On-to-off-path gaze shift cancellations lead to gaze concentration in cognitively loaded car drivers: A simulator study exploring gaze patterns in

Citation for the original published paper (version of record):
Nilsson, E., Victor, T., Ljung Aust, M. et al (2020). On-to-off-path gaze shift cancellations lead to gaze concentration in cognitively loaded car
drivers: A simulator study exploring gaze patterns in relation to a cognitive task and the
traffic environment. Transportation Research Part F: Traffic Psychology and Behaviour, 75: 1-15.
http://dx.doi.org/10.1016/j.trf.2020.09.013

Transportation Research Part F 75 (2020) 1–15

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

On-to-off-path gaze shift cancellations lead to gaze concentration in cognitively loaded car drivers: A simulator study exploring gaze patterns in relation to a cognitive task and the traffic environment

Emma J. Nilsson [a,b,*], Trent Victor [a,b], Mikael Ljung Aust [a], Bo Svanberg [a], Per Lindén [a], Pär Gustavsson [a]

[a] Volvo Cars Safety Centre, Volvo Car Corporation, Göteborg, Sweden
[b] Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Göteborg, Sweden

ARTICLE INFO

Article history:
Received 12 February 2020
Received in revised form 11 September 2020
Accepted 12 September 2020

Keywords:
Driver distraction
Traffic safety
Visual behavior
Gaze concentration
Glance timing
Intersections

ABSTRACT

Appropriate visual behaviour is necessary for safe driving. Many previous studies have found that when performing non-visual cognitive tasks, drivers typically display an increased amount of on-path glances, along with a deteriorated visual scanning pattern towards potential hazards at locations outside their future travel path (off-path locations). This is often referred to as a gaze concentration effect. However, what has not been explored is more precisely how and when gaze concentration arises in relation to the cognitive task, and to what extent the timing of glances towards traffic-situation relevant off-path locations is affected. To investigate these specific topics, a driving simulator study was carried out. Car drivers' visual behaviour during execution of a cognitive task (n-back) was studied during two traffic scenarios; one when driving through an intersection and one when passing a hidden exit. Aside from the expected gaze concentration effect, several novel findings that may explain this effect were observed. It was found that gaze shifts from an on-path to an off-path location were inhibited during increased cognitive load. However, gaze shifts in the other direction, that is, from an off-path to an on-path location, remained unaffected. This resulted in on-path glances increasing in duration, while off-path glances decreased in number. Furthermore, the inhibited off-path glances were typically not compensated for later. That is, off-path glances were cancelled, not delayed. This was the case both in relation to the cognitive task (near-term) and the traffic environment (far-term). There was thus a general reduction in the number of glances towards situationally relevant off-path locations, but the timing of the remaining glances was unaffected. These findings provide a deeper understanding of the mechanism behind gaze concentration and can contribute to both understanding and prediction of safety relevant effects of cognitive load in car drivers.

* Corresponding author at: Volvo Car Corporation, Volvo Cars Safety Centre, Dept., 91450 PV22, SE-405 31 Göteborg, Sweden.
E-mail address: emma.j.nilsson@volvocars.com (E.J. Nilsson).

https://doi.org/10.1016/j.trf.2020.09.013
1369-8478/© 2020 The Authors. Published by Elsevier Ltd.

1. Introduction

Car driving is a largely visual task. It can be described as a form of continuous adaptation to the traffic environment based on visual information. Maintaining a glance behaviour appropriate for the current traffic situation, where areas with important information are appropriately scanned, is thus crucial for safe driving.

In naturalistic tasks, such as driving, gaze patterns are determined both by bottom-up mechanisms such as objects' size, colour, luminance and movement, as well as by top-down mechanisms, or expectations (Itti & Koch, 2001; Wickens, 2015). Most of the time, the eyes are proactive (expectation driven) and gaze leads action (Land, 2006). Timing wise, guiding fixations lead the ongoing action by about one second, while occasional look-ahead-fixations appear to anticipate later actions and target objects or locations further into the future (Land, 2006; Mennie, Hayhoe, & Sullivan, 2007).

When driving in simple environments such as on rural roads with little other traffic, vision is primarily needed for lane keeping and path planning. The gaze is then most of the time fixated on a target point, or a waypoint (a point on the road ahead), defined by where the vehicle will be 1–2 s into the future, with occasional look-ahead-fixations to target points on the road further into the future (Lappi, 2013; Esko Lehtonen, Lappi, Kotkanen, & Summala, 2013).

In more complex environments, such as urban environments and intersections, vision is needed also for keeping track of relevant objects in the traffic environment, such as other road users and traffic signs. Since our vision has high acuity in the foveated (fixated) area only, drivers need to move their gaze between the future vehicle path and other relevant objects in the environment. A very clear example of this is given by Land (2006), where visual time sharing is displayed when a driver passed a bicyclist while driving through a curve. The driver's gaze was shifted back and forth between the future path in the curve and the cyclist in a multitasking fashion.

In intersections, drivers typically have a wider spread of gaze compared to non-intersection driving, that is, they look around more. Where the eyes are fixated largely depend on the traffic situation in terms of, for example, traffic density (Werneke & Vollrath, 2012), having right of way or needing to yield (Lemonnier, Désiré, Brémond, & Baccino, 2020), presence of traffic lights (G. Li et al., 2019), direction of travel (G. Li et al., 2019; Romoser, Pollatsek, Fisher, & Williams, 2013) and situational-relevant objects in the environment (Werneke & Vollrath, 2012). Also, factors such as age (Romoser et al., 2013), experience (Land, 2006) and individual glancing style (G. Li et al., 2019) have an influence.

During execution of cognitively loading secondary tasks (from here on referred to as cognitive tasks), car drivers' gaze behaviour changes so that they look more towards the future path. This has been shown repeatedly in studies on highways and other larger roads (Hammel, Fisher, & Pradhan, 2002; Niezgoda, Tarnowski, Kruszewski, & Kamiński, 2015; Recarte & Nunes, 2000, 2003; Reimer, 2009; Reimer, Mehler, Dobres, & Coughlin, 2013; Reimer, Mehler, Wang, & Coughlin, 2012; Victor, Harbluk, & Engström, 2005; Wang, Reimer, Dobres, & Mehler, 2014). While different measures have been used (e.g. total off-road glance time, percent road center, either in relation to fixed coordinates or the participant's most frequent gaze angle, and standard deviation of gaze positions along the horizontal or vertical axis, or a combination of the two, using data from fixations, glances, or raw eye tracking data) they all demonstrate the same effect: more glance time towards a smaller area that lies on the vehicle's path along the road ahead (for comparisons, see Victor et al., 2005; Wang et al., 2014). This is often referred to as the gaze concentration effect under cognitive load.

Gaze concentration is usually viewed as a stable effect under cognitive load (in comparison to other effects, see Engström, Markkula, Victor, & Merat, 2017). However, a recent study by Desmet and Diependaele (2019) showed a wider spatial gaze distribution when participants were engaged in a handsfree cell phone conversation on a highway with low traffic density. Thus, there is a need to further study which factors influence gaze concentration.

Why drivers performing cognitive tasks display a gaze concentration effect is not yet well understood. It has been suggested that it reflects drivers giving higher priority to the most safety relevant area, that is, the future path (Recarte & Nunes, 2000, 2003). Since highways and larger roads are the type of environments where the most safety relevant information is typically on the future path (i.e. both the information needed for lane keeping and path planning as well as information on objects on an immediate collision course), not many glances towards off-path locations are needed over time for safe driving. Gaze concentration in these environments could therefore actually improve traffic safety and this has been suggested as a way to explain the decreased risk of rear-end collisions during cell phone conversations found in naturalistic data (Victor et al., 2015). It should be noted that although lane keeping typically improves during increased cognitive load (Engström et al., 2017), increased gaze concentration does not seem to be the reason for this effect, at least not on its own (Cooper, Medeiros-Ward, & Strayer, 2013; P. Li, Markkula, Li, & Merat, 2018).

In more complex traffic environments with more safety relevant information in off-path locations, a different visual scanning behaviour with timely glances tied to specific off-path locations is needed. Still, studies in such environments have also displayed an increased gaze concentration under cognitive load, with a decreased number of glances towards situationally relevant places. In simulator studies, drivers have been found to fail to glance towards potential hazards in the traffic environment more often when performing cognitive tasks (Ebadi, Fisher, & Roberts, 2019), as well as failing to look in the rear view mirrors before lane changes in work zones (Muttart, Fisher, Knodler, & Pollatsek, 2007). In on-road studies, cognitively loaded drivers have been found to make fewer glances towards traffic lights and towards the right at intersections in city driving (Harbluk, Noy, Trbovich, & Eizenman, 2007), as well as towards the right and left at crosswalks and intersections in suburban driving (Biondi, Turrill, Coleman, Cooper, & Strayer, 2015; Strayer et al., 2015). Lehtonen, Lappi, and Summala (2012) also found that drivers performing a cognitive task had fewer glances towards the occlusion point (the point after a curve where the road first disappears behind e.g. vegetation and where oncoming vehicles and other potential threats are first visible) on a rural road. This deterioration in scanning of safety relevant areas for cognitively loaded drivers in complex traffic environments is likely to be detrimental to traffic safety.

