time series of the events in bins of 0.5 s. Each point in the curve is defined by first computing the mean percentage of glances on path in the selected bin for each single event. Then the computed values are averaged across all the events. The errors bars indicate the 95% confidence interval (95CI), which is also a measure of the events' inter-variability. The boundaries of the confidence interval are the value of %EOPmean in the selected bin plus/minus 1.96 times the standard error of the mean.

The exploratory variables are the measures related to the driver vehicle and the POV, as introduced in sections 2.4–2.5. In order to facilitate the comparison to the response variable (i.e. the drivers' visual behavior) the same approach used to define the %EOPmean was taken.

2.6.2 Statistics

The non-parametric Friedman test and the Wilcoxon signed rank post-hoc test were used to compare the observations within the glance time-series at different points in time during the events. The significance level was set at 0.05 (with the Holm-Šidák correction for multiple comparisons).

3 RESULTS

3.1 Glance location

3.1.1 Rear-end FCW events

Figure 3a shows the glance location history for the rear-end FCW events, centered at the FCW onset. In general, the drivers' visual attention in the 20 s interval was directed towards the forward path (78.4%). Most of the off path glances were driving-related. The driver information module accounted for 29.3%, followed by L+R windscreen (24.8%), rear view mirror (14.7%), and L+R side mirror/window (11.9%).

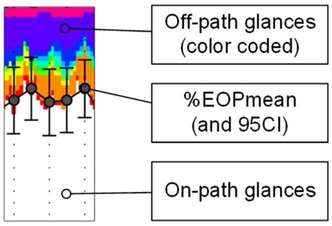

Figure 2. Example of the graph used for visualizing the time-course of the glance location across the events. The graph shows the percentage of glance locations at any given time during the events under analysis. For details on the glances' color code see Appendix A. The black curve indicates the mean percentage of eyes on path (%EOPmean). The error bars indicate the 95% confidence interval.

The cumulative distributions show a noticeable increase in glances towards the rear-view mirror just after the FCW onset (Figure 3b). Moreover, they show that the majority of the glances towards an interior object and the phone were at the beginning and at the end of the events. In contrast, the cumulative distributions of the glances off path towards the other AOIs steadily increased over time.

Based on a graphical analysis of the %EOPmean trend, five intervals could be identified (Figure 3a):

1. In the -9.5 s – -2.5 s interval the %EOPmean oscillated around the value 78%, which is in accordance with the baseline used in (Tivesten et al., 2015). Thus, this interval may be defined as the *steady state driving interval.*
2. In the -2 s – 0 s interval the %EOPmean steadily increased from 80.7% to 95.4% (significant: Friedman test, $\chi^2(2) = 44.09$, $p < .001$; Wilcoxon post-hoc, $z = 3.35$, $p < .01$, $r = 0.25$). This interval may be defined as the *threat anticipation interval*, in conformity with (Tivesten et al., 2015).
3. After the FCW onset, at 0.5 s, the %EOPmean further increased to 97.5%. This interval may be defined as the *threat interval*, as proposed in (Wege et al., 2013).
4. Afterwards, in the 1 s – 6 s interval the %EOPmean decreased to 61.6%, a level that was significantly lower than the beginning of the threat anticipation interval (Friedman test, $\chi^2(2) = 44.09$, $p < .001$; Wilcoxon post-hoc, $z = 2.99$, $p < .01$, $r = 0.23$). This interval may be defined as the *post-threat interval*, as suggested in (Wege et al., 2013).
5. Finally, in the 6.5 s – 9.5 s interval the %EOPmean converged to a value around 70.7%. This interval may be defined as the *(back to) steady state driving interval.*

3.1.2 Random FCW events

Figure 4a shows the glance location history for the random FCW events, centered at the FCW onset. As in the rear-end FCW events, in the 20 s interval the drivers looked at the forward path most (78.1%) of the time. Likewise, most of the glances off path were driving-related. Among them, the driver information module accounted for 34.2%, followed by the rear view mirror (17.9%), L+R windscreen (15.2%) and L+R side mirror/window (13.7%). In general, the cumulative distributions of the off path glances steadily increased over time. In particular, the rapid increase of glances towards the rear-view mirror after the FCW onset, found in the rear-end FCW events, was not present here (Figure 4b).

In Figure 4a, four intervals can be distinguished in the %EOPmean curve. Note that the threat anticipation interval seen in rear-end events was not present in the random FCW events, but the other four are comparable:

1. In the -9.5 s – 0 s interval the %EOPmean oscillated around the value 77.8%. This interval is comparable to the baseline used in (Tivesten et al., 2015) and it may be also defined as the steady state driving interval.
2. After the FCW onset, at 0.5 s, the %EOPmean suddenly increased from the value of 83.2% at

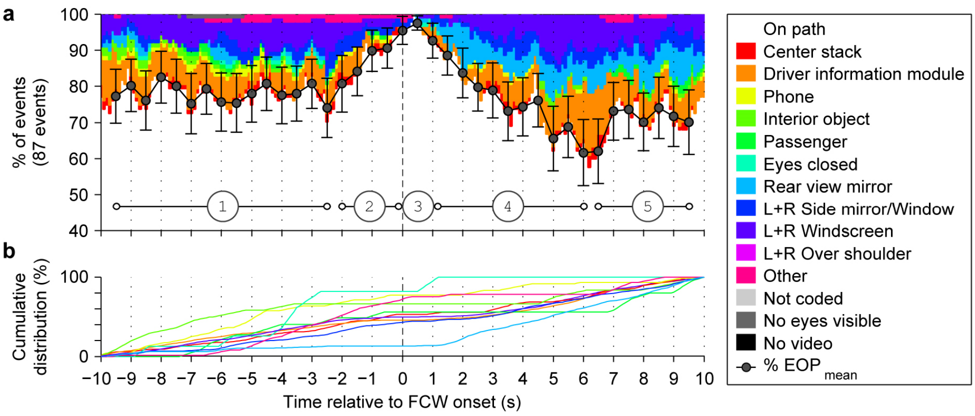

Figure 3. Proportion (a) and cumulative distributions (b) of the glance location over time for the rear-end FCW (frontal collision warning) events. The events are centered at the FCW onset. Numbered circles in (a) indicate the identified intervals described in the text: (1) Steady state driving, (2) Threat anticipation, (3) Threat, (4) Post-threat, (5) (Back to) steady state driving. The curve %EOPmean shows the mean percentage of eyes on path. The error bars indicate the 95% confidence interval.

