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Investigating the situational dynamics of visual information sampling in lateral vehicle control – Subjective vs. objective estimates of spare visual capacity

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ABSTRACT

Drivers continually adapt their information sampling behavior to changing traffic conditions for safe driving. Scientists have studied this sampling behavior for decades; however, the literature on how drivers adapt their visual information sampling in response to observed driving dynamics is still incomplete, especially concerning what might be considered safe adaptation from an external perspective. While occlusion methods are commonly employed to study drivers' visual information sampling, the variability in self-selected occlusion times and their relationship to actual driving performance has yet to be fully understood. In a driving simulator study with 30 participants, we analyzed and compared the situational dynamics influencing visual information sampling and performance in an occluded lane-keeping task. The findings underscore the significant influence of speed, lane position, time-to-line-crossing at the start of occlusion, and steering during occlusion on spare visual capacity in lane-keeping. Although the participants were able to make slight adjustments to their visual sampling based on these variables, their occlusion time choices appeared to be stable and primarily driven by individual preferences, unrelated to their driving experience or general lateral control instability under occlusion. In contrast, drivers' general instability in lateral control under single-occlusion driving emerged as the strongest predictor of lane crossing during continuous, intermittently occluded driving. These insights contribute to the understanding of information sampling dynamics and spare visual capacity in lateral vehicle control, potentially guiding the development of personalized and contextually intelligent driver attention monitoring and warning systems.

1 Introduction

A responsible driver continually responds to changes in traffic conditions, whether they arise within the vehicle, appear in the road environment, or involve one's own skills or state (Summala, 1996). Accordingly, an attentive driver needs to perceive the relevant aspects of the dynamic driving environment, comprehend the current situation, anticipate its future status, and prepare actions to mitigate future situations when needed (Endsley, 1995). In essence, attentive drivers must adapt their information sampling behavior in accordance with the changing dynamics of the driving situation – and this adaptation has generally observed in empirical studies

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(Kujala et al., 2023).

In this paper, we aim to develop a more detailed understanding of how drivers adapt their visual sampling depending on the dynamic and evolving driving situation. For instance, driver attention monitoring systems often assess distraction by monitoring whether drivers' eyes are on the forward road scene, making "eyes off the road" a commonly used metric (Halin et al., 2021). However, drivers possess individually varying levels of spare visual capacity, allowing them to look away from the forward roadway for variable durations while still being able to drive safely (Ahlström et al., 2021; Safford, 1971). Additionally, this spare visual capacity is influenced by contextual factors (Kujala et al., 2023) such as traffic conditions, road curvature, and weather. The need to visually sample the forward roadway may differ significantly based on factors like approaching traffic or sharp curves compared to driving on an empty, straight road. Therefore, not all instances of looking away for a predefined duration should be considered distraction; driver monitoring systems should also consider the demands of the driving context, the driver's relative skills and capacities, and the driver's ability to adapt visual sampling accordingly.

Despite the importance of this adaptation, the scientific literature has paid less attention to investigating drivers' subjective estimation of the amount of visual information needed to drive safely – especially when compared to what can be regarded as safe behavior from the viewpoint of an external observer. Consequently, there is insufficient understanding of whether drivers can adapt their visual information sampling safely according to the objective situational requirements. Studies on drivers' information sampling – and their behaviors in general – typically involve averaging across various driving situations and drivers (Chen and Milgram, 2013), potentially obscuring interesting behaviors and effects that may appear for individual drivers.

In this study, we investigate how drivers adjust their visual sampling during lateral vehicle control in response to situational variables such as lateral offset, speed, and steering amplitude (Grahn et al., 2023). In addition to examining individual variation in spare visual capacity, we explore how other individual factors, such as driving experience (Kujala, Grahn, et al., 2016; Kujala, Mäkelä, et al., 2016) and lateral control stability (Verster & Roth, 2011), influence lateral vehicle control under occlusion. Specifically, we aim to assess the relationship between objective estimates of drivers' situational spare visual capacity, their subjective estimates of this capacity, and their actual driving performance. We utilize multilevel modeling to avoid averaging over situational variables and participants. Our approach involves comparing the situational variables affecting time-to-line crossing (TLC; Godthelp et al., 1984) as an objective estimate of spare visual capacity in a lane-keeping task with variables affecting their self-chosen visual sampling behavior (i.e., occlusion times: Senders et al., 1967). Furthermore, we compare self-selected occlusion times to TLC estimates in general, and aim to develop a model for predicting the odds for lane crossing during an occlusion (cf. Grahn et al., 2023). To this end, we posited the following research questions:

1) How is lateral vehicle control (TLC) during an occlusion affected by situational and individual variables?
2) How do drivers adapt their visual sampling behavior according to situational and individual variables?
3) What situational and individual variables best predict lane crossing during an occlusion?
4) How do the variables affecting the lateral control of the vehicle during an occlusion compare to the variables affecting visual information sampling?

This article is organized as follows. First, we provide an overview of the occlusion method, followed by a deeper discussion of studies that have utilized this method to examine vehicle control. Next, we describe the materials and methods used in the conducted driving simulator experiment. Then, we present the results of the experiment, which are presented in the form of descriptive statistics and five multilevel models; the first four models address research questions 1 and 2, and the fifth model address research question 3. In a subsequent discussion, we address research question 4 by comparing the variables across models 1 to 4. We conclude with an overview of our findings, including a discussion of how this study might guide the development of personalized and contextually intelligent driver attention monitoring and warning systems.

2 Related literature

2.1 Occlusion method

One approach to investigating drivers' visual information sampling uses the occlusion method introduced by Senders et al. (1967). This method involves intermittently obstructing the driver's vision, such as shielding vision with a helmet visor (like Senders et al., 1967) or, more recently, by blanking the screens of a driving simulator. The durations of these self-selected occluded intervals are measured and termed as *occlusion time* (OT). The occlusion method can employ either self-paced or fixed occlusion (Kujala et al., 2023); in this paper, we focus specifically on self-paced occlusion, as it allows drivers to decide when to end the occlusion, thereby representing their own subjective estimate of spare visual capacity in a given situation.

It is assumed that the OT measure reflects a driver's spare visual capacity while driving – that is, the time during which the driver can divert visual attention elsewhere (i.e., other than the forward roadway) while still being able to drive safely (Kujala et al., 2023; Safford, 1971). However, the large situational and individual differences in OTs that have been observed in similar scenarios are not yet fully understood (e.g., as in Kujala, Mäkelä, et al., 2016). Accordingly, Chen and Milgram (2013) argue that instead of gross metrics, the focus in occlusion research should be in the situational and individual variability of information sampling. In addition, a gap appears to exist within the scientific literature concerning the extent to which self-selected OTs can be equated with drivers' actual driving performance, and thereby with their true spare visual capacity (Kujala et al., 2023).