In summary, cognitive tasks have repeatedly and consistently been shown to cause a gaze concentration effect in car drivers. The drivers exhibit an increased glance time towards the road ahead and fewer glances towards off-path locations, regardless of which traffic environment they are in. However, most studies up to date have only analyzed the effects over larger driving segments and not considered time-bound effects on gaze patterns.

The current study therefore aims to expand existing knowledge on gaze concentration by exploring the relationship between cognitive tasks and gaze concentration on a high-resolution time scale. In particular, how and when gaze concentration arises in relation to fluctuations in cognitive load will be studied, as will the effects of cognitive load on timing of glances towards situationally relevant off-path locations. A deeper understanding of these relationships would give a better understanding of the mechanisms underlying gaze concentration, which is needed to better predict and prevent negative effects of cognitive load in car drivers.

This study used a high fidelity driving simulator to investigate how car drivers' visual scanning behaviour in two different simulated traffic environments was affected by the execution of cognitive tasks. We chose to study an intersection scenario and a hidden exit scenario, both in a rural setting. These traffic environments require glances towards off-path locations in order to detect potential conflicts with the own vehicle's future path. Based on previous research, we expected to see a gaze concentration effect with fewer glances towards the potential threats in off-path locations and more glance time towards the road ahead. We also explored the gaze concentration effect on a high-resolution time scale in relation to both the traffic environment and the variations in cognitive load caused by the cognitive tasks. Additionally, we considered the consistency of the gaze concentration effect within and between individuals.

2. Method

Data was collected in the driving simulator at the Swedish National Road and Transport Research Institute (VTI) in Linköping, Sweden. The experiment was approved by the regional ethical vetting board (Regionala etikprövningsnämnden) in Linköping.

2.1. Participants

Thirty-six participants were recruited from a random selection of the vehicle register over people living in the Linköping area. We aimed to limit the between-subject variance in participants' physiological and behavioural responses and subjective experiences by controlling for potential confounders (physiological data was recorded, but to answer a separate research question, and they will thus be reported in a separate manuscript). The participants were therefore all men, had an age ranging from 35 to 50 years ($M = 44$, $SD = 4$), a BMI below 30 and considered themselves not to have extreme traits in terms of morningness, eveningness, introversion, extroversion and stress sensitivity. They did not have health issues and could refrain from nicotine for at least three hours. They drove on average between 75 and 1200 km/week ($M = 388$, $SD = 243$), were not professional drivers and had held a driver's license for between 15 and 32 years ($M = 25$, $SD = 5$). All had normal hearing and normal, or with contact lenses corrected to normal, vision. All participants were paid 1500 SEK for their participation.

2.2. Apparatus

The experiments were carried out in an advanced moving base driving simulator. The car body consisted of the front part of a SAAB 9–3 with automatic transmission, mounted on a cradle allowing for four degree of freedom movement. The field of vision was 120 degrees and three LCD displays were used to simulate rear-view mirrors.

Eye movement data were gathered with SensoMotoric Instuments (SMI) eye tracking glasses at 60 Hz and with an accuracy of 0.5 degrees. Physiological data, namely electrocardiography (ECG), electrooculography (EOG), electroencephalography (EEG), electromyography (EMG), skin conductance (SC) and respiratory inductance plethysmography (RIP) were also recorded.

2.3. Cognitive load task

The cognitively loading task was an auditory-nonverbal version of the n-back task. A number between zero and nine was orally presented to the participants every other second. The participants were instructed to press a button mounted on their right index finger against the steering wheel when the number most recently presented was the same as the number presented n numbers ago. The task was used at the 1-back and 2-back levels, see Fig. 1. The participants were instructed to respond as fast and accurately as possible. All number series were unique, consisting of 30 numbers, including six target numbers. It is well-established that increasing n-back levels cause increasing levels of cognitive load (Jaeggi, Buschkuehl, Perrig, & Meier, 2010). The fixed pace of number presentations also induce a cyclic cognitive load pattern, allowing for analyses on gaze behaviour in relation to the different phases of the task.

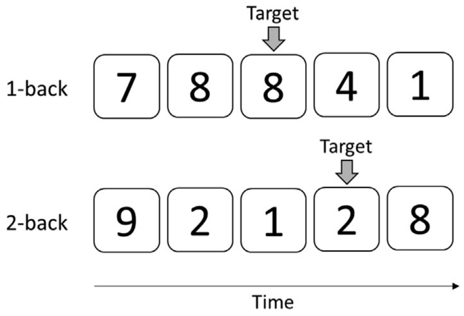

Fig. 1. Illustration of the simple 1-back task (top) and difficult 2-back task (bottom).

2.4. Driving scenarios

The simulated driving environment consisted of a two lane rural road with a speed limit of 80 km/h. The participants were told to follow the road towards the town Målilla. Occasional traffic signs indicated remaining distance to Målilla. The drive lasted for approximately 40 min. There was some oncoming traffic and other vehicles occasionally overtook the participant's car.

Two different traffic scenarios (measurement scenarios) recurred four times each during the drive. The first scenario was a hidden exit scenario (see Fig. 2a). It consisted of a sharp right turn with a high hedge along the inner curve. Before the curve there was a warning sign for the hidden exit, then the hedge on the right side, and then the exit. There was no vehicle at the exit, nor any other traffic in the scenario. The second scenario was an intersection scenario (see Fig. 2b). After a slight right turn the driver approached a four-way intersection, in which the participant had right of way and the crossing roads had yield signs. Another car approached the intersection from the right. The car became visible for the participant as it drove past a house when the participant was 180 m from the intersection. The other car came to a stop at the intersection 2 s before the participant reached the intersection. There was also a bus in the oncoming lane, passing the participant's car 70 m before the intersection. While passing the hidden exit scenario and the intersection scenario, the drivers were once engaged in the 1-back task, twice in the 2-back task, and once in no task besides driving. The tasks started approximately 45 s before the participants reached the hidden exit or intersection. The order of the tasks were counterbalanced across participants.

In-between the measurement scenarios there were two more hidden exits with a car standing still at the exit with indicators on. There were also two additional four-way intersections with a car approaching from the left, and two four-way

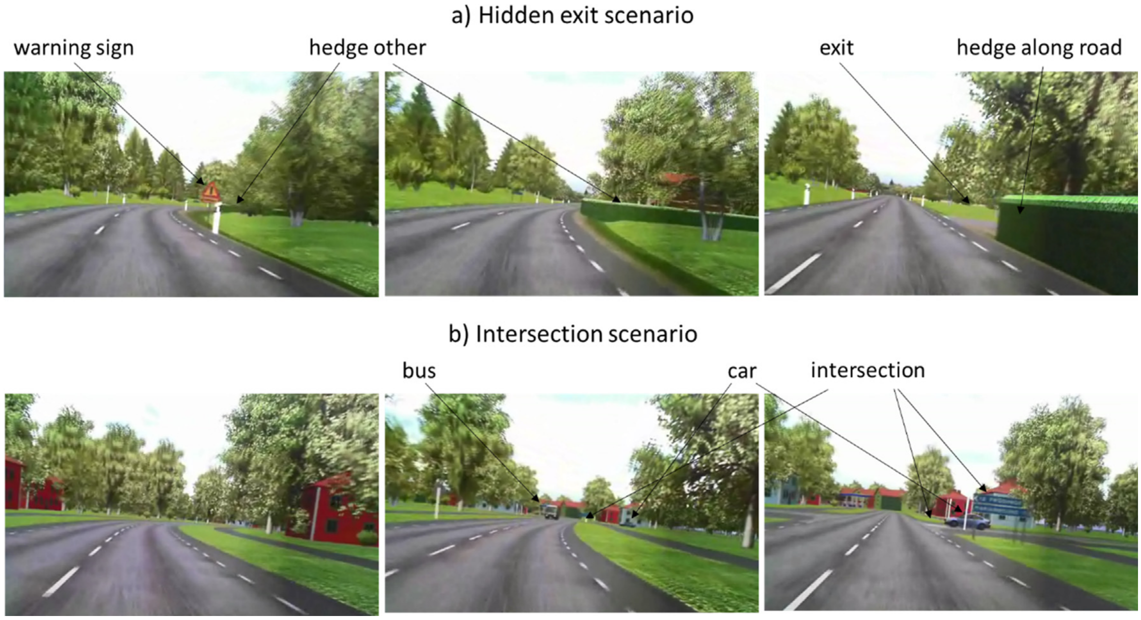

Fig. 2. Moments from when the participants approached the two measurement scenarios; the hidden exit scenario (a) and the intersection scenario (b). Arrows point out areas of interest (AOIs, described in Section 2.6) in off-path locations. Images are blurry due to poor camera resolution (the participants experienced them in high resolution in the driving simulator).

intersections with no other traffic. These scenarios were there to create variation in order to reduce any learning effects in the measurement scenarios. Also, the participants performed the 2-back task at two other occasions, outside the measurement scenarios.

2.5. Procedure

Participants were sent a written description of the study prior to participating, where it was stated that the purpose of the study was to investigate physiological effects of secondary task execution during driving. It was not mentioned that their behaviour would be studied in specific traffic scenarios, in order not to unintentionally affect their glance or driving behaviour there. They were asked to abstain from alcohol for 72 h before the trial, and nicotine and caffeine for 1 h before the trial. They were also sent a background questionnaire which they handed in when arriving at the laboratory. On arrival, the study setup and purpose was once again explained and they gave their written consent. Next, they were equipped with the physiological monitoring equipment and taken to the simulator where the physiological equipment was connected and the eye tracker was calibrated.