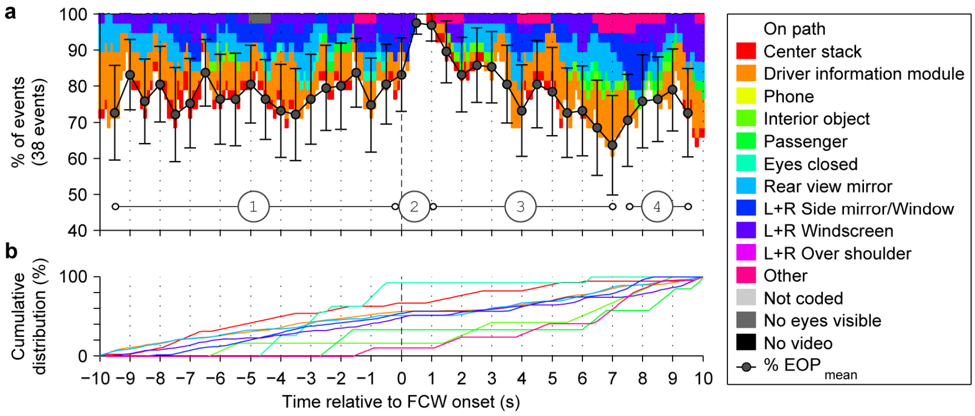

Figure 4. Proportion (a) and cumulative distributions (b) of the glance location over time for the random FCW (frontal collision warning) events. The events are centered at the FCW onset. Numbered circles in (a) indicate the identified intervals described in the text: (1) Steady state driving, (2) Threat, (3) Post-threat, (4) (Back to) steady state driving. The curve %EOPmean shows the mean percentage of eyes on path. The error bars indicate the 95% confidence interval.

the end of the steady state driving interval to 97.4% (significant: Friedman test, $\chi^2(2) = 13.23$, $p < .01$; Wilcoxon post-hoc, $z = 2.68$, $p < .05$, $r = 0.31$). This interval may be defined as the threat interval.

3. In the 1 s – 7 s interval the %EOPmean decreased to 63.7%, a level that was significantly lower than the end of the steady state driving interval (Friedman test, $\chi^2(2) = 13.23$, $p < .01$; Wilcoxon post-hoc, $z = 2.05$, $p < .05$, $r = 0.24$). This interval may be defined as the post-threat interval.
4. At the end, in the 7.5 s – 9.5 s interval, the %EOPmean rose to an average value of 74.8%. This interval may be defined as the (back to) steady state driving interval.

3.2 Glance eccentricity

3.2.1 Rear-end FCW events

Figure 5a shows the glance history in terms of eccentricity level, time-centered at the FCW onset for the rear-end FCW events. In the 20 s interval, among the glances away from the forward path, the glances at low eccentricity accounted for 54.1%, whereas the ones at medium and high eccentricity accounted for 27.6% and 17.8%, respectively. The view of the forward path was thus mostly contained within the near-peripheral visual region (i.e., eccentricity within 30°).

In addition to the results described section 3.1.1, it is worth noting that:

- The average percentage of glances at high eccentricity, in the steady state driving and threat anticipation intervals, had a value of 5.1%, which is greater than the average value of 2.7% in the post-threat and (back to) steady state driving intervals. On the other hand, the opposite held for the glances at medium eccentricity, with an average value of 3.3% before the threat interval and 9.0% after. These results are also evident in the cumulative distributions in Figure 5b, which show that the distributions for the glances at high and medium eccentricity were skewed towards the first and second half of the events, respectively.
- The steady increase in %EOPmean during the threat anticipation interval was primarily a consequence of the steady decrease of glances at low eccentricity, from 8.7% to 0.2% (Figure 5d). Similarly, the steady decrease in %EOPmean during the post-threat interval was mainly a consequence of the steady increase of glances at low eccentricity, from 3.2% to 26.2%.
- The median of the distribution of the POV brake onset times across all the events corresponded to the beginning of the threat anticipation interval. The whiskers extended into the 4 s interval before the FCW onset. Three events were not coded because the POV brake lights did not turn on or were not visible in the video.

3.2.2 Random FCW events

Figure 6a shows the glance history in terms of eccentricity level, centered at the FCW onset, for the random FCW events. In the 20 s interval, among the glances away from the forward path, the glances at low eccentricity accounted for 49.4%, whereas the ones at medium and high eccentricity accounted for 38.6% and 12%, respectively. As in the rear-end events, the view of the forward path was then mostly contained within the near peripheral region. The cumulative distributions of the glances at low and medium eccentricity steadily increased over time, whereas that of the high-eccentricity glances was slightly skewed towards the end of the events (Figure 6b).