2.2 Occlusion studies in the context of vehicle control

The relationship between occlusion measurements and actual driving performance remains a relatively unexplored area. Previous studies on occlusion in the context of longitudinal vehicle control have been conducted by Senders et al. (1967), Krammes et al. (1995), Pekkanen et al. (2017, 2018), Kiefer et al. (2006), Kircher et al. (2018), Kaptein et al. (1996), Saffarian et al. (2015), and de Winter et al. (2022). These studies have revealed how occlusion times are affected by changes in speed or how occlusion can alter braking intensity and timing, occasionally leading to collisions or excessive braking. Furthermore, previous research has been conducted on steering accuracy and lane-keeping capabilities under occlusion (e.g., Farber & Gallagher, 1972; Zwahlen & Balasubramanian, 1974; Zwahlen & DeBald, 1986). These studies first indicated the existence of spare visual capacity in lateral vehicle control.

In more detailed studies of lateral vehicle control under occlusion, Blaauw et al. (1984) applied their Supervisory Driver Model to predict behavior in straight driving scenarios with disturbances. Comparing predicted OTs from the model to actual data from studies involving experienced drivers, they found a good fit with the model's predictions. In a parallel study, Godthelp et al. (1984) used a preview prediction model and the TLC measurement to explore drivers' strategies during occlusion in straight road driving. Their findings highlighted a close relationship between TLC and the OTs chosen by drivers (i.e., OTs close to 15 % TLC regardless of speed). Later, utilizing the TLC measurement, Godthelp (1986) analyzed how drivers anticipate and steer through curves, particularly considering the role of error-neglecting strategies regarding small deviations in lane position. The field study examined drivers' actions while negotiating curves at different speeds and curvatures, including instances of temporary visual feedback withdrawal. Furthermore, Godthelp's (1985) investigation into steering during a lane-change maneuver framed it as a precognitive control task. By analyzing the impact of steering force and steering wheel angle amplitude under conditions of visual occlusion, the study revealed that while occlusion affects the synchronization of steering amplitude and timing, its overall effects on vehicle motion are minimal. They also reported that during occlusion, the variability in steering amplitude increases linearly with the amplitude itself (SDs roughly equal to 9 % of the amplitude). In a broader context, Godthelp and Käuppler (1988) delved into how TLC could illuminate the relationship between vehicle handling characteristics and drivers' visual sampling and lateral control during lane-keeping on a straight road. Their study unveiled differences in OTs and driver strategies based on a vehicle's understeering and oversteering tendencies. Besides indicating that drivers can maintain lateral control during a temporary withdrawal of visual information, these studies indicate the usefulness of the TLC metric for assessing drivers' spare visual capacity in lateral control tasks and as a comparison point for their self-selected OTs.

Furthermore, Hildreth et al. (2000) investigated the dynamics of steering under visual occlusion using a driving simulator. The study investigated the role of visual cues in guiding steering and presented two distinct steering control models based on their findings. In a complementary study, Wallis et al. (2007) gained insight on steering behavior during lane changes in a driving simulator. Their findings emphasized the indispensability of visual feedback, as participants struggled to complete a lane change without it. Notably, however, the study revealed that brief visual updates could restore normal steering behavior, suggesting that steering control operates through open-loop steering movements with periodic visual checks. Examining compensatory steering control, Johns and Cole (2015) focused on the cognitive processes involved. Their study, utilizing a fixed-base driving simulator with periodic visual occlusions, identified an intermittent serial-ballistic control strategy as the most fitting model for explaining observed driver behavior. Together, these studies and models contribute to the understanding that successful lateral vehicle control operates as an open-loop (i.e., intermittent) control process, aligning with how human drivers naturally steer. This means that continuous visual sampling of the road is not required for sufficiently accurate steering—for example, to simply stay in one's lane.

Examining the impact of driving experience on the anticipation and execution of curve negotiation actions, Cavallo et al. (1988) conducted a study that compared the behaviors of novice and experienced drivers under both normal and occluded conditions. The research revealed differences in anticipatory abilities between the two groups and stressed the role of visual control for realignment post curve. In a related investigation, Kujala, Mäkelä, et al. (2016) measured 97 participants' lane-keeping accuracy as a function of OT and driving performance. Notably, the study found that more experienced drivers made fewer errors with long OTs, compared to their less experienced counterparts. Collectively, these studies emphasize the significance of anticipation skills in driving and suggest that spare visual capacity in lane keeping is dependent on driving experience.

Table 1
Independent variables in the trials.

Trial	Independent variable					
Single-occlusion	1) TLC when occlusion starts (Chen & Milgram, 2013; Grahn et al., 2023)	2) Steering amplitude during occlusion (Grahn et al., 2023; Chen & Milgram, 2013; Godthelp, 1985)	3) Offset at the end of the previous occlusion (Chen & Milgram, 2013)	4) Previous occlusion time (Grahn et al., 2023)	5) Driving experience (Kujala, Grahn, et al., 2016; Kujala, Mäkelä, et al., 2016)	6) Repetition (i.e., occlusion number, to control for learning and order effects)
Multiple-occlusion	1) TLC when occlusion starts (Chen & Milgram, 2013)	2) Steering amplitude during occlusion (Chen & Milgram, 2013; Grahn et al., 2023, Godthelp, 1985)	3) Offset at the end of previous occlusion (Chen & Milgram, 2013)	4) Previous occlusion time (Grahn et al., 2023)	5) Driving experience (Kujala, Grahn, et al., 2016; Kujala, Mäkelä, et al., 2016)	6) Repetition (i.e., occlusion number, to control for learning and order effects)
	7) Speed (60 vs. 100 km/h) (Liu et al., 2020)	8) Driver's standard deviation of lane position (SDLP) in single-occlusion trials (averaged over 50 occlusions) (Verster & Roth, 2011)				

As suggested by this brief review, research where participants' OTs are compared against the objective visual demands of the situation or their situational driving performance remains sparse. Two notable exceptions are the study by Godthelp et al. (1984), who compared OTs to TLC, and a more recent simulator study by Grahn et al. (2023), who found that OT increased by TLC at the onset of an occlusion whereas steering during occlusion decreased OT. In the latter study, OT was also positively associated with the odds to leave one's lane during an occlusion. In addition, Chen and Milgram (2013) studied situational variability in OTs in the context of lane deviations. They found that variability in occlusion durations depended on the information drivers acquired about the roadway or vehicle system during in-between glances. Furthermore, they concluded that drivers are capable not only of actively monitoring the system, but also of predicting how the situation will evolve during occlusion, which they referred to as Level 4 in their framework of human visual information sampling.

Here, inspired by the many studies above and especially by Chen and Milgram (2013) and Godthelp et al. (1984), we set out to investigate how individual and situational variables affect TLC performance and OT, and in turn, how these variables compare to each other.

3 Materials and method

3.1 Participants

A total of 30 individuals (17 male, 13 female) were recruited via university mailing lists. The age of these participants ranged from 20 to 65 years old, with a mean of 29.9 years, median of 27 years, and standard deviation of 9.7 years. Their driving experience ranged from 2 to 44 years, with a mean of 11.8 years, median of 8.5 years, and standard deviation of 9.3 years. The mean (self-estimated) annual distance driven was 14,455 km (range: 100–60,000 km), with a median of 10,000 km and standard deviation of 14,091 km. The mean lifetime distance driven (self-estimated) was 196,767 km (range: 3000–1,200,000 km), with a median of 75,000 km and standard deviation of 280,711 km.

Fig. 1. The experimental setup for the single-occlusion trial, with signposts indicating the beginning of occlusion.