The participants then practiced both the 1-back task and the 2-back task in the simulator in parked mode. They were allowed to practice the tasks until they felt comfortable in executing them.

After being informed about the simulator, participants did a practice drive for approximately 10 min. The practice drive included 1 one-minute period of 1-back, and 2 one-minute periods of 2-back task execution. The practice drive also included one hidden exit scenario with a car standing still at the exit with its indicators on, and one four-way intersection scenario identical to the intersection-measurement scenario.

During practice, the participants were allowed to speak to the researchers. After the practice drive, the actual experiment of approximately 40 min of driving took place. During this time, participants were asked not to talk to the researchers unless it was urgent. After the drive, there was a debriefing session where open questions were answered and the participants filled out a questionnaire about their test experience. Participants' subjective experiences are out of the scope for this paper though and will not be further reported.

2.6. Data processing and analysis

Eye tracking data was analysed using SMI BeGaze. In the intersection scenario, gaze position was annotated from 50 m before the point where the car approaching the intersection from the right became visible to the participant, until the participant had passed the intersection. In the hidden exit scenario, gaze position was annotated from the position where the hidden exit warning sign became visible to the participant, until the participant had passed the hidden exit. All analyses were made over these time windows, from here on referred to as events.

Start and end times of fixations were automatically identified by SMI BeGaze, and the corresponding gaze positions were manually annotated in SMI BeGaze in accordance with a number of pre-defined areas of interest (AOIs), described in Table 1 and visualized in Fig. 2. The time between identified fixations were labelled No data. If the duration of a No data epoch was shorter than 300 ms, it was assumed to be an eye blink and/or a saccade (International Organization of Standardization, 2014). If the AOI before and after such No data epoch was the same, the No data epoch was given the same AOI as the surrounding fixations and was by that included in the ongoing glance. If the AOI before and after the No data epoch differed, it was given the AOI of the following fixation so that it was appended to the subsequent glance (in accordance with ISO150007-1:2014). Periods of No data that exceeded 300 ms were assumed to be due to loss of tracking and were kept as No data.

Sometimes the measurement precision was insufficient, such as for glances from a distance towards the AOIs Bus, Intersection and Path, or glances towards Hedge other, Hedge along road and Path when approaching and entering the curve. The annotator then looked at continuous glance sequences to detect patterns (such as gaze shifts towards and away from the road ahead) and determine each glance's gaze direction.

Data processing, figures and statistical analyses were done using MATLAB R2015b (with Statistics and Machine Learning Toolbox), except the speed analysis which was done in SAS Enterprise Guide 7.1.

3. Results

In the hidden exit scenario, the AOIs Exit and Hedge along road were merged in parts of the analysis because of the low number of data points (few glances) in the Exit category and because the two AOIs were sometimes hard to differentiate from each other during AOI annotation. Because glances towards the hedge along the road appear to be searching for the exit, both the Exit and the Hedge along road AOIs can be considered as glances towards the potential threat.

It was only possible to annotate gaze positions for 25 out of the 36 participants due to data loss and eye tracker signal quality issues.

Table 1
Descriptions of the areas of interest (AOIs) used in the gaze position annotation.

Scenario	AOI	Description
Intersection	No data	No fixation identified for >300 ms due to loss of tracking
	Path	Gaze directed towards the future path (i.e. the road ahead)
	Bus	Gaze directed towards the bus in the oncoming lane
	Intersection	Gaze directed towards the area where the crossing road connects to the right side of the main road (which the participant is on), including towards the signs at the intersection
	Car	Gaze directed towards the car approaching the intersection from the right
	Other	Gaze directed towards any other area
Hidden exit	No data	No fixation identified for >300 ms due to loss of tracking
	Path	Gaze directed towards the future path (i.e. the road ahead)
	Warning sign	Gaze directed towards the hidden exit warning sign before the curve
	Hedge along road	Gaze directed towards the hedge further along the road, as if the driver is looking for the hidden exit*
	Hedge other	Gaze directed towards any other area of the hedge*
	Exit	Gaze directed towards the exit
	Other	Gaze directed towards any other area

Note. *The annotator used his expert judgement to assess whether a glance towards the hedge appeared to be searching for the hidden exit (AOI Hedge along road) or was directed towards the hedge itself (AOI Hedge other).

3.1. Task performance

A *t*-test revealed that n-back response times were significantly shorter in the easier 1-back condition ($M = 0.76$, $SD = 0.31$) compared to the more difficult 2-back condition ($M = 1.01$, $SD = 0.40$), $t(176) = -4.16$, $p < .001$.

3.2. Gaze concentration

The proportion of the total event time that the glances belonged to each of the AOIs in each of the task conditions (No task, 1-back and 2-back) are presented in Table 2. Events with more than 10% No data were excluded from the analysis. The number of included events in each condition is also presented in Table 2. Recall that the drivers performed the No task and 1-back conditions once and the 2-back condition twice in each scenario.

The proportion of time in the off-path AOIs were not normally distributed and hence Kruskal-Wallis tests were used to look for significant ($p < .05$) effects of the tasks in each of the AOIs. In the intersection scenario, there was a significant effect of task in the AOIs Path ($H(2) = 13.24$, $p = .001$), Intersection ($H(2) = 6.90$, $p = .032$), Car ($H(2) = 11.05$, $p = .004$) and Bus ($H(2) = 8.85$, $p = .012$), but not in No data ($H(2) = 0.87$, $p = .65$) and Other ($H(2) = 1.72$, $p = .42$). In the hidden exit scenario, there was a significant effect of task in the AOIs Path ($H(2) = 11.13$, $p = .004$) and Other ($H(2) = 12.02$, $p = .003$), but not in No data ($H(2) = 0.0013$, $p = 1.00$), Warning sign ($H(2) = 2.96$, $p = .23$), Hedge other ($H(2) = 0.24$, $p = .89$) and Hedge along road and Exit

Table 2
Percent of the total time that the glances belonged to each of the AOIs in each of the task conditions.

Intersection scenario				Hidden exit scenario			
	No task	1-back	2-back		No task	1-back	2-back
Path	M = 49.7	M = 56.6	M = 66.4	Path	M = 64.7	M = 72.1	M = 76.5
	Md = 47.6^{A}	Md = 58.2	Md = 72.1^{A}		Md = 63.2^{A}	Md = 70.9	7Md = 80.2^{A}
	SD = 12.2	SD = 16.2	SD = 17.8		SD = 12.2	SD = 10.3	SD = 13.1
Car	M = 17.4	M = 11.7	M = 9.2	Exit and Hedge along road	M = 9.1	M = 6.8	M = 6.2
	Md = 14.6^{A}	Md = 9.8	Md = 8.3^{A}		Md = 9.2	Md = 5.2	Md = 5.1
	SD = 9.3	SD = 8.3	SD = 7.6		SD = 7.2	SD = 6.4	SD = 4.9
Bus	M = 9.9	M = 13.4	M = 8.0	Hedge other	M = 6.0	M = 5.2	M = 5.7
	Md = 10.5	Md = 10.3^{A}	Md = 6.2^{A}		Md = 5.8	Md = 3.9	Md = 6.1
	SD = 5.4	SD = 7.3	SD = 6.6		SD = 4.3	SD = 4.3	SD = 4.5
Intersection	M = 12.6	M = 8.0	M = 7.6	Warning sign	M = 5.4	M = 3.3	M = 3.7
	Md = 11.0^{A}	Md = 6.3	Md = 6.1^{A}		Md = 4.4	Md = 3.3	Md = 1.9
	SD = 8.1	SD = 8.0	SD = 7.5		SD = 5.2	SD = 3.2	SD = 5.3
Other	M = 8.9	M = 8.2	M = 7.2	Other	M = 13.2	M = 10.4	M = 6.2
	Md = 8.4	Md = 6.7	Md = 5.5		Md = 11.8^{A}	Md = 9.5	Md = 5.2^{A}
	SD = 6.0	SD = 4.1	SD = 5.2		SD = 8.3	SD = 7.2	SD = 5.4
No data	M = 1.5	M = 2.2	M = 1.6	No data	M = 1.7	M = 2.1	M = 1.7
	Md = 0	Md = 0	Md = 0		Md = 0	Md = 0	Md = 0
	SD = 2.9	SD = 3.1	SD = 2.6		SD = 2.4	SD = 3.2	SD = 2.5
Included events	22	21	38	Included events	19	18	35

M = mean, Md = median, SD = standard deviation. Medians that have a letter in common are significantly different from each other ($\alpha = 0.05$).

($H(2) = 2.01$, $p = .37$). Bonferroni corrected post hoc tests were conducted for those AOIs that had a significant effect of task. The results are reported in Table 2. The results confirm the expected gaze concentration effect with an increased on-path glance time.