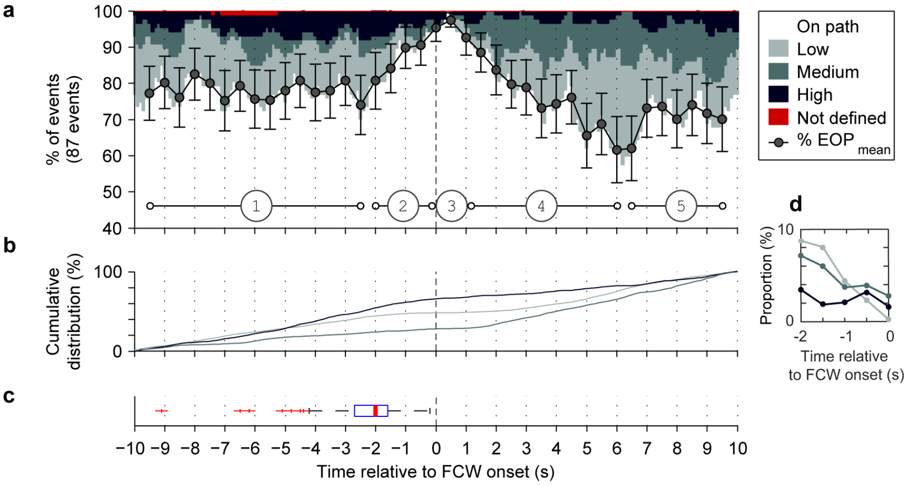

Figure 5. Proportion (a) and cumulative distributions (b) of the glance eccentricity over time, and box plot of the POV (principal other vehicle) brake onset times (c) for the rear-end FCW (frontal collision warning) events. The events are centered at the FCW onset. Numbered circles in (a) indicate the identified intervals described in the text: (1) Steady state driving, (2) Threat anticipation, (3) Threat, (4) Post-threat, (5) (Back to) steady state driving. The curve %EOPmean shows the mean percentage of eyes on path. The error bars indicate the 95% confidence interval. In (d) is displayed the proportion of low, medium, and high glance eccentricity over time in the threat anticipation interval.

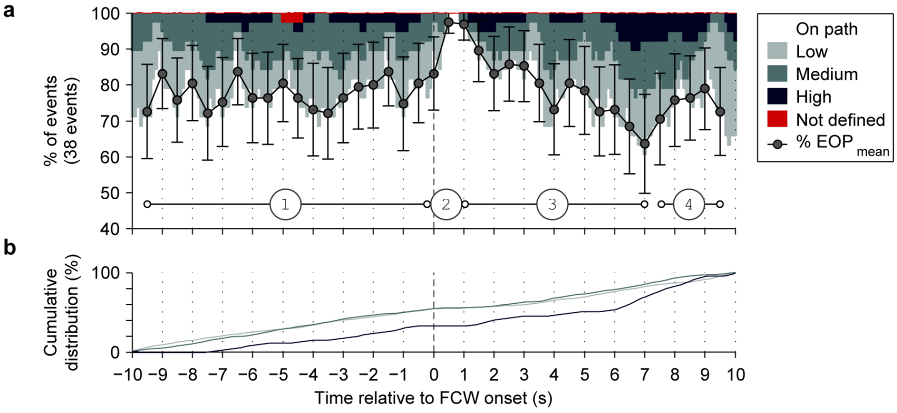

Figure 6. Proportion (a) and cumulative distributions (b) of the glance eccentricity over time for the random FCW (frontal collision warning) events. The events are centered at the FCW onset. Numbered circles in (a) indicate the identified intervals described in the text: (1) Steady state driving, (2) Threat, (3) Post-threat, (4) (Back to) steady state driving. The curve %EOPmean shows the mean percentage of eyes on path. The error bars indicate the 95% confidence interval.

3.3 Vehicle dynamics

3.3.1 Rear-end FCW events

Figure 7 shows the %EOPmean curve (and the intervals described in section 3.1.1), aligned with the curves of the selected vehicle measures and centered at the FCW onset. In general, the speed and the range to the POV monotonically decreased, with one inflection point after the FCW onset. The range rate had a global minimum of -5.76 m/s at 0.5 s. The longitudinal acceleration had a similar result, but the global minimum of -3.48 m/s^2 was at 1 s. The TTC^{-1} and the brake pressure had a global maximum at 1 s, with values of 0.285 s^{-1} and 29.16%, respectively. The THW behaved differently; it had a global minimum at 1 s with a value of 1.30 s, and at the end of the post-threat interval there was a noticeable increase in both mean value (4.84 s) and 95 CI as a result of the variable driving conditions. During the (back to) steady state driving interval, THW decreased again. Table 1 reports the values at the interval ends, and the average value in the interval. Note that in the steady state driving interval the vehicle measures were slowly changing over time, as would be expected in car-following, whereas noticeable changes happened between the threat-anticipation and post-threat intervals. At the beginning of the threat-anticipation interval (i.e. at the boundary between intervals 1 and 2 in Figure 7) the value of the longitudinal acceleration was about -0.20 m/s^2, which is in accordance with the detection threshold found in (Lee et al., 2007). Finally, in the (back to) steady state driving interval, the measures became stable again.

3.3.2 Random FCW events

Due to the absence of a POV, the analysis of vehicle measures such as range, range rate, TTC^{-1}, and THW is not relevant in these events. The longitudinal acceleration was negligible and braking was never applied. As a consequence, the speed was steady at around 86 km/h, a value higher than the one found in section 3.3.1, yet still comparable (Figure 8).