3.2 Experimental design

The present study employed a within-subject experimental design with two parts: a series of single-occlusion tasks repeated 50 times, and two multiple-occlusion tasks. More precisely, in the multiple-occlusion trial, self-paced occlusion was utilized with the default state of occlusion and a fixed unocclusion (visible) duration of 500 ms (Kujala et al., 2023). The primary task in both parts was lane keeping while occluded, and the dependent variables measured were OT and TLC. TLC was calculated as the true TLC if the participant had crossed a lane boundary during an occlusion. If the participant did not cross the lane boundary, the situational TLC measured at the end of the occlusion was added to OT. However, it is important to note that this resulting TLC measurement is not the same as the situational TLC; instead, it is equivalent to the measurement of $T_{occ} + TLC_e$ as described by Godthelp et al. (1984), albeit with different terminology and a correction for lane crossings during occlusion. In line with Godthelp et al. (1984), this TLC represents the "spare time at the end of the occlusion interval" (p. 9) counted from the beginning of occlusion (unless corrected for the time to actual lane crossing from the beginning of occlusion). TLC marks the last moment at which the driver should observe the road to stay in the lane. While it is necessary to observe a bit sooner than at TLC to accommodate for the perception and reaction time required for a corrective maneuver, we chose not to unnecessarily complicate the analyses by including this additional time requirement.

In the trials, we investigated the impacts of several variables on OT and TLC. The independent variables are listed in Table 1 for each trial. Furthermore, we also examined the effects of these variables on the probability of a lane crossing during occlusion. The variables were chosen for their expected effects on OT, TLC, or both, according to the reviewed literature or for controlling possible order effects.

The purpose of the single-occlusion trial was to control for the car's lane position and TLC at the beginning of each occlusion. Conducting repeated measurements in controlled conditions aimed to provide a better understanding of possible learning and adaptation effects across 50 occlusions, compared to continuous intermittently occluded driving. Furthermore, the trial aimed to enable reliable measurement of inter-individual variability in participants' lane-keeping accuracy during occlusion (SDLP in Table 1).

The purpose of the multiple-occlusion trial was to simulate a driving task that more closely mimics ecologically valid conditions, involving intermittent vision (cf. glancing off from the forward roadway), in comparison to the single-occlusion trial. This setup was designed to analyze potential longer-term adaptation effects in a continuous drive. We conducted the experiment in accordance with the University of Jyväskylä's ethical guidelines.

3.3 Apparatus

The University of Jyväskylä's driving simulator laboratory was utilized to conduct the experiment. The medium-fidelity driving simulator featured a CKAS Mechatronics 2-DOF motion platform, a Logitech G27 force-feedback steering wheel, a longitudinally adjustable seat, and pedals. The simulator consisted of three 40″ LED screens (95.6 cm × 57.4 cm), each with a resolution of 1440x900 pixels. The middle screen showed a rear-view mirror, a HUD (head-up display) speedometer, and a HUD tachometer, while the side screens displayed side mirrors (refer to Fig. 1). The lane width was 3.75 m and the participant's car was 1.69 m wide (not including mirrors). During the test, automatic transmission and cruise control were utilized. Eepsoft (https://eepsoft.fi/) supplied the simulator software, which saved the driving log data at 10 Hz. The steering wheel included a lever that exposed (unoccluded) the driving scene for 500 ms when pulled; otherwise, the screens were blank.

In this study, the motion platform was not employed, and the simulator was muted, thus the participants had to rely solely on their vision when unoccluded and on their mental representations of the environment while occluded. This approach was used to focus the study exclusively on visual information sampling behavior, as participants may have varying abilities to use motion and sound cues, which could impact their glancing behavior.

3.4 Driving scenario

The road was a perfect circle (radius 1.5 km) with a consistent, mild curvature to the right that necessitated minor steering adjustments (see Fig. 1). Consequently, the tasks induced uncertainty in lane positioning, which was contingent on the participant's proficiency in maintaining their lane during occlusion. There was no other traffic in the driving scenario, no road crown, and no other perturbations, such as gusty winds. The same road was used in both parts of the experiment.

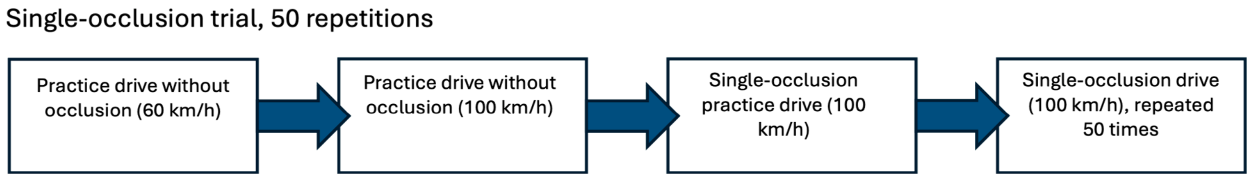

Fig. 2. Single-occlusion trial.

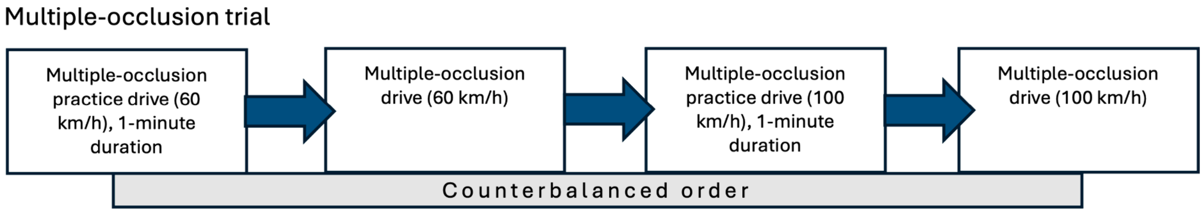

Fig. 3. Multiple-occlusion trial.

3.5 Tasks and procedure

Participants were tasked with maintaining their own lane while occluded and with unoccluding at the moment when they felt that the vehicle was leaving the lane. Participants were motivated to maintain occlusion for as long as possible while staying within the lane boundaries. The dependent variables were OT and TLC. The study consisted of two parts: single-occlusion trials and multiple-occlusion trials. The structure of the single-occlusion trial is depicted in Fig. 2, while Fig. 3 illustrates the structure of the multiple-occlusion trial.

We collected demographic data via email prior to the participants' arrival. Upon their arrival, participants were informed about the study's purpose and setup and were asked to read and sign the informed consent form. Initially, participants adjusted their seat and practiced driving without occlusion using the driving simulator at a constant speed of 60 km/h (with cruise control) on the same road as used in the actual study. The practice session was then repeated at a speed of 100 km/h. These practice drives were approximately 2–3.5 min long, depending on the speed. Next, participants engaged in the occlusion drive practice session. They were instructed to accelerate to a speed of 100 km/h and enter a specific section of the road, identified by two signposts (see Fig. 1). Once they reached the signposts, the screens would intentionally go blank, simulating visual occlusion. During this exercise, participants were tasked to stay within their own lane while attempting to drive as far as possible without visual cues. When they felt they needed to see the road, they could unocclude themselves by pulling the lever located behind the steering wheel. After unoccluding, participants were instructed to brake, and the practice trial ended. This practice trial was repeated twice.