3.3. Time course of gaze directions throughout the scenarios

The distributions of gaze directions throughout the scenarios are illustrated in Fig. 3, using the same events that were included in Table 2. The discrete, manually annotated, AOIs were interpolated into a continuous AOI signal with constant time steps for each event. The signal was then chunked in bins of 10 m of driving (corresponding to a duration of approximately 0.5 s) and the percentage of glance time belonging to each AOI was calculated for each bin. The derived values were

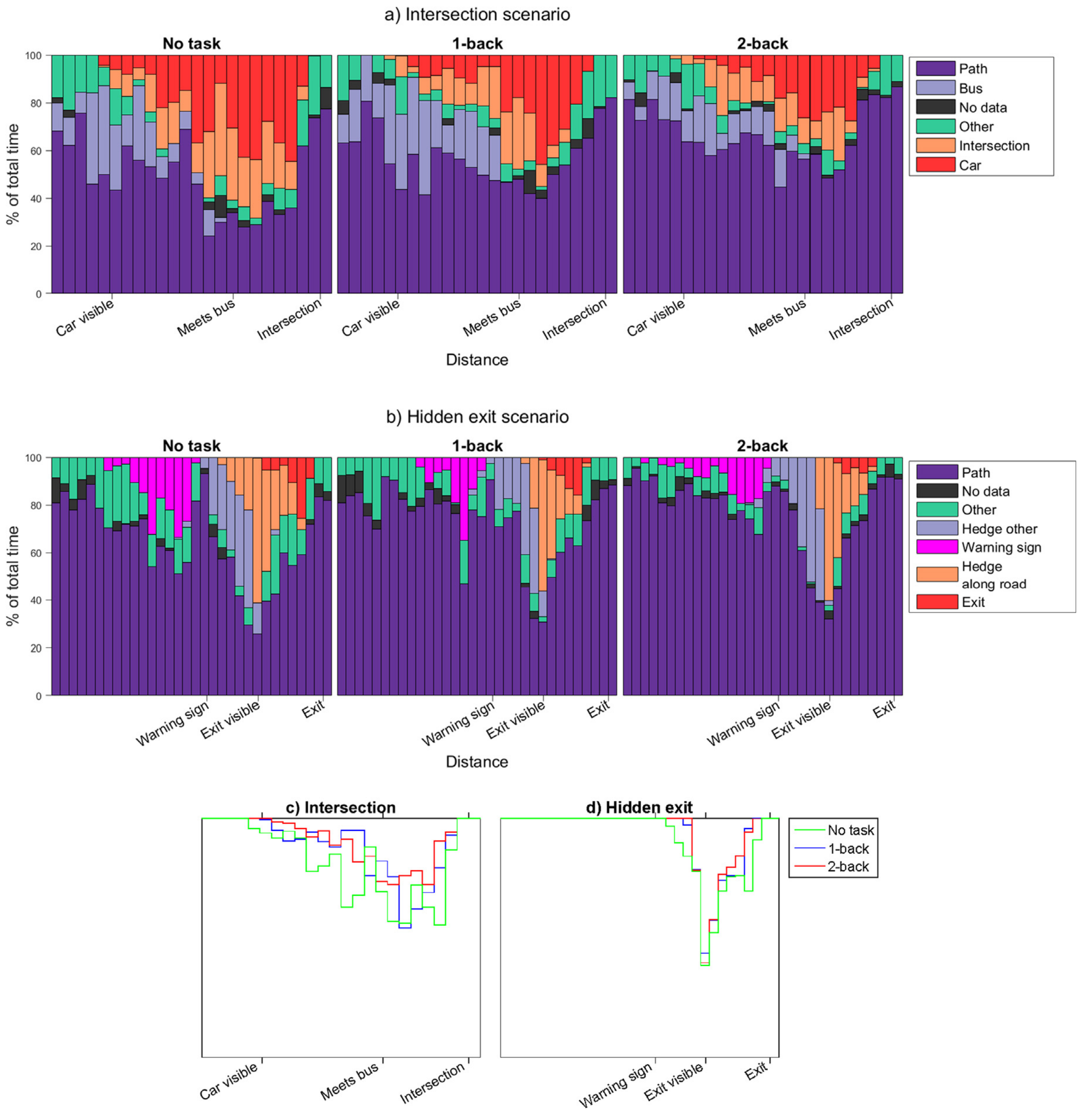

Fig. 3. Percentage of total time the glances belong to each of the AOIs for each task condition in the intersection scenario (a) and hidden exit scenario (b). Each bin represents a 10 m road section. In the intersection scenario, the car approaching the intersection from the right becomes visible to the participant at Car visible, the participant's car meets with the bus at Meets bus and passes the intersection at Intersection. In the hidden exit scenario, the participant's car passes the warning sign at Warning sign, the exit becomes visible to the participant at Exit visible and the participant's car passes the exit at Exit. At the bottom, the AOIs Car (c) and Hedge along road and Exit (d) are plotted for all three task conditions in the same figure. The curves are plotted at the same positions as in the stacked histograms for easier comparisons between figures and the y-axis is therefore not labeled.

then averaged across all the events. Each bin in Fig. 3 thus illustrates the percentage of the total time that the glances belong to each of the AOIs in a 10 m road section. For better comparisons of the effects of the cognitive tasks on the time course of the glances towards the potential threats (i.e. the AOI Car in the intersection scenario and the AOIs Hedge along road and Exit in the hidden exit scenario), the outlines of those AOIs are overlaid in Fig. 3c and d.

Fig. 3 clearly shows that the drivers adapted their glance behavior to the traffic environment. The proportion of on-path glances decreased when the drivers approached and passed the intersection and hidden exit and glances were instead directed towards relevant information in off-path locations. During increased cognitive load, the drivers still directed their gaze to the relevant off-path areas with similar timing in relation to the environment (see Fig. 3c and d). Statistical analyses have not been performed on individual bins, but as far as the limited data set allows, it seems that the entire curves in the loaded conditions have been ''shifted upwards''. In other words, there seems to be a similar reduction in the time the eyes are directed towards the potential threats throughout the scenarios. This is most prominent in the intersection scenario where the potential threat is visible over a longer period of time. Worth noticing is that this general reduction causes the first glances towards the potential threats to occur somewhat later.

3.4. Time course of gaze direction in relation to cognitive load

The proportion of on-path glances is plotted in relation to the cognitive task in Fig. 4. All events were split into two seconds segments (since there was two seconds between n-back number presentations), time locked to the start of the presentation of a new n-back number. In the No task condition, the start time of the first two second segment was set to the start of the event plus a random time between zero and two seconds to compensate for there being no n-back number to time lock it to. Segments containing No data were excluded from the analysis. The intersection and hidden exit scenarios were analyzed together in order to increase the number of segments. In total, there was 265 segments in the No task condition, 213 in 1-back and 440 in 2-back.

The larger proportion of on-path glances during the cognitive tasks (i.e. the gaze concentration effect) is clearly visible also in Fig. 4. It can also be seen that the proportion of on-path glances increased after number presentation and then decreased again to a level closer to the No task level. The decrease was steeper in the easier 1-back task than in the more difficult 2-back task. That is, the proportion of on-path glances was higher when the cognitive demand was higher due to new information that required cognitive work.

3.5. Gaze shifts

Next, it was explored whether the increased proportion of on-path glances after a number presentation was caused by more off-path glances shifting to an on-path direction, or by fewer on-path glances shifting to an off-path direction. We hence studied the time it took for glances that were on-path when the n-back number was presented (time interval 0 to 0.1 s) to shift to an off-path direction (any AOI other than Path), respectively how long it took for glances that were off-path when the n-back number was presented to shift to an on-path direction. Cumulative distributions of the time from number presentation to the first gaze direction shift are illustrated in Fig. 5, separated into segments starting with an on-path gaze direction respectively an off-path gaze direction.

Glances which had an off-path gaze direction at the time when a new n-back number was beginning to be read out (time 0 to 0.1 s) shifted to an on-path directions in roughly the same pace regardless of cognitive load, as can be seen in Fig. 5, right pane. In other words, the presentation of a new n-back number did not affect the off-to-on-path gaze shifts. Glances with an on-path gaze direction at the beginning of n-back number presentation were however more likely to remain on-path for a longer period of time before they shifted to an off-path gaze direction (seen in the flatter curves in 1-back and 2-back compared to No task in Fig. 5, left pane). For example, one second after an n-back number had started to be presented, 56% of the glances in the No task condition had changed (or started to change) from an on-path to an off-path direction. The same number for glances in the 1-back condition was 43% and in the 2-back condition 29%.