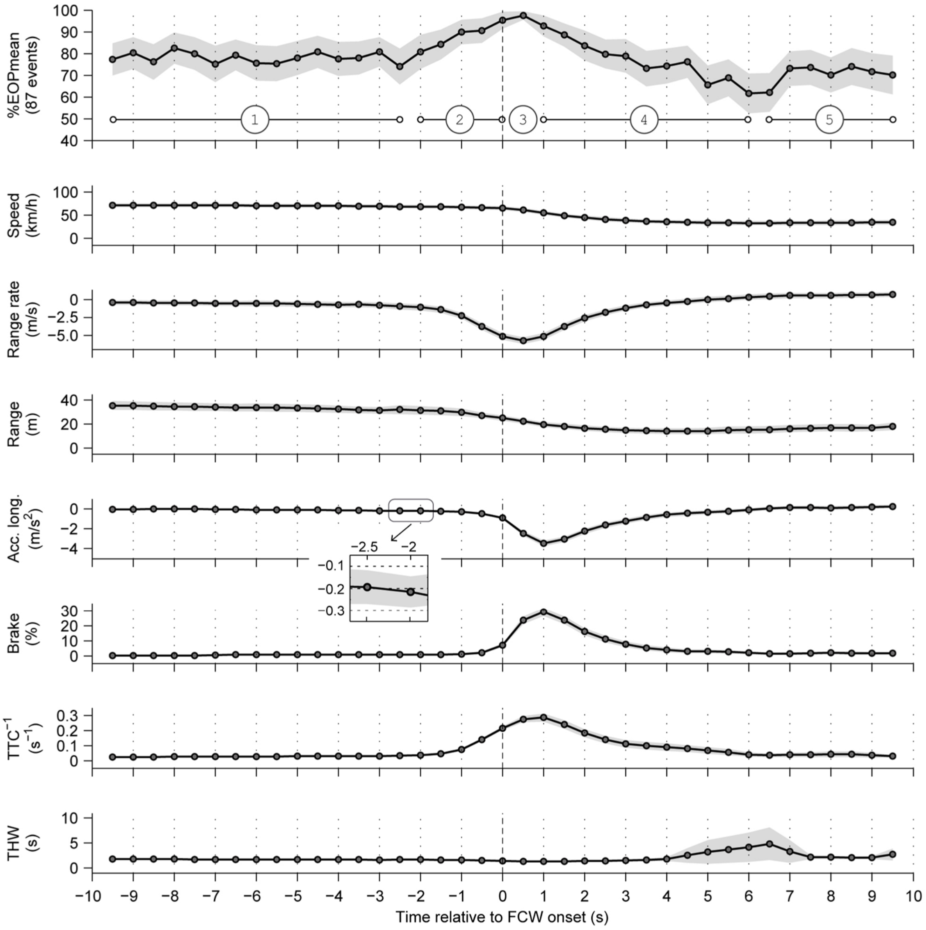

Figure 7. Comparison of %EOPmean (mean percentage of eyes on path) to several vehicle measures for the rear-end FCW (frontal collision warning) events. The events are centered at the FCW onset. The gray area is the 95% confidence interval. Numbered circles indicate the identified intervals described in the text: (1) Steady state driving, (2) Threat anticipation, (3) Threat, (4) Post-threat, (5) (Back to) steady state driving.

Table 1. Summary of the values of the vehicle measures for the rear-end FCW (frontal collision warning) events in the identified intervals described in the text. The events are centered at the FCW onset. The values are reported in the format [*start, end*] (*mean*).

		Interval				
Measure	**Unit**	**1 Steady state driving**	**2 Threat anticipation**	**3 Threat**	**4 Post-threat**	**5 (Back to) steady state driving**
Speed	km/h	[71.73, 68.92] (70.72)	[68.49, 65.03] (67.08)	[61.25]	[55.14, 33.06] (39.70)	[33.06, 34.65] (33.76)
Acceleration	m/s^2	[-0.06, -0.19] (-0.10)	[-0.22, -0.93] (-0.44)	[2.49]	[-3.48, 0.13] (1.30)	[0.05, 0.23] (0.13)
Brake pressure	%	[0.29, 0.70] (0.55)	[0.67, 7.11] (2.35)	[23.48]	[29.16, 1.92] (9.72)	[1.30, 1.64] (1.64)
Range	m	[35.55, 32.16] (33.61)	[31.54, 24.94] (28.89)	[22.43]	[19.66, 15.23] (15.60)	[15.43, 17.88] (16.66)
Range rate	m/s	[-0.44, -0.97] (-0.60)	[-1.10, -5.14] (-2.73)	[-5.76]	[-5.12, 0.31] (-1.41)	[0.44, 0.71] (0.58)
TTC^{-1}	s^{-1}	[0.02, 0.03] (0.03)	[0.04, 0.21] (0.10)	[0.27]	[0.28, 0.04] (0.13)	[0.04, 0.03] (0.04)
THW	s	[1.78, 1.68] (1.71)	[1.66, 1.40] (1.56)	[1.33]	[1.30, 4.17] (2.18)	[4.84, 2.69] (2.75)

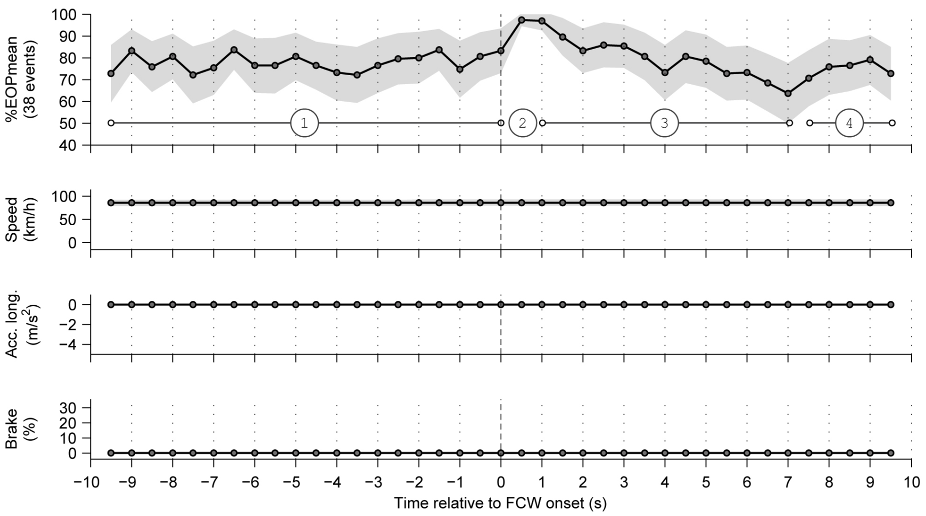

Figure 8. Comparison of %EOPmean (mean percentage of eyes on path) to the vehicle measures for the random FCW (frontal collision warning) events. The gray area is the 95% confidence interval. Numbered circles indicate the identified intervals described in the text: (1) Steady state driving, (2) Threat anticipation, (3) Threat, (4) Post-threat, (5) back to steady state driving.