Subsequently, the actual experiment began. In the first part of the study, each participant completed 50 repeated single occlusions within a constant segment of the three-lane road. The participants' task remained the same as during the last practice. Participants were instructed to accelerate to 100 km/h and steer close to the middle of the center lane, guided by two signposts (see Fig. 1). After accelerating, the vehicle's speed was maintained at a constant 100 km/h using cruise control. Their view was then occluded upon passing the posts. Once the drivers unoccluded and viewed the forward roadway, they were instructed to stop the car. A short break was offered twice during the experiment. Before beginning the driving task, participants received additional instructions. They were informed that their performance would be scored based on their ability to maintain their position within the lane during the occlusion period. For each occlusion, participants would earn points per time unit spent within the lane. Conversely, if they departed from the lane during the occlusion, they would receive negative points per time unit spent outside the lane. The top ten participants with the highest scores were awarded an additional gift certificate worth 10 euros each. The implementation of the scoring system aimed to enhance participant engagement and to optimize task performance.

After completing 50 trials of the single-occlusion task, participants proceeded to another practice session. In this session, participants engaged in a drive where they were occluded by default, but could briefly view the road for 500 ms intervals to make steering corrections by pulling the lever located behind the steering wheel. Once the desired speed (either 60 km/h or 100 km/h, depending on the counterbalanced order) was reached and cruise control activated at that speed, their task was to remain within their own lane while driving as far as possible without relying on visual cues. They were also instructed to pull the lever when needed to briefly view the road for 500 ms intervals and steer back to the lane center if necessary. Unlike the single-occlusion task, the drive did not end after the first unocclusion; instead, the practice trial ended after one minute of driving. Next, participants engaged in the actual multiple-occlusion drive. Following that, they completed another practice session at the alternate speed, followed by the subsequent actual drive. Before the actual drives, they were reminded of the same scoring system as in the single-occlusion task. Participants drove a route of exactly the same length at both 60 km/h and 100 km/h, for which the drives lasted from 2 to 3.5 min, respectively. In total, the duration of the experiment was approximately 90 min. Finally, participants were thanked for their participation and rewarded with a gift certificate worth 20 euros.

3.6 Data preparation and analysis

The log data of the driving simulator was utilized in conjunction with an R script for data processing to measure OT (seconds) and TLC (seconds). IBM SPSS Statistics 28 was used for statistical analyses.

First, all data points where the speed was not at the target level (60 or 100 km/h) were omitted. This includes data points from the multiple-occlusion drives where participants were still accelerating to the target speed and the actual measurement had not yet started. Then, to employ multilevel modeling in the analysis, the data was reformatted in a longitudinal structure with occlusion as the observation unit. Multilevel models were employed because the data exhibited a clustered or hierarchical structure (Hox, 1998), with OTs and TLCs nested within individual drivers. Following the 30/30 rule of thumb, Level 1 in the multilevel model should consist of at least 30 observations, and these observations should be nested within 30 units on Level 2 for adequate statistical power (Richter, 2006). In the current data, there are either 1499 (single-occlusion trial) or 3575 (multiple-occlusion trial) occlusions nested within 30 participants. However, to handle outliers, TLCs exceeding 70 s were excluded as well as steering amplitudes exceeding 15 degrees and offsets when occlusion started exceeding 7 m. (These unrealistic outliers were possible if the car's heading and the steering wheel angle happened to be in just the right position in relation to the curvature of the road at the end of occlusion.) Also, occlusions that began when the participant's car was not in the center lane were excluded from the multiple-occlusion trial data to enable modeling of TLC. After applying these filtering criteria, there were 1468 occlusions in the single-occlusion trial (i.e., 31 observations excluded) and 2964 occlusions in the multiple-occlusion trial (i.e., 611 observations excluded).

We initiated model construction by examining the intraclass correlation (ICC) in an intercept-only model with participant as a random effect. If the ICC deviated from zero, this justified the adoption of a multilevel model (Peugh, 2010). Next, we added fixed factors incrementally, assessing the -2 Log-Likelihood Ratio (-2LLR) after each addition to evaluate the model fit. We also used a chi-squared test (χ^2) to evaluate whether the added fixed factor substantially improved model fit ($p < 0.05$). If a fixed factor did not lead to significant improvement in model fit, we removed it from the model, indicating that it did not enhance model fit (Peugh, 2010). This procedure was applied to all subsequent models. The standardized estimates included in the models were obtained by subtracting out the mean and dividing by the standard deviation for each variable before running the models. The standardized estimates were used to facilitate the comparison of effect sizes between variables with different units. Because of potential suppressor effects in forward modeling, we also constructed models using backward stepwise selection. The significant effects identified did not vary between these two modeling approaches.

4 Results

The first section presents descriptive statistics at the participant level, including variables utilized in the subsequent multilevel models. In this section, we also compare the OT and TLC descriptive statistics to those of Godthelp et al. (1984) and analyze the relationship between OT and TLC at the participant level. Following this, subsequent multilevel models investigate drivers' adaptation of visual sampling behavior based on situational and individual variables (Models 1 and 3), as well as the factors influencing lateral vehicle control during occlusion (Models 2 and 4) at the occlusion level. Models 1 and 2 are derived from single-occlusion trials, while Models 3 and 4 are based on multiple-occlusion trials, as indicated in the section headings. Lastly, the final model explores the predictors of lane crossing during occlusion in the multiple-occlusion trial (Model 5).

4.1 Descriptive statistics

The descriptive statistics per trial, as averaged over the participant sample, can be seen in Tables 2 and 3. The number of occlusions and lane crossings in the single- and multiple-occlusion trials are described in Tables 4 and 5. In the single-occlusion trial, participants crossed the lane markings in 25.5 % of the occlusions. In the multiple-occlusion trial, participants crossed the lane markings in 6.9 % of the occlusions (60 km/h: 7.1 %, 100 km/h: 6.7 %). Due to a technical issue, one participant's data for a single drive is missing, resulting in a sample size of 29 in Table 3.

Following the analyses by Godthelp et al. (1984), OT/TLC ratios were calculated using the median values of OT and TLC (defined by Godthelp et al. as T_{occ} / [T_{occ} + TLC_e]) per trial (Table 6). In addition, the mean OT values were compared to the mean TLC, 15 % TLC, and minimum TLC to understand whether participants exhibited caution in their sampling behaviors by considering lower-end TLC values or even the observed minimum TLC (i.e., the worst-case scenario), or if they targeted the expected value of the TLC distribution. Godthelp et al. (1984) report that their participants' mean OTs were close to the mean 15 % TLCs, regardless of driving speed.

A mixed effects linear model predicting OT with TLC as a fixed effect and participant as a random effect indicated that the association between TLC and OT was not significant in the single-occlusion trial ($p = 0.266$). There was a weak association between TLC and OT in the multiple-occlusion trials, with a 0.02-second change in OT per 1-second change in TLC ($p < 0.001$). At the participant level, there were significant correlations between TLC and TLC when occlusion started, with intermediate correlation in the single-occlusion trial ($r = 0.47$) and strong correlations in the multiple-occlusion trials (60 km/h: $r = 0.92$, 100 km/h: $r = 0.82$).