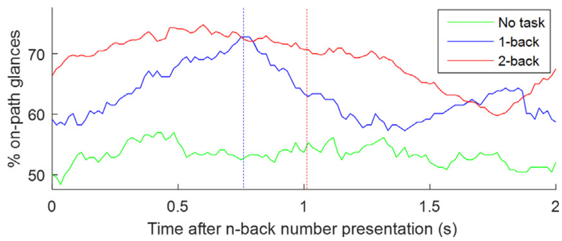

Fig. 4. Proportion of on-path glances in the time period from when an n-back number was starting to be read out to the participant (at 0 s) to when the next number was starting to be read out (at 2 s). No n-back numbers were presented in the No task condition. Vertical dashed lines mark average response times in 1-back (blue) and 2-back (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

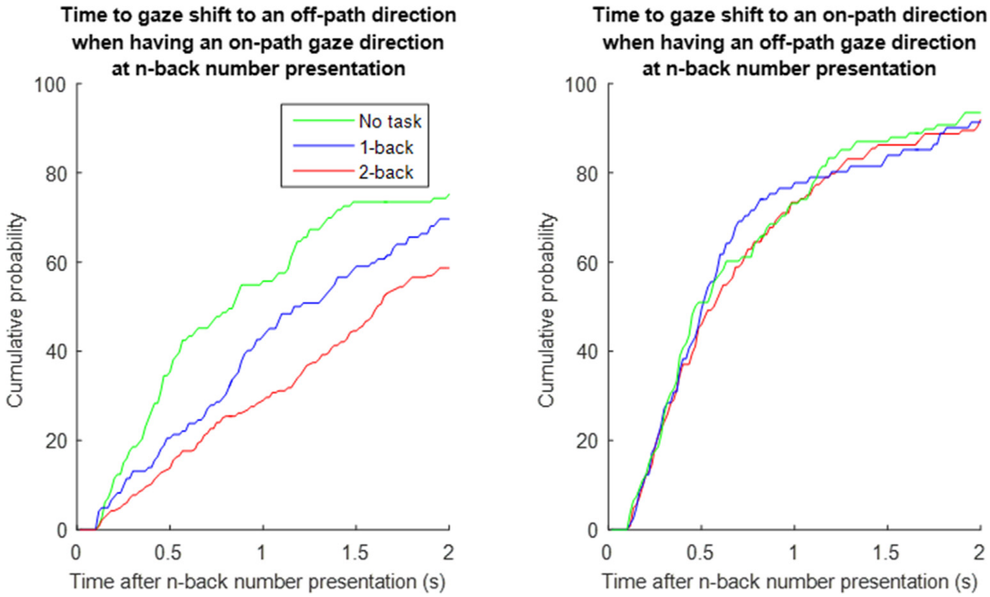

Fig. 5. Cumulative distributions of time to first gaze direction shift after n-back number presentation. To the left are all segments with an on-path glance in the time interval 0–0.1 s. The cumulative distribution shows the time it took until their gaze was first shifted towards an off-path direction. To the right are all segments with an off-path glance in the time interval 0–0.1 s, and the cumulative distribution of the time until their gaze was first shifted towards an on-path direction. A new n-back number was started to be orally presented at time 0 s, and the next n-back number at time 2 s. No n-back numbers were presented in the No task condition.

3.6. Glance durations

Glance durations were derived for all glances that did not have any adjacent No data period (since the glance duration could not be reliably assessed in such cases) and are plotted in Fig. 6. Events with more than 10% No data were excluded from the analysis. Because the glance durations were not normally distributed, differences in glance durations between the task conditions were tested for with Kruskal-Wallis tests for each AOI. The only significant effect ($p < .05$) that was found was in the AOI Path in the intersection scenario ($H(2) = 8.62$, $p = .013$). A Bonferroni corrected post hoc test revealed a significant difference between No task ($Md = 508$) and 2-back ($Md = 682$), but no significant difference between either of them compared to 1-back ($Md = 616$). Although the task conditions had longer average glance durations compared to the No task condition in the AOI Path in the hidden exit scenario too, the Kruskal-Wallis test failed to reach significance ($H(2) = 4.33$, $p = .12$). Worth noticing is that the skewness in the on-path glance duration distributions also increased in the task conditions compared to the No task conditions. That is, instead of a general increase in all on-path glance durations, only some of the on-path glances increased in duration. Also worth noticing is the longer on-path glance durations in the hidden exit scenario compared to the intersection scenario. This difference is likely due to the sharp curve in the hidden exit scenario, which increased the driving demand at an operational level (i.e. made the steering more demanding).

3.7. Number of glances towards potential threats

For each event, the number of glances towards the potential threat was derived, see Fig. 7. In the hidden exit scenario, both the number of glances towards the exit (middle pane) and towards either the exit or the hedge along the road (right pane) were included in the analysis. To reduce the risk of incorrect assessments of the number of glances towards the potential threats due to missing data (No data), events with more than 5% No data in the interval where such glances could occur were excluded. In the intersection scenario, this interval started where the car approaching the intersection from the right became visible and ended where the intersection was passed. In the hidden exit scenario, the interval started where the group as a whole had their first glance towards the hedge along the road and ended where the exit was passed.

A Kruskal-Wallis test showed a statistically significant effect of task on the number of glances towards the approaching car in the intersection scenario ($H(2) = 14.95$, $p < .001$). Bonferroni corrected post-hoc tests revealed that the No task condition was significantly different from both the 1-back and 2-back conditions, while those were not significantly different from each other. The Kruskal-Wallis tests just failed to reach significance in the hidden exit scenario, both when including only glances towards the exit ($H(2) = 5.95$, $p = .051$) and when including glances towards both the exit and the hedge along the road ($H(2) = 5.52$, $p = .063$).

In other words, the number of glances towards the potential threats decreased as cognitive load increased. Especially noteworthy is that the number of events in which the driver did not look towards the potential threat at any time during

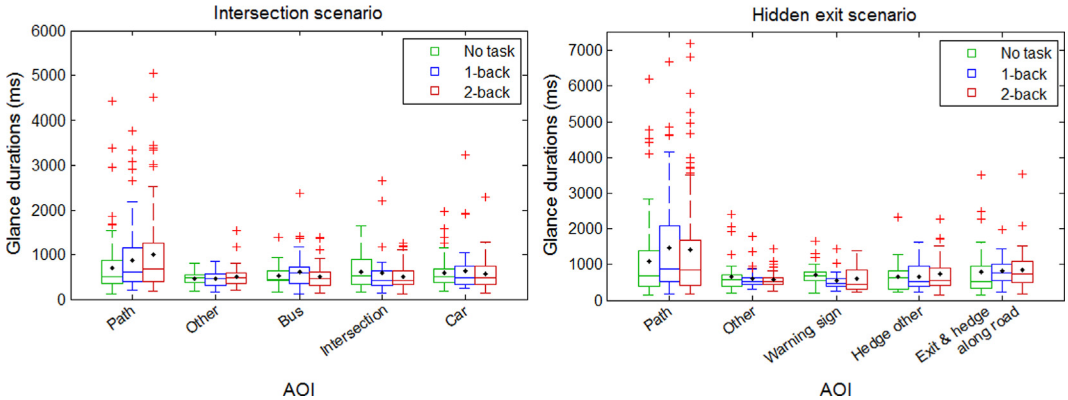

Fig. 6. Glance durations for each AOI and task condition. Mean values are plotted as black dots and outliers (values that are more than 1.5 times the interquartile range away from the top of the box) as red crosses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

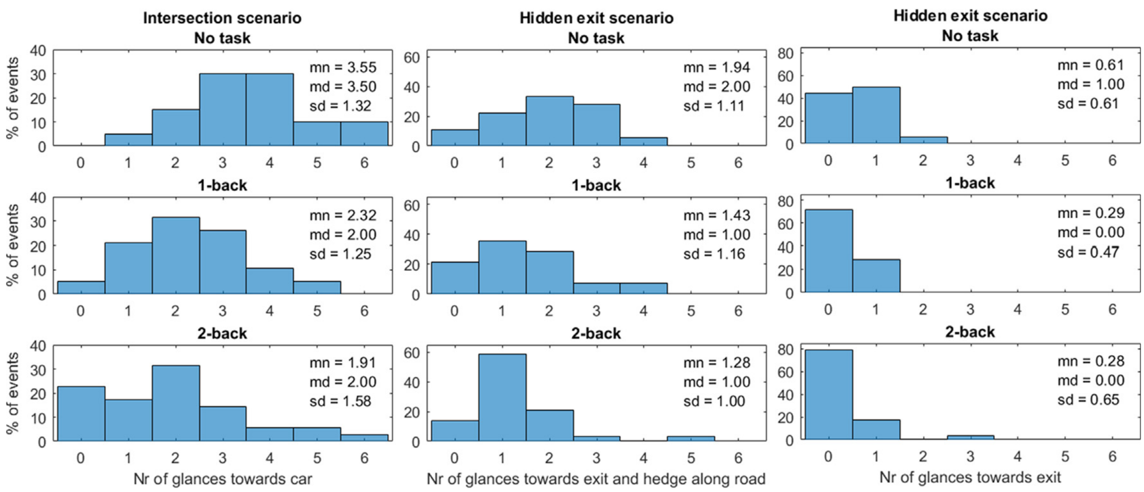

Fig. 7. Histograms of the proportion of events that had a certain number of glances towards the potential threat (numbers were between 0 and 6), split into scenario and task condition. In the hidden exit scenario, both glances towards the exit alone are used (right pane), and the sum of the glances towards the exit and the hedge along the road (middle pane). The mean (mn) and median (md) number of glances towards the potential threat, as well as the standard deviation (sd), are noted for each condition.

the scenario increased during cognitive load. In the intersection scenario, 0% of the events in the No task condition had no glances towards the approaching car, while approximately 5% of the events in the 1-back condition and more than 20% of the events in the 2-back condition had no glances at all towards the approaching car.