3.4 Optical variables

Note that there were no optical variables for the random FCW events due to the absence of a POV. For rear-end FCW events, Figure 9 shows. For the rear-end FCW events, Figure 9 shows the %EOPmean curve (and the intervals described in section 3.1.1) aligned with the curves of the optical measures associated with the POV, centered at the FCW onset. In general, we can see that θ steadily increased up to the post-threat interval from 0.062 to 0.202 rad, whereas in the (back to) steady state driving interval it slightly decreased. The variables $\dot{\theta}$ and τ^{-1} had the global maximum at 1 s, with a value of 0.035 rad/s and 0.284 s^{-1}, respectively.

Looking at Table 2, one can note that the variables in the steady state driving interval are slowly changing, and a noticeable change occurs between the threat-anticipation and post-threat intervals. In the threat-anticipation interval, the variable $\dot{\theta}$ crossed the threshold for detecting the looming of the POV when looking on path (of about 0.0036–0.0038 rad/s; see gray area in Table B.1) between -2 s and -1.5 s. The threshold for detecting the looming at low eccentricity (of about 0.0058–0.0067 rad/s) was crossed at about -1 s. At the end of the events, i.e. in the (back to) steady state driving intervals, the variables began to settle down.

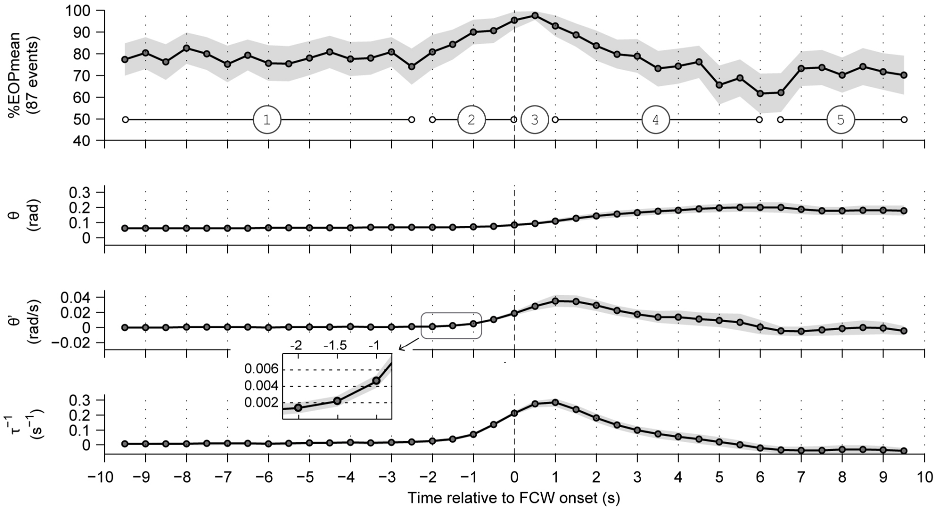

Figure 9. Comparison of %EOPmean (mean percentage of eyes on path) to the optical measures for the rear-end FCW (frontal collision warning) events. The events are centered at the FCW onset. The gray area is the 95% confidence interval. Numbered circles indicate the identified intervals described in the text. (1) Steady state driving, (2) Threat anticipation, (3) Threat, (4) Post-threat, (5) (Back to) steady state driving.

Table 2. Summary of the values of the optical variables for the rear-end FCW (frontal collision warning) events in the identified intervals described in the text. The events are centered at the FCW onset. The values are reported in the format *[start, end] (mean)*.

		Interval				
Measure	**Unit**	**1 Steady state driving**	**2 Threat anticipation**	**3 Threat**	**4 Post-threat**	**5 (Back to) steady state driving**
θ	rad	[0.062, 0.067] (0.064)	[0.068, 0.083] (0.073)	[0.094]	[0.110, 0.202] (0.168)	[0.201, 0.179] (0.183)
$\dot{\theta}$	rad/s	[0.000, 0.001] (0.000)	[0.001, 0.019] (0.007)	[0.028]	[0.035, 0.001] (0.018)	[-0.005, -0.004] (-0.003)
τ^{-1}	s^{-1}	[0.007, 0.022] (0.012)	[0.027, 0.214] (0.097)	[0.275]	[0.284, -0.020] (0.101)	[-0.034, -0.041] (-0.035)

4 DISCUSSION

This study used data from the naturalistic database EuroFOT (Kessler et al., 2012) to analyze drivers' visual behavior in potential critical situations while driving with ACC. The critical events were selected anytime a FCW (true positive and false positive) was issued while the ACC was active. The visual behavior was examined with respect to two manually-coded metrics, glance location and glance eccentricity, together with other measures based upon several recorded CAN signals.

4.1 Visual behavior with respect to the identified intervals

4.1.1 Steady state driving interval: glance behavior

The mean percentage of eyes on path (%EOPmean) with ACC in the steady state driving interval, in both rear-end and random FCW events, is in accordance with the results in (Tivesten et al., 2015). This study found that the attention to the forward path with ACC was lower than without (~77% mean eyes on path with ACC, compared to ~85% for manual driving). The use of ACC might have reduced the driving task demand, which in turn affected visual attention allocation. While diverting attention away from the forward path could lead to severe consequences, two distinctions must be made: (a) whether the driver's glances off path are driving-related or not, and (b) whether eye behavior is described as 'eyes off path' or 'eyes off threat'. With regard to the former, the results in sections 3.1.1–3.1.2 show that most of the glances off path were driving-related (e.g. towards the driver information module, L+R windscreen, rear-view mirror) thus signifying that attention is actually directed towards the driving task. Concerning the latter, discriminating between glances off path and glances off threat is important, taking also into account the benefit of the benefit of the ACC in reducing the risk exposure by maintaining a safe speed and headway, as mentioned in the introduction. The threat anticipation response suggests that drivers direct the eyes off path when there is no impending critical situation, but that they are ready to redirect their visual attention towards a traffic-related threat when needed.

4.1.2 Threat anticipation interval: what did drivers respond to?

In accordance with the findings in (Tivesten et al., 2015), Figure 3a shows that drivers anticipated the impending critical situations by directing their eyes to the forward roadway before a situation became critical (that is, before the FCW onset). In line with the literature review presented in the introduction, the results in this study show that there might be three exogenous cues for attracting drivers' attention: deceleration, looming, and brake light cue. The relevance of these cues is corroborated by the analysis of the random FCW events, which demonstrated that the anticipatory response was absent when the cues were absent.