4.2 Model 1: Occlusion time in single-occlusion trial

For Model 1 (Table 7), the dependent variable was OT in single-occlusion trials. The ICC yielded a value of 59.5 % for the intercept-

Table 2
Descriptive statistics, single-occlusion trial ($N = 30$).

	Mean	Standard deviation	Median	Range
Occlusion time (OT, s)	5.328	1.840	5.199	2.410–8.762
Time-to-line-crossing (TLC, s)	11.263	2.240	11.209	7.251–16.246
TLC when occlusion started (s)	13.947	2.471	14.489	8.817–17.992
Steering amplitude (degrees)	2.083	1.311	1.950	0.597–6.302
Offset at the end of occlusion (m)	0.675	0.228	0.685	0.360–1.346
Driver's SDLP* (m, averaged over the 50 occlusions)	0.282	0.146	0.255	0.094–0.644

* SDLP: standard deviation of lane position

Table 3
Descriptive statistics, multiple-occlusion trial (60 km/h: $N = 30$, 100 km/h: $N = 29$).

	Mean, 60 km/h	Mean, 100 km/h	Standard deviation, 60 km/h	Standard deviation, 100 km/h	Median, 60 km/h	Median, 100 km/h	Range, 60 km/h	Range, 100 km/h
Occlusion time (OT, s)	2.796	2.215	0.737	0.602	2.687	2.188	1.586–4.545	1.133–3.109
Time-to-line crossing (TLC, s)	12.408	10.387	3.332	3.209	12.078	9.625	6.722–20.388	3.901–16.821
TLC when occlusion started (s)	12.374	9.486	3.267	2.567	11.988	9.347	5.783–18.739	4.400–15.035
Steering amplitude (degrees)	3.077	2.288	1.992	1.477	2.254	1.941	0.911–7.991	0.478–5.380
Offset at the end of occlusion (m)	0.520	0.537	0.156	0.163	0.501	0.509	0.272–0.855	0.292–0.997

Table 4
Number of occlusions and lane crossings (during occlusions) in the single-occlusion trial (100 km/h, $N = 30$).

	Mean	Standard deviation	Median	Sum
Lane crossings	12.5	10.28	8	375
Occlusions	48.93	2.23	49	1468

only model. We included the following variables as fixed factors: OT from the previous occlusion, offset at the end of the previous occlusion, occlusion number, and steering amplitude. TLC could not be included as a predictor in this model as TLC was measured as an outcome of each OT, and therefore TLC could not have had causally affected the OT. The offset when occlusion started was found to be a significant predictor in the model; however, its inclusion increased the value of −2LLR, so it was subsequently removed from Model 1. Occlusion number and driving experience were not significant predictors and were not added to the final model (Table 7).

The intercept (grand mean) of Model 1 is 2.61 s. Based on the standardized estimates, the previous occlusion's OT had the largest effect, increasing the OT by 0.57 s per second. Another predictor variable was the offset at the end of previous occlusion. When the offset increased by a meter, the OT decreased by 0.85 s. When participant's steering amplitude increased by a degree during an occlusion, the OT increased by 0.13 s. The ICC of Model 1 decreased to 37.5 % with the inclusion of these predictors. On visual inspection, the residuals showed a close-to-normal distribution with a slight skewness to the left. However, there were some deviations from normality observed on both ends in the Q-Q plot. No clear indications of heteroscedasticity were observed.

4.3 Model 2: Time-to-line crossing in single-occlusion trial

In Model 2 (Table 8), the dependent variable was TLC in the single-occlusion trial. In the intercept-only model, the ICC was 5.9 %. Identified as statistically significant fixed factors, we entered steering amplitude, offset at the end of previous occlusion, occlusion number, and TLC when occlusion started. Also, the offset at the end of the previous occlusion was initially identified as a significant predictor in the model. However, its inclusion did not lead to an improvement in the model's fit, resulting in its subsequent removal. Similarly, the occlusion number and driving experience were deemed as insignificant predictors and were subsequently eliminated from Model 2.

The intercept (grand mean) of Model 2 was 10.92 s. When a participant increased steering amplitude during occlusion by a degree, the TLC decreased by 0.69 s. Additionally, TLC at the start of occlusion was found to be a significant predictor of TLC, with an increase in TLC of one meter leading to an increase in TLC by 0.13 s. After including these predictors, the ICC decreased to 3.5 %.

In Model 2, the residuals exhibited a skewed distribution, and the Q-Q plot revealed clear deviations from the regression line. However, no clear evidence of heteroscedasticity was observed. These factors should be kept in mind when interpreting the results of the model.

4.4 Model 3: Occlusion time in multiple-occlusions trial

In Model 3 (Table 9), the dependent variable was OT in the multiple-occlusion trial. In the intercept model only, the ICC was 27.5 %. For Model 3, as fixed factors, we entered the previous occlusion's OT, speed (60 or 80 km/h), the TLC when occlusion started, steering amplitude, the offset at the end of previous occlusion, and the running number of occlusions. Additionally, utilizing data from the single-occlusion trial, we computed a variable that captures the individual variations in lateral vehicle control among the drivers. This was achieved by calculating the average standard deviation of the offset (i.e., SDLP) across the 50 occlusions in the single-occlusion trial. Within Model 3, this predictor did not show significance and was consequently excluded. Additionally, driving experience was not a statistically significant predictor of OT. Again, TLC could not be included as a predictor in Model 3 as TLC was

Table 5

Number of occlusions and lane crossings per speed (during occlusions) in the multiple-occlusion trial (60 km/h: $N = 30$, 100 km/h: $N = 29$).

	Mean, 60 km/h	Mean, 100 km/h	Standard deviation, 60 km/h	Standard deviation, 100 km/h	Median, 60 km/h	Median, 100 km/h	Sum, 60 km/h	Sum, 100 km/h
Lane crossings	4.07	2.83	3.71	2.67	3.5	2.0	122	82
Occlusions	57.27	42.10	18.18	14.97	58.5	42	1718	1221

Table 6
OT/TLC ratios per trial (single-occlusion: $N = 30$, multiple-occlusion 60 km/h: $N = 30$, multiple-occlusion 100 km/h: $N = 29$).

	Single-occlusion	Multiple-occlusion 60 km/h	Multiple-occlusion 100 km/h
Median OT / Median TLC	0.46	0.26	0.24
Mean OT / Mean TLC	0.47	0.23	0.21
Mean OT / Mean 15 % TLC	1.06	0.53	0.52
Mean OT / Mean min TLC	1.80	1.75	1.39

Table 7
Model 1 predicting occlusion time in single-occlusion trial.

Fixed effects	Standardized estimate	Estimate	Standard error	p	95 % confidence interval lower bound	95 % confidence interval upper bound
Intercept	0.000	2.618	0.214	<0.001	2.188	3.048
Previous occlusion's occlusion time (s)	0.571	0.569	0.022	<0.001	0.526	0.612
Offset at the end of previous occlusion (m)	−0.187	−0.850	0.072	<0.001	−0.992	−0.708
Steering amplitude during occlusion (degrees)	0.094	0.125	0.026	<0.001	0.073	0.176
Random effects		σ^2				
Intercept (participant)	0.168	0.926	0.264	<0.001	0.530	1.619
Residual	0.281	1.547	0.058	<0.001	1.438	1.619
Intraclass correlation (ICC)						
Participant		0.375				
Model fit (−2RLL)		4924.703				

Table 8
Model 2 predicting TLC in single-occlusion trial.