3.8. Individual differences

The consistency among the participants of having fewer glances towards the potential threats during cognitive load is illustrated in Fig. 8. For each participant, the number of glances towards the potential threat in the No task condition is plotted against the number of glances towards the potential threat in the 1-back respectively 2-back conditions. Data points above the grey diagonal have a higher number of glances towards the potential threat in the No task condition compared to the Task condition. The colours indicate the consistency of the pattern for that individual (explained in the Fig. 8 caption).

Especially in the intersection scenario, the large majority of the data points are above the diagonal, indicating a strong consistency among participants of having fewer glances towards the potential threat during cognitive load. The pattern is the same, although less strong, in the hidden exit scenario.

Simple linear regressions were calculated to predict the number of glances towards the threat in the task conditions based on the number of glances towards the threat in the No task condition. In the hidden exit scenario, regression analyses were made only on the data including glances towards both the exit and the hedge along the road, due to the low number of glances towards the exit alone. The regression equations for the 1-back conditions were significant in both the intersection

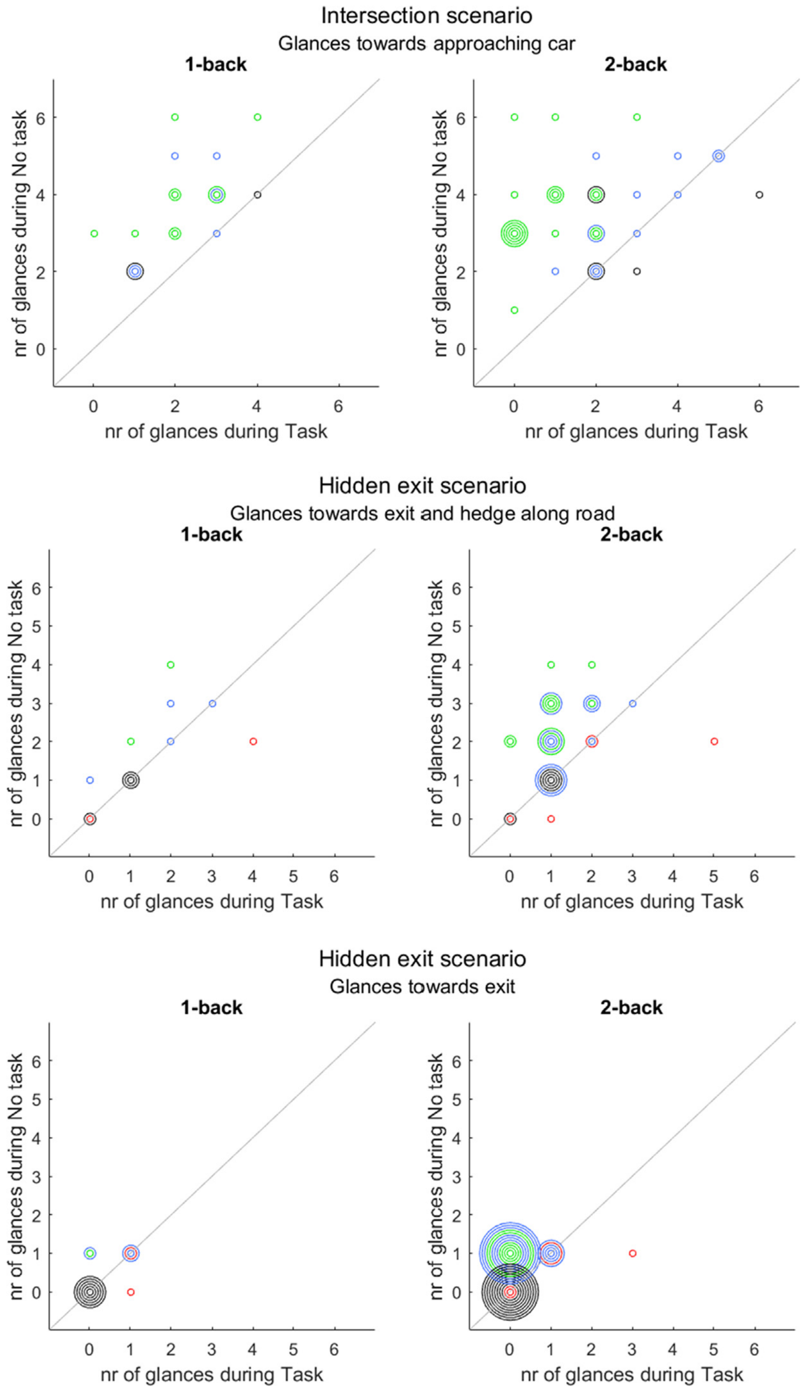

Fig. 8. The number of glances towards the potential threats in each task condition in comparison to the same participant's number of glances towards the potential threats in the No task condition. Green circles represent drivers that had more glances towards the potential threats in the No task condition than in any of the task conditions (all circles are above the diagonal). Black circles represent drivers that had either the same number of glances towards the potential threats in all task conditions as in the No task condition (all circles are on the diagonal), or that had both more and less glances towards the potential threats in the task conditions compared to the No task condition (circles are both above and below diagonal). Red circles represent drivers that had either more glances towards the potential threats in all task conditions compared to the No task condition (all circles are below diagonal), or that had both the same and more glances towards the potential threats in the task conditions compared to the No task condition (circles are both on and below diagonal). Blue circles represent drivers that had both the same and less glances towards the potential threats in the task conditions compared to the No task condition (circles both on and above diagonal). In the case where data points overlap, they are plotted in increasing size for visibility. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scenario ($F(1,16) = 9.18$, $p = .008$) and the hidden exit scenario ($F(1,10) = 9.33$, $p = .012$), with coefficients of determination, R^2, of 0.36 and 0.48, respectively. In the 2-back conditions, the regression equations just failed to reach significance in both the intersection scenario ($F(1,31) = 2.75$, $p = .11$) and the hidden exit scenario ($F(1,27) = 3.96$, $p = .06$), and the R^2 values were only 0.08 and 0.13, respectively. The number of glances towards the threat in the No task condition was hence a very poor predictor of the number of glances in the task conditions, especially in the 2-back condition.

3.9. Speed

The average vehicle speeds in the different task conditions were compared in order to acknowledge if the time available for glances towards the potential threats differed between conditions. The average vehicle speed in the intersection scenario was 71.8 km/h in the No task condition (SD = 4.4), 72.7 km/h in the 1-back condition (SD = 6.1) and 71.2 km/h in the 2-back condition (SD = 5.2). A mixed model ANOVA with test participant as random factor revealed no significant difference in vehicle speed between the task conditions. The average vehicle speed in the hidden exit scenario was 73.5 km/h in the No task condition (SD = 4.7), 73.4 km/h in the 1-back condition (SD = 5.6) and 74.2 km/h in the 2-back condition (SD = 5.9). Again, there was no significant difference in vehicle speed between the task conditions. The effects of the cognitive tasks on the visual behaviour are hence unlikely to be attributed to differences in vehicle speed.

4. Discussion

The present study explored effects of a cognitive task (n-back) on car drivers' visual scanning behaviour in two simulated traffic scenarios (an intersection and a hidden exit) in high temporal resolution. The aim was to better understand gaze concentration in terms of how and when it arises in relation to the cognitive task, as well as the effect of cognitive load on the timing of glances towards off-path locations relevant to the traffic-situation.

As expected, an increase in cognitive load led to a gaze concentration effect. That is, drivers spent more time looking towards the future path and less time looking towards off-path locations when performing cognitive tasks. This is in line with previous research (e.g. Harbluk et al., 2007; Recarte & Nunes, 2000, 2003; Reimer et al., 2012; Victor et al., 2005; Wang et al., 2014). The mechanism behind this gaze concentration effect could be seen when studying the visual behaviour in relation to the two seconds cyclic pattern of the cognitive task.

4.1. The mechanism behind gaze concentration

Cognitive load was found to have different effects on gaze shifts depending on whether the gaze was about to be shifted towards or away from the road ahead. While gaze shifts from an on-path to an off-path direction were inhibited by cognitive load, gaze shifts in the other direction, that is, from an off-path to an on-path direction, were unaffected. This resulted in an increased gaze concentration, as illustrated in Fig. 9.

When cognitive load was highest (i.e. the time when a new n-back number had been presented and had to be compared to the previously presented number(s) held in working memory to decide if it was a target or not), substantially fewer on-to-off-path gaze shifts were thus initiated and on-path glance durations increased. Because off-to-on-path gaze shifts were not inhibited by cognitive load, there was no effect on their durations.

A question that follows when seeing this effect is whether the on-to-off-path gaze shifts that were inhibited during n-back number presentation were delayed (i.e. shifted to the later part of the two seconds n-back cycle where the level of cognitive load temporarily decreased) or if they were cancelled. Had they been delayed, one would expect the proportion of on-path glances during either task to decrease below the No task condition level in that later part of the cycle. Since this did not occur (see Fig. 4), we deduce that the gaze shifts were cancelled rather than delayed.

In summary, the separate effects of cognitive load on on-to-off-path and off-to-on-path gaze shifts is what drives the gaze concentration effect, as illustrated in Fig. 9.