Deceleration cue

Figure 7 shows that the increase in %EOPmean in the rear-end FCW events started when the average deceleration of the vehicle in the events was about 0.20 m/s^2, which is in accordance with the detection threshold found in (Lee et al., 2007). This threshold was crossed between -2.5 s and -2 s, at the beginning of the threat-anticipation interval. This mild deceleration might have been the effect of either the throttle release or the brake onset by the ACC. This cue might have informed the drivers of the approaching phase to a POV, making them look at the road. This behavior seems to be in line with the subjective data collected by Fancher et al. (1998), which indicates that drivers perceived the ACC-induced deceleration as a cue to look ahead because of an arising headway conflict.

Looming cue

Figure 5a shows that the steady decrease of glances towards low eccentricity locations was the main contributor to the steady increase in %EOPmean in the rear-end FCW events. The glances at medium and, in particular, at high eccentricity locations were less influenced, up until the onset of the FCW. When using the detection threshold for the optical variable $\dot{\theta}$ (because, unlike τ^{-1}, this variable is less sensitive to the different experimental setup, as shown in Appendix B), the threshold for detecting the closure of the POV at low eccentricity was approximately at -1 s, which is 1 s later than the onset of the deceleration cue. This finding suggests that the deceleration cue is more effective than the looming stimulus (in the drivers' peripheral vision) at redirecting visual attention towards the forward path, since the former is detected sooner. However, once the glance is on the forward roadway, drivers might rely on the looming stimulus to perceive the imminent threat. Thus the driver keeps looking at the road, without diverting attention away, when the looming is detectable. In other words, the looming threshold value was initially crossed when looking at the forward path at the beginning of the threat anticipation interval (i.e., between -2 s and -1.5 s); thereafter the glance continued to be on path (for example, as an effect of the deceleration cue) because the looming of the lead vehicle was above threshold. Note that the looming threshold reference values summarized in the introduction and in Table B.1 were gathered from studies that were carried out with alert drivers in favorable conditions on an empty road (Lamble et al., 1999; Summala et al., 1998). In contrast, looming detection may be more difficult in real-world driving, due to cluttered driving scenes (e.g. in congested traffic) and less favorable weather and lighting conditions (Victor et al., 2015).

Brake light cue

Figure 5c shows that the beginning of the steady state driving interval corresponded to the median of the distribution of the POV brake light onset times across the events. This correspondence suggests that brake light onset may be influencing drivers to look at the road. However, as pointed out in the introduction, previous studies have yielded conflicting results. It is difficult to assess from our results whether the brake lights increase the drivers' visual attention to the forward path. The majority of events in this study (~87%) occurred in daylight and clear weather (see Table A.3), which reduced the saliency of the brake light stimulus; Summala et al. (1998) found that detection was significantly impaired in the visual periphery, even at a low level of eccentricity. This suggests that the brake lights might not be intense enough to capture the driver's attention in daylight and clear weather circumstances when the driver isn't looking directly ahead. However, in adverse conditions and for night driving, the brake lights might be more easily detected at the periphery and they could have played a primary role in the detection of lead vehicle looming (Janssen, 1974). However, note that even if the brake light stimulus is salient enough it still would not necessarily be the cue that causes a brake reaction or inhibits an off-road glance, as argued by Victor et al. (2015) and Markkula et al. (2016).

4.1.3 Threat interval: how did drivers respond?

Figure 5a shows that the onset of the FCW redirected the glances at medium and, in particular, at high eccentricity locations. However, as a consequence of the threat anticipation, the %EOPmean was already 95.4% at the onset of the FCW. Interestingly, the random FCW events clearly showed a rapid orienting effect of the FCW (Figure 4 and Figure 6). These results suggest that the FCW was effective at making the drivers glance at the forward path, but the absence of a threat allowed drivers to quickly divert their attention again.

4.1.4 Post-threat interval: what did drivers do after the response?

Figure 3 shows that drivers started to divert visual attention away from the forward path just after the onset of the FCW. The increase of glances towards the rear-view mirror was particularly noticeable from 1 s after the FCW onset. This behavior might be interpreted as an improvement of situation awareness (e.g. checking if the driver vehicle was about to be struck by a following one). In the end of the post-threat interval one can notice a large proportion of glances towards the driver information module. This behavior might be the consequence of the drivers' controlling the ACC settings or re-engaging the system. Although less noticeable, the post-threat interval was also found in the random FCW (Figure 4). It could be argued that the increased frequency of glances to the driver information module and other types of glances indicate enhanced situation awareness: for example, drivers may look towards the driver information module to search the settings for the cause of the warning, and towards other areas to check for the presence of objects in front of the car.

4.2 Outstanding question

Why did the drivers receive a FCW even when they were already looking at the forward path and anticipated the threat? Here we propose to answer this question in terms of trust, expectancy, and satisficing behavior.

Trust

Trust can be defined as "the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability" (Lee & See, 2004, p. 54). In this regard, the driver would have waited until the last second, i.e. the FCW onset, before deciding to intervene and override the ACC, for example by manually braking, as suggested in (Rudin-Brown & Parker, 2004). Larsson et al. (2014) argue that an increased brake reaction time during ACC control is not necessarily a disadvantage of the system; experienced drivers clearly trust the ACC to perform its task appropriately, so they only intervene at the last second.

Expectancy

Expectancy is the subjective prediction, associated with a degree of uncertainty, about how a specific situation will develop, based on previous experience and contextual information (Engström et al., 2013; Sanders, 1966). Expectancy largely regulates the driver's behavior in steady state driving (Engström et al., 2013). If the need for a response is expected to disappear, drivers might delay their response (Summala, 2000). For example, the drivers could have waited to proactively brake because they did not expect the slowing leading car to suddenly brake, or they expected it to start accelerating again. When the FCW was issued and the drivers detected that the situation didn't develop as expected, they acted in order to recover the safety margins.