Fixed effects	Standardized estimate	Estimate	Standard error	p	95 % confidence interval lower bound	95 % confidence interval upper bound
Intercept	0.000	10.920	0.568	<0.001	9.798	12.042
Steering amplitude during occlusion (degrees)	−0.154	−0.691	0.139	<0.001	−0.964	−0.417
TLC when occlusion started (s)	0.145	0.127	0.023	<0.001	0.083	0.172
Random effects		σ^2				
Intercept (participant)	0.033	2.077	0.866	<0.016	0.917	4.701
Residual	0.912	58.161	2.170	<0.001	54.060	62.572
Intraclass correlation (ICC)						
Participant		0.034				
Model fit (−2RLL)		10173.265				

Table 9
Model 3 predicting occlusion time in multiple-occlusion trial.

Fixed effects	Standardized estimate	Estimate	Standard error	p	95 % confidence interval lower bound	95 % confidence interval upper bound
Intercept	−0.078	1.134	0.101	<0.001	0.932	1.335
Previous occlusion's OT (s)	0.489	0.512	0.016	<0.001	0.481	0.543
Speed 60 km/h	0.189	0.220	0.033	<0.001	0.156	0.285
Speed 100 km/h[*]	0	0				
TLC when occlusion started (s)	0.122	0.017	0.002	<0.001	0.013	0.021
Steering amplitude during occlusion (degrees)	−0.076	−0.035	0.008	<0.001	−0.050	−0.200
Offset at the end of previous occlusion (m)	−0.068	−0.259	0.052	<0.001	−0.360	−0.158
Occlusion number	0.002	0.003	0.001	<0.001	0.001	0.004
Random effects		σ^2				
Intercept (participant)	0.150	0.205	0.057	<0.001	0.118	0.355
Residual	0.459	0.626	0.016	<0.001	0.594	0.658
Intraclass correlation (ICC)						
Participant		0.247				
Model fit (−2RLL)		7167.338				

[*] The factor above is compared to factor that gets the value of zero.

Table 10
Model 4 predicting TLC in multiple-occlusion trial.

Fixed effects	Standardized estimate	Estimate	Standard error	*p*	95 % confidence interval lower bound	95 % confidence interval upper bound
Intercept	−0.126	11.371	0.867	<0.001	9.626	13.116
TLC when occlusion started (s)	0.205	0.215	0.020	<0.001	0.175	0.255
Speed 60 km/h	0.191	1.720	0.325	<0.001	1.083	2.356
Speed 100 km/h*	0	0				
Steering amplitude during occlusion (degrees)	−0.092	−0.331	0.077	<0.001	−0.482	−0.180
Driver's SDLP averaged over 50 occlusions in the single-occlusion trial (m)	−0.085	−5.421	2.412	0.033	−10.367	−0.476
Offset at the end of previous occlusion (m)	−0.051	−1.512	0.529	0.004	−2.549	−0.475
Random effects		σ^2				
Intercept (participant)	0.041	2.814	0.967	0.004	1.435	5.519
Residual	0.847	68.764	1.797	<0.001	65.331	72.377
Intraclass correlation (ICC)						
Participant		0.039				
Model fit (−2RLL)		20998.600				

measured as an outcome of each OT, and therefore TLC could not have had causally affected the OT.

The intercept for OT (grand mean) was 1.13 s. The previous OT had the greatest impact on the predicted OT, as an increase of one second in the previous OT resulted in a 0.51-second increase in the OT. Decreasing speed from 100 km/h to 60 km/h increased the OT by 0.22 s. The TLC when occlusion started also had an impact on OT, as a one-second increase in the TLC led to an increase of 0.02 s in the OT. For instance, a 10-second increase in TLC translates to a 200 ms increase in OT, highlighting its impact. According to Model 3, a one-degree increase in steering amplitude was associated with a decrease in OT of 0.04 s. Additionally, when the offset at the end of the previous occlusion increased by a meter, a decrease of 0.26 s was predicted for the OT. Finally, as the running occlusion number increased by 10, the OT increased by 0.03 s. The ICC for Model 3 with the predictors decreased to 24.7 %.

The residual plots revealed a generally normal distribution of residuals, except for some deviations from normality observed in the shortest and longest OTs, as depicted in the Q-Q plot. As before, there were no clear signs of heteroscedasticity.

4.5 Model 4: Time-to-line crossing in multiple-occlusions trial

In Model 4 (Table 10), the dependent variable was TLC in the multiple-occlusion trials. ICC was 9.1 % for the intercept-only model. For Model 4, we entered as fixed factors the TLC when occlusion started, speed (60 or 80 km/h), steering amplitude, driver's SDLP averaged over 50 occlusions in the single-occlusion trial, and the offset at the end of the previous occlusion. Driving experience was not significant and was removed from Model 4.

The intercept for TLC (grand mean) was 11.37 s. A one-second increase in the TLC when the occlusion began resulted in an increase of 0.13 s in TLC. As the speed decreased from 100 km/h to 60 km/h, the TLC increased by 1.72 s. A one-degree increase in steering amplitude resulted in a decrease of 0.33 s in TLC. Driver's SDLP averaged over 50 occlusions in the single-occlusion trial—a measure that signifies individual variances—emerged as the third most influential predictor in the model. An increment of one meter in this variable resulted in a reduction of 0.09 s in TLC. Like Models 1 and 3, the current model indicated that an increase in the offset at the end of previous occlusion of one meter led to a decrease of 1.51 s in TLC. The ICC for Model 4 with the predictors decreased to 3.9 %.

Upon visual inspection, the residuals of Model 4 appeared to follow a relatively normal distribution, although with a slight tail towards the longer TLCs. The Q-Q plot revealed moderate deviations at both ends of the line, which should be considered when

Table 11
Model 5 predicting lane crossings in multiple-occlusion trial.

Fixed effects	Coefficient	Standard error	*p*	95 % confidence interval lower bound	95 % confidence interval upper bound	Expected odds
Intercept	−3.426	0.476	<0.001	−4.359	−2.494	0.033
Driver's SDLP averaged over 50 occlusions in the single-occlusion trial (m)	2.441	1.135	0.032	0.217	4.666	11.489
Occlusion time (s)	0.608	0.074	<0.001	0.464	0.752	1.837
Offset at the end of previous occlusion (m)	0.511	0.245	0.037	0.030	0.992	1.667
TLC when occlusion started (s)	−0.263	0.027	<0.001	−0.316	−0.210	0.769
Steering amplitude during occlusion (degrees)	0.069	0.031	0.023	0.009	0.129	1.072
Random effects	σ^2					
Intercept (participant)	0.555	0.252	0.028	0.218	1.353	
Intraclass correlation (ICC)						
Participant 0.144						

interpreting the model's results. Nevertheless, no clear indications of heteroscedasticity were observed.