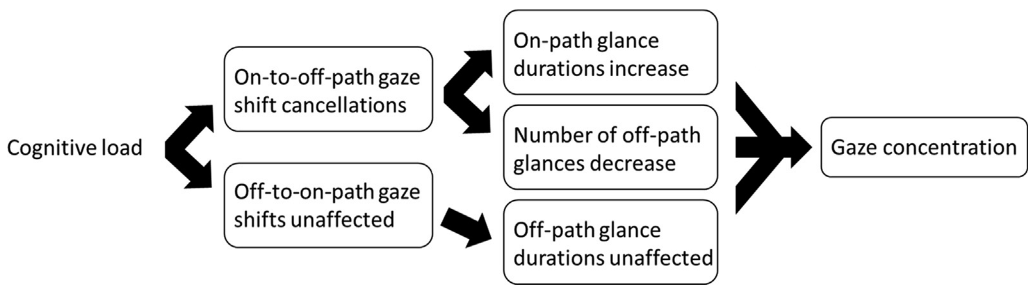

Fig. 9. Effects of cognitive load in car drivers causing gaze concentration.

4.2. Timing of glances in relation to the traffic environment

Cognitive load did not have an effect on the timing of glances in relation to the traffic environment. The time course plots in Fig. 3 show a similar visual adaptation to the traffic environment with and without cognitive load, and the relative timing of off-path glances remained the same. The only difference is that the cognitively loaded drivers had a general reduction in the proportion of time spent gazing towards potential threats. The off-path glances that never occurred due to a cancellation of an on-to-off-path gaze shift were thus generally not compensated for, neither within the two seconds cognitive load cycle of the cognitive task (as discussed earlier), nor within the larger time course of the full traffic scenario.

This is an interesting finding as it differs compared to the effect which cognitive load has on responses to artificial stimuli. These responses are so consistently delayed during increased cognitive load that the detection response task (DRT) has become an ISO standard for assessing cognitive load in car drivers (Conti, Dlugosch, Vilimek, Keinath, & Bengler, 2012; International Organization of Standardization, 2016; Stojmenova & Sodnik, 2018). Cognitive load thus have different effects on different mechanisms. While response times are delayed, on-to-off-path gaze shifts are not postponed, but rather cancelled. Gaze direction control in itself thus appears unaffected by cognitive load (since the drivers still glance towards the same off-path areas), while gaze shift initiations are instantaneous and transient and if missed, not compensated for. More research is however needed to find out if these observations persist.

4.3. Consistency in gaze concentration effect within and between participants

The general effect of drivers having fewer glances towards the potential threats during increased cognitive load was quite consistent among the participants and events (see Fig. 8). This is in line with (although not as consistent as) Ebadi et al. (2019)'s finding that all of their 24 participants were less likely to glance towards potential hazards during a cognitive task.

From a traffic safety perspective, drivers with no glances towards potential threats in the traffic environment are most interesting as they are likely to entail the largest risk. We found that the proportion of events in which the driver did not look towards the potential threat at all was higher during the cognitive tasks compared to the No task condition. In a previous study, Harbluk et al. (2007) found that the probability that their participants, driving in real city traffic, never looked at traffic lights was higher when performing a more difficult cognitive task compared to an easier cognitive task. In this study, such a gradual effect of cognitive load was only seen in the intersection scenario. To prevent risky situations that may occur if a cognitively loaded driver neglects off-path threats, it would be desirable to be able to tell beforehand which drivers might display this behaviour. Unfortunately, on the individual driver level, the number of glances towards the threat in the non-loaded condition was a poor predictor of the number of glances towards the threat during cognitive load. Deducing who might be at risk of having no glances towards potential threats just by studying drivers' non-loaded glance patterns therefore does not seem to be an option.

4.4. Implications and interpretations

In certain driving environments such as motorways, having an increased amount of on-path glances is likely beneficial for safety. In the type of traffic scenarios studied here, gaze concentration is however more likely detrimental to safety as the drivers are at risk of missing relevant information in peripheral locations (Biondi, Turrill, Coleman, Cooper, & Strayer, 2015).

Understanding the mechanisms behind gaze concentration is thus very important if one wants to predict and counteract negative effects of cognitive load on traffic safety. The Cognitive Control Hypothesis (Engström et al., 2017) could offer a plausible explanation to the different effects of cognitive load on on-to-off-path gaze shifts and off-to-on-path gaze shifts. The Cognitive Control Hypothesis states that cognitive load only affects driver behaviours that rely on cognitive control but not those that are automatically performed. Because the on-path gaze direction is the, by margin, most common gaze direction in car drivers (Ahlstrom, Victor, Wege, & Steinmetz, 2012; Harbluk et al., 2007; Victor et al., 2005; Wang et al., 2014), one could assume that looking on-path is an automatized behaviour. Glances that have an on-path gaze direction during increased cognitive load would hence remain in that direction since cognitive control would be required to change to an off-path gaze direction. Off-path glances on the other hand would return to an on-path direction automatically and off-to-on-path gaze shifts would thus not be affected by cognitive load.

4.5. Limitations and future research

To our knowledge, car drivers' glance behaviour during cognitive load has not previously been studied in such high temporal resolution as in the present study. The analysis was therefore often explorative and largely focused on visualizing patterns in the data, rather than statistical testing. Future research thus needs to test the presented findings in other datasets. In addition, there are several noteworthy limitations to the current study, as discussed below.

When task effects were studied in each scenario and/or AOI, the multiple statistical tests were not compensated for and the results should thus be interpreted with caution. Patterns in the results were however quite consistent, both between the two scenarios (the intersection and the hidden exit) and between the off-path AOIs, suggesting that the results are not just coincidental.

High experimental control was prioritized in the experiment. It was therefore conducted in a simulator and glance behaviours could differ in real traffic. To reduce the risk of glance behaviour changes in comparison to real driving, efforts were made to make the driving as natural as possible for the participants by doing one long, continuous drive rather than exposing them to short, repeated scenarios. The cognitive task, the n-back task, with its fixed pace and task levels well separated in terms of cognitive demand, also allowed high experimental control. The n-back task is however not representative of most cognitively loading activities that car drivers can engage in during real driving, such as cell phone conversations, listening to podcasts and using voice control. Effects of variations of cognitive load in other cognitive tasks (for example other levels and types of cognitive load and other paces, including self-paced task) on gaze shifts and gaze concentration thus need exploration. Also, the group of participants was constricted to control for potential confounders and to limit the between-subject variance in all measures taken (also the physiological measures that will be reported in a separate manuscript), and the results thus need to be validated in other populations. There could for example be effects of gender or driving skills.

Finally, the proportion of missing data is large and systematic errors (e.g. that certain gaze directions entail an increased risk of lost tracking) cannot be ruled out. Limitations in the eye tracker system also make some uncertainties in the gaze coding unavoidable, even though a semi-manual gaze annotation method was employed to improve the annotation reliability.

5. Conclusions

The present study found that the gaze concentration effect was caused by cognitive load having different effects on gaze shifts towards and away from an on-path direction: On-to-off-path gaze shifts were inhibited while off-to-on-path gaze shifts were unaffected. The inhibited on-to-off-path gaze shifts were typically not compensated for. That is, they were cancelled rather than postponed, both in relation to the cognitive task and the traffic environment. The car drivers' visual adaptation in terms of timing of glances in relation to situational relevant off-path locations was hence unaffected, only the total number of off-path glances was reduced. This was a surprising finding considering the consistent effect of delayed response times to artificial stimuli during increased cognitive load. It suggests that gaze direction control is not affected by cognitive load, while gaze shift initiations are instantaneous and transient and permanently missed if not initiated in time.

The finding that on-to-off-path, but not off-to-on-path, gaze shifts were affected by cognitive load can be considered as further evidence supporting the idea that highly automatized behaviours are protected during cognitive load, in line with the Cognitive Control Hypothesis (Engström et al., 2017). Since the future path is the most common gaze direction for car drivers, moving the gaze towards this direction appears to happen automatically with no coupling to cognitive load, while the opposite is true for gaze shifts moving away from this direction.

These results can contribute to the understanding of the mechanisms behind gaze concentration in cognitively loaded car drivers, which is important for predicting and counteracting negative effects of cognitive load on traffic safety.

CRediT authorship contribution statement

Emma J. Nilsson: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Trent Victor:** Writing - review & editing, Supervision. **Mikael Ljung Aust:** Writing - review & editing, Supervision. **Bo Svanberg:** Conceptualization, Methodology, Investigation, Project administration, Funding acquisition. **Per Lindén:** Investigation, Data curation. **Pär Gustavsson:** Investigation, Data curation.

Acknowledgement

The work presented herein is part of the Vehicle Driver Monitoring (VDM) project, sponsored by Vinnova, the Swedish governmental agency for innovation systems.

References

Ahlstrom, C., Victor, T., Wege, C., & Steinmetz, E. (2012). Processing of eye/head-tracking data in large-scale naturalistic driving data sets. *IEEE Transactions on Intelligent Transportation Systems, 13*(2), 553–564. https://doi.org/10.1109/TITS.2011.2174786.

Biondi, F., Turrill, J. M., Coleman, J. R., Cooper, J. M., & Strayer, D. L. (2015). Cognitive distraction impairs drivers' anticipatory glances: an on-road study. Proceedings of the Eighth International Driving Sypmosium on Human Factors in Driver Assessment, Training and Vehicle Design, 23–29.