Satisficing behavior

Satisficing behavior is the behavior supported by the notion of acceptable, rather than optimal, performance (Boer, 1999). In normal driving drivers tend to satisfice to remain within a subjective comfort zone whose boundaries are primarily determined by safety margins (Summala, 2007). Additionally, the comfort zone's boundary may be stretched by extra motives (Summala, 2007), from which the driver could gain a benefit that justifies the cost of getting closer to the discomfort zone. For example, drivers may decide to wait until the last moment before pressing the brake pedal, thus decreasing the following distance (cost), in order to avoid disengaging, and having to reengage, the ACC (benefit).

4.3 Limitations

Naturalistic studies have some limitations intrinsic to their design, such as lack of experimental control of participants, scenarios, and vehicle systems. These same considerations should be taken into account in interpreting these results. Video data reduction (such as eye glance behavior) was conducted by the primary author. Inter-rater reliability was not established.

5 CONCLUSION

This study corroborates and extends the results from (Tivesten et al., 2015) and proposes an explanation for drivers' reactions to potential critical situations, identified as FCW onsets while ACC is active. The findings indicate that vestibular/somatosensory and visual cues (i.e., deceleration, looming, and lead vehicle brake lights) attract the drivers' attention to the forward road before the onset of the FCW. This explanation is further supported by the absence of an anticipatory response in the random FCW events, in which these three cues were absent.

It is argued that the deceleration cue might be the predominant cue for triggering glances towards the forward roadway before a longitudinal threat develops into a conflict. (If this argument is correct, simulator experiments could, whenever possible, exploit moving base motion cues to re-engage the drivers when an intervention is required in critical situations.) Once the driver's attention has been captured, the looming cue (together with the brake light cue) is probably the main stimulus maintaining the driver attention to the forward path, providing more information about an impending conflict and supporting the driver's response.

The findings provide evidence of two kind of driver responses, to a warning and to a threat. The response to a warning is characterized by a quick (but temporary) reorientation to the forward path, whereas the response to a threat is characterized by a slower, longer-lasting increase of glances on-path. The former behavior is particularly noticeable in the random FCW events.

The random FCW events clearly show that, when there is a warning without an external threat (and visual and deceleration cues are not provided), there is no anticipatory response. These events show that the FCW alone acts as an effective attention-orienting mechanism. In contrast, in rear-end FCW events, the FCW was effective at re-orienting the glances that were further away from the forward roadway (i.e., at medium and high levels of eccentricity).

This study also showed that the time-course of visual behavior in critical situations can be divided into intervals with different glance characteristics according to the driving situation. The identified intervals were defined as steady state driving, threat-anticipation, threat, post-threat and (back to) steady state driving. These contextually defined intervals are essential for understanding the attention response process.

This work is also of interest for automated driving research, because it provides additional information about drivers' perception of the driving situation and shows how important visual and vestibular/somatosensory cues can be for alerting drivers to critical situations, and for starting planning a proper avoidance action. Furthermore, these results are relevant for the design of higher levels of automation, specifically when re-engaging the driver if the system automation capabilities are exceeded. The results from this study suggest that it is important to design a vehicle that can communicate system limitations through actuation and to develop a warning strategy that incorporates knowledge of driver glance responses to safety systems.

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APPENDIX A. CODING SCHEMA

Table A.1 Coding scheme for the glance location. The coding was adapted from (Victor et al., 2015, p. 24)

Color code	Glance location*	Description
○	On path	Any glance directed toward the direction of the vehicle's travel. When the vehicle is turning, these glances may be directed toward the vehicle's heading.
●	Center stack	Any glance to the vehicle's vertical center stack.
●	Driver information module	Any glance to the driver information module (e.g., speedometer, control stalks, and steering wheel).
●	Phone	Any glance at a cell phone or other electronic communications device, no matter where it is located.
●	Interior object	Any glance to an identifiable object in the vehicle (e.g., personal items, the cup-holder area between passenger seat and driver seat)
●	Passenger	Any glance to a passenger, whether in front or rear seat. Context will be needed (e.g., they're talking or passing something) in some situations.
●	Eyes closed	Any time that both participant's eyes are closed outside of normal blinking (e.g., the subject is falling asleep or rubbing eyes).
●	Other	Any glance that cannot be categorized using the above codes (e.g., the driver looks straight up at the sky as if watching a plane fly by, the driver looks at the bonnet, the driver is tilting his or her head back to drink and the eyes leave the forward glance but do not really focus on anything at all...).
●	Rear-view mirror	Any glance to the rearview mirror.
●	L+R Side mirror L+R Window	Any glance to the left or right side mirror or window.
●	L+R windscreen	Any glance out the forward windshield when the driver appears to be looking out the windshield but clearly not in the direction of travel (e.g., at road signs or buildings)
●	L+R over shoulder	Any glance over either of the participant's shoulders. In general, this will require the eyes to pass the B-pillar. If over the left shoulder, the eyes may not be visible, but this glance location can be inferred from context.
●	No eyes visible	Glance location unknown: Unable to complete glance analysis due to an inability to see the driver's eyes/face (due to obstruction or glare).
●	No video	Unable to complete glance analysis because the video source is temporarily unavailable.
●	Not coded	Time-series data for which glance annotation was not performed.

Table A.2 Coding scheme for the glance eccentricity.

Color code	Eccentricity level	Average angle	Area of interest
○	On path	Between 0° and 10°	On path
●	Low	Between 10° and 30°	L windscreen R windscreen Driver information module
●	Medium	Between 30° and 60°	L side mirror L window Rear-view mirror Center stack
●	High	Above 60°	R side mirror R window L over shoulder R over shoulder Interior object Passenger Phone Other Eyes closed
●	Not defined	Not defined	Eyes not visible No video Not coded

Table A.3 Summary of the annotations of the environmental variables.