4.6 Model 5: Lane crossings in multiple-occlusion trial

Model 5 (Table 11) uses a multilevel binary logistic regression analysis, which is a type of multilevel modeling that focuses on a binary outcome variable. Specifically, a value of 0 represents the car staying in the lane (i.e., no lane crossing), while a value of 1 indicates that the car crossed the lane. The primary goal of Model 5 was to investigate the relationship between the predictor variables and the probability of the outcome variable getting the value 1 (i.e., a lane crossing). In Model 5, the ICC of the intercept model was 39.7 %. According to the intercept-only model, the expected probability of lane crossings during an occlusion in the multiple-occlusion trial was 5.1 % (as calculated in Crowson, 2020).

In our analysis, we considered the driver's SDLP averaged over 50 occlusions in the single-occlusion trial, OT, the offset at the end of the previous occlusion, the TLC when the occlusion started, speed, and steering amplitude as fixed factors. Here, TLC was too closely related to the dependent variable and therefore not used as a predictor, whereas OT was added as a control to study the effects of the situational variables while OT is held constant. As a random factor, we had intercepts for the participants (i.e., drivers). Here, we included the driver's SDLP averaged over 50 occlusions in the single occlusion trial as a possible factor in explaining both individual differences and OT, because it is anticipated that the probability of lane crossing increases as the OT increases. Speed, occlusion number, and driving experience were not significant predictors and were therefore removed from Model 5.

In the final model, the expected probability of lane crossing is 3.2 % (as calculated in Crowson, 2020). The regression slope for the driver's SDLP averaged over 50 occlusions in the single-occlusion trial was positive, indicating that as the SDLP increased, the likelihood of crossing the lane during an occlusion in the multiple-occlusion trial increased. The odds ratio for this predictor suggests that for every unit increase (m) in the SDLP in the single-occlusion trial, the odds of lane crossing during occlusion in the multiple-occlusion trial increases by a factor of 11.5. The OT also had a positive regression slope, suggesting that as the OT increased, the probability of lane crossing also increased. This predictor had the second highest odds of 1.8 per second. Similarly, the offset at the end of previous occlusion had a positive regression slope. This means that as this predictor increased, the probability of lane crossing also increased, with odds of 1.7 per meter. The TLC when the occlusion started showed a negative regression slope, suggesting that as TLC increased, the probability of lane crossing decreased. The odds for this predictor were the smallest, at 0.8 per second. Lastly, the steering amplitude had a positive effect, indicating that as the steering amplitude increased, the likelihood of deviation the lane during the occlusion also increased, with odds of 1.1 per degree. With the addition of the predictors, the ICC decreased to 14.4 %.

5 Discussion

In this paper, we set out to investigate and compare situational variables predicting subjective attentional demands (OT) and objective attentional demands (TLC) in lateral vehicle control. Across occlusions in the single-occlusion trial, participants seemed to target 15 % TLC with their OTs, consistent with the OT behavior observed in Godthelp et al.'s (1984) experiment. This suggests a cautious visual sampling strategy in relation to their spare visual capacity. They seemed to adopt an even more cautious strategy in the multiple-occlusion trials, as the ratio of mean OTs to 15 % TLC was around 0.5. This may be due to more varied lane positions and TLCs at the beginning of the occlusions. However, in general, drivers' mean OTs were significantly longer than their minimum TLCs, indicating a deviation from the most cautious approach relying on the observed worst-case scenario. Alternatively, short minimum TLCs could result from initial excessive steering efforts in the first drives, with drivers learning to avoid these in subsequent occlusions, enabling them to drive successfully for longer periods while occluded. At the participant level, the intermediate correlation between TLC and TLC when occlusion started in the single-occlusion trial ($r = 0.47$) compared to the strong correlations in the multiple-occlusion trials (>0.80) suggests that drivers steered significantly more during the occlusion in the single-occlusion trial than in the multiple-occlusion trial. However, the connection is much weaker in the multilevel models when the effects of other factors are controlled for at the occlusion level. In addition, statistically significant learning effects as estimated by the occlusion number were not observed in the single-occlusion trial. It is also worth considering whether the observed variability in OTs could be attributed, at least in part, to the inherent noise in driver's internal clock (Taatgen et al., 2007).

Next, we compare the OT and TLC models in both single-occlusion and multiple-occlusion trials to differentiate between variables that affect subjective attentional demands and those that affect objective attentional demands. Finally, we discuss the variables affecting the odds of lane crossing in the multiple-occlusions trial.

5.1 OT vs. TLC in the single-occlusion trial

To reiterate, in the single-occlusion trial, participants experienced 50 single occlusions, with their vehicle being repositioned near the lane center between each occlusion.

Model 1 represents the subjectively experienced spare visual capacity, or conversely, the experienced visual demand of the lane-keeping task in the single-occlusion trial. The previous occlusion's OT was the strongest predictor of OT by increasing it, while the offset at the end of the previous occlusion and steering amplitude during occlusion were also predictors, decreasing OT. The strongest predictor implies that drivers varied their OT cautiously and perhaps preferred to maintain an individual preference level, which could be based on a personal uncertainty tolerance threshold (Kujala, Mäkelä, et al., 2016) or rate of uncertainty growth while occluded (Lee et al., 2015; Senders et al., 1967). This is evident also by the high variance between the individual intercepts that describes the variability in the participants' individual differences in their baseline OTs. However, they also made smaller adjustments to OT based on the observation of their car's deviation from lane center at the end of the previous occlusion, indicating situational adaptation similar to that observed in Chen and Milgram (2013). The effect of steering amplitude is different from all other models in that it is positive, indicating that larger steering movements increased OT. It suggests that drivers estimated they can drive for a longer duration without vision if they steer during occlusion. In the single-occlusion trial, there may have been an effort to identify the optimal steering pattern to increase TLC rather than minimizing steering wheel movements during the occlusion. However, the occlusion number, indicating repetition, did not serve as a predicting variable. This observation could suggest that drivers were unable to learn or adapt their behavior over the extended duration. Instead, their performance seemed to be based on a general preference for OT and their previous observations of lane position. Additionally, the TLC when occlusion started did not emerge as a significant predictor of OT, potentially due to the challenge of observing small variations in these metrics. In contrast to studies such as those by Chen and Milgram (2013) and Godthelp (1984), driving experience was not a significant factor in the model (or any other model). However, the sample size ($N = 30$) was limited in this respect.

Notably, the ICC of the final Model 1 was 0.375, which indicates that 37.5 % of the unexplained variability in OT is attributed to differences between participants. Furthermore, OTs were longer in the single-occlusion trial compared to the multiple-occlusion trial, as expected due to greater variability in offsets and TLCs in the latter. Conversely, the mean number of lane crossings was 12.5 out of 50 (25.5 %) in the single-occlusion trial (100 km/h), compared to 7.1 % (60 km/h) and 6.7 % (100 km/h) in the multiple-occlusion trial. While the driving scenarios and instructions were same in both trials, these findings suggest that drivers may have attempted to maximize the OT while remaining on the lane in the single-occlusion trial, while in the significantly longer multiple-occlusion trial, they might have adopted a satisficing approach. This interpretation is also supported by the participant level OT to 15 % TLC ratio, which is much lower for the multiple-occlusion trials (approximately 0.5) compared to the single-occlusion trial (approximately 1.0).