Conti, A. S., Dlugosch, C., Vilimek, R., Keinath, A., & Bengler, K. (2012). An assessment of cognitive workload using detection response tasks. In N. A. Stanton (Ed.), Advances in Human Aspects of Road and Rail Transportation (pp. 735–743). https://doi.org/10.1201/b12320.

Cooper, J. M., Medeiros-Ward, N., & Strayer, D. L. (2013). The impact of eye movements and cognitive workload on lateral position variability in driving. *Human Factors, 55*(5), 1001–1014. https://doi.org/10.1177/0018720813480177.

Desmet, C., & Diependaele, K. (2019). An eye-tracking study on the road examining the effects of handsfree phoning on visual attention. *Transportation Research Part F: Traffic Psychology and Behaviour, 60*, 549–559. https://doi.org/10.1016/j.trf.2018.11.013.

Ebadi, Y., Fisher, D. L., & Roberts, S. C. (2019). Impact of Cognitive Distractions on Drivers' Hazard Anticipation Behavior in Complex Scenarios. *Transportation Research Record, 1–12*. https://doi.org/10.1177/0361198119846463.

Engström, J., Markkula, G., Victor, T., & Merat, N. (2017). Effects of Cognitive Load on Driving Performance: The Cognitive Control Hypothesis. *Human Factors, 59*(5), 734–764. https://doi.org/10.1177/0018720817690639.

Hammel, K. R., Fisher, D. L., & Pradhan, A. K. (2002). Verbal and spatial loading effects on eye movements in driving simulators: A comparison to real world driving. In *Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting* (pp. 2174–2178).

Harbluk, J. L., Noy, Y. I., Trbovich, P. L., & Eizenman, M. (2007). An on-road assessment of cognitive distraction: Impacts on drivers' visual behavior and braking performance. *Accident Analysis and Prevention, 39*(2), 372–379. https://doi.org/10.1016/j.aap.2006.08.013.

International Organization of Standardization (2016). Road vehicles - Transport information and control systems - Detection-response task (DRT) for assessing attentional effects of cognitive load in driving. *ISO, 17488*, 2016.

International Organization of Standardization (2014). Road vehicles - Measurement of driver visual behaviour with respect to transport information and control systems Part 1: Definitions and parameters. *BS EN ISO, 150007–1*, 2014.

Itti, L., & Koch, C. (2001). Computational modelling of visual attention. *Nature Reviews Neuroscience, 2*(3), 194–203. https://doi.org/10.1038/35058500.

Jaeggi, S. M., Buschkuehl, M., Perrig, W. J., & Meier, B. (2010). The concurrent validity of the N-back task as a working memory measure. *Memory, 18*(4), 394–412. https://doi.org/10.1080/09658211003702171.

Land, M. F. (2006). Eye movements and the control of actions in everyday life. *Progress in Retinal and Eye Research, 25*(3), 296–324. https://doi.org/10.1016/j.preteyeres.2006.01.002.

Lappi, O. (2013). Eyes on the Road - Eye movements and the visual control of locomotion in curve driving (Doctoral thesis, University of Helsinki, Helsinki, Finland). Retrieved from https://researchportal.helsinki.fi/en/publications/eyes-on-the-road-eye-movements-and-the-visual-control-of-locomoti.

Lehtonen, E., Lappi, O., & Summala, H. (2012). Anticipatory eye movements when approaching a curve on a rural road depend on working memory load. *Transportation Research Part F: Traffic Psychology and Behaviour, 15*(3), 369–377. https://doi.org/10.1016/j.trf.2011.08.007.

Lehtonen, Esko, Lappi, O., Kotkanen, H., & Summala, H. (2013). Look-ahead fixations in curve driving. *Ergonomics, 56*(1), 34–44. https://doi.org/10.1080/00140139.2012.739205.

Lemonnier, S., Désiré, L., Brémond, R., & Baccino, T. (2020). Drivers' visual attention: A field study at intersections. *Transportation Research Part F: Traffic Psychology and Behaviour, 69*, 206–221. https://doi.org/10.1016/j.trf.2020.01.012.

Li, G., Wang, Y., Zhu, F., Sui, X., Wang, N., Qu, X., & Green, P. (2019). Drivers' visual scanning behavior at signalized and unsignalized intersections: A naturalistic driving study in China. *Journal of Safety Research, 71*, 219–229. https://doi.org/10.1016/j.jsr.2019.09.012.

Li, P., Markkula, G., Li, Y., & Merat, N. (2018). Is improved lane keeping during cognitive load caused by increased physical arousal or gaze concentration toward the road center?. *Accident Analysis and Prevention, 117*, 65–74. https://doi.org/10.1016/j.aap.2018.03.034.

Mennie, N., Hayhoe, M., & Sullivan, B. (2007). Look-ahead fixations: Anticipatory eye movements in natural tasks. *Experimental Brain Research, 179*(3), 427–442. https://doi.org/10.1007/s00221-006-0804-0.

Muttart, J. W., Fisher, D. L., Knodler, M., & Pollatsek, A. (2007). Driving without a clue: Evaluation of driver simulator performance during hands-free cell phone operation in a work zone. *Transportation Research Record*. https://doi.org/10.3141/2018-02.

Niezgoda, M., Tarnowski, A., Kruszewski, M., & Kamiński, T. (2015). Towards testing auditory-vocal interfaces and detecting distraction while driving: A comparison of eye-movement measures in the assessment of cognitive workload. *Transportation Research Part F: Traffic Psychology and Behaviour, 32*, 23–34. https://doi.org/10.1016/j.trf.2015.04.012.

Recarte, M. A., & Nunes, L. M. (2000). Effects of verbal and spatial-imagery tasks on eye fixations while driving. *Journal of Experimental Psychology: Applied, 6*(1), 31–43. https://doi.org/10.1037/1076-898X.6.1.31.

Recarte, M. A., & Nunes, L. M. (2003). Mental Workload While Driving: Effects on Visual Search, Discrimination, and Decision Making. *Journal of Experimental Psychology: Applied, 9*(2), 119–137. https://doi.org/10.1037/1076-898X.9.2.119.

Reimer, B. (2009). Impact of cognitive task complexity on drivers' visual tunneling. *Transportation Research Record, 2138*, 13–19. https://doi.org/10.3141/2138-03.

Reimer, B., Mehler, B., Dobres, J., & Coughlin, J. F. (2013). The Effects of a Production Level "Voice-Command" Interface on Driver Behavior: Reported Workload, Physiology, Visual Attention, and Driving Performance (Technical Report No. 2013-17A). Cambridge, MA. Massachusets Institute of Technology, AgeLab.

Reimer, B., Mehler, B., Wang, Y., & Coughlin, J. F. (2012). A field study on the impact of variations in short-term memory demands on drivers' visual attention and driving performance across three age groups. *Human Factors, 54*(3), 454–468. https://doi.org/10.1177/0018720812437274.

Romoser, M. R. E., Pollatsek, A., Fisher, D. L., & Williams, C. C. (2013). Comparing the glance patterns of older versus younger experienced drivers: Scanning for hazards while approaching and entering the intersection. *Transportation Research Part F: Traffic Psychology and Behaviour, 16*, 104–116. https://doi.org/10.1016/j.trf.2012.08.004.

Stojmenova, K., & Sodnik, J. (2018). Detection-response task—uses and limitations. *Sensors, 18*(2). https://doi.org/10.3390/s18020594.

Strayer, D. L., Turrill, J., Cooper, J. M., Coleman, J. R., Medeiros-Ward, N., & Biondi, F. (2015). Assessing Cognitive Distraction in the Automobile. *Human Factors, 57*(8), 1300–1324. https://doi.org/10.1177/0018720815575149.

Victor, T., Dozza, M., Bärgman, J., Boda, C.-N., Engström, J., Flannagan, C., ... Markkula, G. (2015). *Analysis of Naturalistic Driving Study Data: Safer Glances, Driver Inattention, and Crash Risk (SHRP 2 Report S2–S08A-RW-1)*. Washington, DC: Transportation Research Board. https://doi.org/10.17226/22297.

Victor, T. W., Harbluk, J. L., & Engström, J. A. (2005). Sensitivity of eye-movement measures to in-vehicle task difficulty. *Transportation Research Part F: Traffic Psychology and Behaviour, 8*(2 SPEC. ISS), 167–190. https://doi.org/10.1016/j.trf.2005.04.014.

Wang, Y., Reimer, B., Dobres, J., & Mehler, B. (2014). The sensitivity of different methodologies for characterizing drivers' gaze concentration under increased cognitive demand. *Transportation Research Part F: Traffic Psychology and Behaviour, 26*(PA), 227–237. https://doi.org/10.1016/j.trf.2014.08.003.

Werneke, J., & Vollrath, M. (2012). What does the driver look at? The influence of intersection characteristics on attention allocation and driving behavior. *Accident Analysis and Prevention, 45*, 610–619. https://doi.org/10.1016/j.aap.2011.09.048.

Wickens, C. D. (2015). Noticing events in the visual workplace: The SEEV and NSEEV models. In R. R. Hoffman, P. A. Hancock, M. W. Scerbo, R. Parasuraman, & J. L. Szalma (Eds.), Cambridge handbooks in psychology. The Cambridge handbook of applied perception research, Vol. 2 (pp. 749–768). https://doi.org/10.1017/CBO9780511973017.046.