		Number of events	
Variable	**Category**	**Rear-end FCW (total of 87 events)**	**Random FCW (total of 38 events)**
Lightening	Daylight	71	12
	Darkness lighted	12	8
	Darkness unlighted	2	8
	Artificial darkness (e.g. tunnel)	2	10
Weather condition	No adverse condition	80	37
	Mist/Light rain	3	1
	Rain	4	0
Road geometry	Straight road	80	31
	Curve	7	7

APPENDIX B. COMPILATION OF RELATED STUDIES ON THE LOOMING DETECTION THRESHOLD

Table B.1 presents a compilation of related research on the threshold for detecting the looming of a lead vehicle as a function of glance eccentricity. Summala et al. (1998) and Lamble et al. (1999) performed test track studies in which the participants were asked to detect the lead vehicle closure while performing a visual secondary task. The visual secondary task forced the participants to look away from the forward pathway at increasing degrees of eccentricity. The methodologies in the two papers were similar except for (a) different experimental conditions (lead vehicle deceleration, following speed, range and degrees of eccentricity) and (b) different measures presented in the results. Summala et al. (1998) provided the detection threshold in terms of τ^{-1}, whereas Lamble et al. (1999) provided the results in terms of $\dot{\theta}$ and TTC. To facilitate the comparison, we integrated and merged the results.

The results in (Summala et al., 1998) were integrated by computing the detection threshold in terms of $\dot{\theta}$. The car-following scenario used in the study was simulated by implementing a MATLAB-based script, and the values of $\dot{\theta}$ at detection were calculated via the equations in section 2.5. (Please note that only the data at 60 km/h were used since the ACC in the present study was not active at speeds below 30 km/h.) The results in (Lamble et al., 1999) were integrated by approximating TTC with τ^{-1} (Lee, 1976). (Please note that the data at 4° were excluded as suggested by the authors in (Lamble et al., 1999).)

Subsequently, the looming detection thresholds at eccentricities of 0°, 30°, 60° and 90° were predicted via linear regression. Moreover, the results obtained under varying experimental conditions (i.e., range and following speed) were merged, to obtain an average reference value for $\dot{\theta}$ and τ^{-1} (gray area in Table B.1).

Table B.1 Compilation of related results from test track studies on the visual perceptual threshold in terms of $\dot{\theta}$ and τ^{-1}. The detection threshold, as a function of glance eccentricity, was predicted via regression at 0°, 30°, 60°, and 90°. The gray area indicates the analysis over the merged data provided by the studies.

Study	Variable	Predicted threshold as a function of glance eccentricity		Notes
Summala et al. (1998)				Test track study. Lead vehicle (1.62m wide) braking at ~-2.1m/s^2 with brake lights deactivated. Clear weather. Participants were requested to brake as soon as they noticed the lead vehicle approaching.
				Range = 30m, speed = 60km/h
		0.0051	@0°	
	$\dot{\theta}$	0.0073	@30°	$\dot{\theta} = 0.0050781 + 0.00007445 \cdot x°$
	[rad/s]	0.0095	@60°	$R^2 = 0.94$
		0.0118	@90°	
		0.0939	@0°	
	τ^{-1}	0.1348	@30°	$\tau^{-1} = 0.093899 + 0.0013646 \cdot x°$
	[s^{-1}]	0.1758	@60°	$R^2 = 0.93$
		0.2167	@90°	
				Range = 60m, speed = 60km/h
		0.0022	@0°	
	$\dot{\theta}$	0.0043	@30°	$\dot{\theta} = 0.0022014 + 0.000069697 \cdot x°$
		0.0064	@60°	$R^2 = 0.94$
		0.0085	@90°	
		0.0815	@0°	
	τ^{-1}	0.1569	@30°	$\tau^{-1} = 0.081462 + 0.0025156 \cdot x°$
		0.2324	@60°	$R^2 = 0.93$
		0.3079	@90°	
				Range = 30–60m, speed = 60km/h
		0.0036	@0°	
	$\dot{\theta}$	0.0058	@30°	$\dot{\theta} = 0.0036397 + 0.000072073 \cdot x°$
		0.0080	@60°	$R^2 = 0.42$
		0.0101	@90°	
		0.0877	@0°	
	τ^{-1}	0.1459	@30°	$\tau^{-1} = 0.08768 + 0.0019401 \cdot x°$
		0.2041	@60°	$R^2 = 0.83$
		0.2623	@90°	
Lamble et al. (1999)				Test track study. Lead vehicle (1.62m wide) coasting at ~-0.7m/s^2. Clear weather. Participants were requested to brake as soon as they noticed the lead vehicle approaching.
				Range = 20m, speed = 50km/h
		0.0038	@0°	
	$\dot{\theta}$	0.0072	@30°	$\dot{\theta} = 0.0038459 + 0.0001116 \cdot x°$
		0.0105	@60°	$R^2 = 0.85$
		0.0139	@90°	
		0.2357	@0°	
	τ^{-1}	0.2569	@30°	$\tau^{-1} = 0.23567 + 0.00070727 \cdot x°$
		0.2781	@60°	$R^2 = 0.79$ ***
		0.2993	@90°	
				Range = 40m, speed = 50km/h
		0.0031	@0°	
	$\dot{\theta}$	0.0062	@30°	$\dot{\theta} = 0.0031146 + 0.0001014 \cdot x°$
		0.0092	@60°	$R^2 = 0.79$
		0.0122	@90°	
		0.1955	@0°	
	τ^{-1}	0.2327	@30°	$\tau^{-1} = 0.1955 + 0.0012402 \cdot x°$
		0.2699	@60°	$R^2 = 0.73$ ***
		0.3071	@90°	
				Range = 20–40m, speed = 50km/h
		0.0036	@0°	
	$\dot{\theta}$	0.0067	@30°	$\dot{\theta} = 0.003635 + 0.00010376 \cdot x°$
		0.0099	@60°	$R^2 = 0.80$
		0.0130	@90°	
		0.2171	@0°	
	τ^{-1}	0.2455	@30°	$\tau^{-1} = 0.21708 + 0.00094742 \cdot x°$
		0.2739	@60°	$R^2 = 0.62$
		0.3023	@90°	