Model 2 is intended to represent the objective spare visual capacity in the lane-keeping task as TLC at the end of occlusion. TLC was considered the true TLC if the participant had crossed the lane during an occlusion. Alternatively, it was calculated as the OT plus the predicted TLC from the end of occlusion, assuming the participant would maintain the current trajectory. Steering amplitude during occlusion decreased TLC, while TLC at the start of occlusion increased it. The effect of steering amplitude was the opposite compared to Model 1 and in line with Godthelp (1985). This effect indicates that the more the participants steered during occlusion, the sooner they were or were estimated to cross the lane boundary. The effect of TLC at the start of the occlusion on the realized TLC is rather self-evident but provides construct validity for the measurement. However, it should be noted that in the single-occlusion trial, the vehicle's position at the center of the lane remained relatively consistent for each occlusion, with only minor deviations in its heading that had a slight impact on TLC. Here, the ICC of the final Model 2 was 0.034, indicating that 3.4 % of the unexplained variability in TLC is attributed to differences between participants. This is significantly lower than the ICC of Model 1, which predicted OT. This suggests that participants' estimates of their lane-keeping performance (or uncertainty growth or tolerance) varies much more than their actual lane-keeping performance.

5.2 OT vs. TLC in the multiple-occlusion trial

To reiterate, multiple-occlusion trial consisted of two approximately 2–3.5-minute drives in which occlusion was the default mode, and drivers were able to view the driving scene for 500 ms when needed by pulling a lever.

In Model 3, as in the single-occlusion trial, the strongest predictor of OT was the previous occlusion's OT, suggesting again only gradual adjustments to OT. The second largest predictor was speed (decrease from 100 to 60 km/h). This was an expected result and is similar to findings in, for instance, Liu et al. (2020) where participants were aware that lower speeds enable longer OTs. Another predictor of OT was the TLC when occlusion started, which corresponded with an increase in OT. Again, this implies that drivers were capable of using the last gist of the driving scene to adjust their OT based on TLC – which can be seen as adaptation to situational circumstances. This finding is like those of Chen and Milgram (2013) and Godthelp et al. (1984). Also, the offsets and TLCs at the start of occlusion varied significantly more in the multiple-occlusion trials than in the single-occlusion trials, and therefore this finding provides stronger evidence for this perceptual ability. Furthermore, offset at the end of the previous occlusion acted as a predictor, with an increased offset associated with a reduction in OT. Again, drivers demonstrated the ability to adapt their subsequent OT based on their perception of lane position at the end of previous occlusion. These behaviors may be viewed as an anticipation of the future status of a dynamic situation (Endsley, 1995) without visual information (Chen & Milgram, 2022), indicating the ability to adapt to these situational circumstances.

In contrast to the single-occlusion models, in Model 3, the occlusion number emerged as a predictor of OT—specifically, as the drive progressed further, the OTs increased. This observation suggests a progressive shift in OTs towards greater confidence during the multiple-occlusion trial. Since in this trial the drive continued after unoccluding the driving view, it may have been more feasible to use the information during unoccluded periods to adjust the durations of subsequent occlusions due to the continuous nature of the drive. Here, in contrast to Model 1, greater steering amplitude during occlusion was associated with a decrease in OT. It is possible that drivers' uncertainty regarding lane position increased as they made larger steering wheel movements, which in turn led them to unocclude the scene faster, as suggested by Grahn et al. (2023). This effect could also be a result of correcting the lane position towards the lane center after an observed large offset and shortening the subsequent occlusions while making larger steering wheel movements until close to the center (cf. Wallis et al., 2007). Overall, given that OTs were shorter in the multiple-occlusion trial and there were fewer lane crossings compared to the single-occlusion trial, the OTs might have been based more on satisficing than on pushing to one's limits.

In Model 4, predicting TLC in the multiple-occlusion trial, the most influential predictor was the TLC at the onset of occlusion; a longer TLC before occlusion predicted a longer TLC during the occlusion. Additionally, the offset at the end of the previous occlusion was a predictor of TLC; an increase in the offset corresponded to a decrease in TLC. These findings are expected, as both variables can be regarded as (situational) indicator of lateral control performance, affecting one's performance during the following occlusion (Godthelp et al. 1984). As expected, lower driving speeds (from 100 to 60 km/h) were associated with longer TLCs, as lower speeds increased the time to cross the lane boundary. Similar to Model 2, larger steering movements during occlusion resulted in shorter TLCs, indicating that the participants' steering during occlusion was highly inaccurate and the inaccuracy increased with larger steering amplitudes, in line with, for instance, Godthelp (1985). Occlusion number was not a significant predictor of TLC, indicating that the participants did not learn to drive better under occlusion during the multiple-occlusion trial.

Additionally, a variable representing individual variability in lateral control performance (SDLP) during occlusion in the single-occlusion trial played the strongest role as a predictor of TLC: when the individual SDLP increased, TLC decreased. According to Verster and Roth (2011), SDLP values vary greatly between individual drivers also in normal driving. However, in Model 3, this individual factor was not a significant predictor for OT. Again, the ICC for TLC (Model 4: 3.9 %) was significantly lower than the ICC for OT (Model 3: 24.7 %), indicating that the subjective assessments of the spare visual capacity – or their individual OT preference levels – varied much more than their actual spare visual capacity in this lane-keeping task.

5.3 Lane crossings in the multiple-occlusion trial

TLC in Model 3 included both realized TLCs and estimated TLCs from the end of occlusion. In contrast, Model 5 investigated the predictors of odds to cross the lane boundary during an occlusion in the multiple-occlusion trial. The strongest predictor was individual variation in lateral control (SDLP) averaged over the 50 single-occlusion drives: when SDLP increased, the probability of lane crossing also increased. The second strongest predictor, although much smaller, was OT – a result that aligns with expectations and is similar finding as in Grahn et al. (2023). These findings, together with Model 3 predicting TLC, indicate that there are significant individual variations in the spare visual capacity even in a simple lane-keeping task. According to Spearman's rho test, there was no correlation between the SDLP and driving experience in years ($p = 0.275$), kilometers driven per year ($p = 0.710$), or lifetime kilometers ($p = 0.186$). This suggests that driving experience does not predict the inter-individual differences in lane-keeping accuracy while occluded, as suggested by the studies of Cavallo et al. (1988) and Kujala, Mäkelä, et al. (2016).

In Model 5, an increase in the offset at the end of the previous occlusion was associated with increased odds of a lane crossing in the following occlusion. Conversely, an increase in TLC when occlusion started was linked to decreased odds of a lane crossing. Based on Model 1 and 3, these variables are ones that drivers can perceive during unoccluded periods and should use for adapting their occlusion and steering behavior. However, it is worth noting that this adaptation may have not been sufficient – perhaps due to perceptual limitations – as according to Model 5, this did not help much in avoiding lane crossings. Additionally, larger steering amplitude during occlusion was associated with increased odds of a lane crossing, in line with Model 3 (TLC). Surprisingly, speed was not a significant predictor in this model. This might suggest that the participants were able to adjust their OTs and steering appropriately based on the driving speed for avoiding lane crossings.

5.4 Limitations and further research

There are some limitations to consider when evaluating the results. Firstly, even if the vehicle dynamics were accurately modelled, the experiment was conducted in a driving simulator, potentially limiting the generalizability of the findings. Also, the use of limited scenarios in the experiment could pose similar limitations to generalizability. Additionally, the absence of motion cues in the simulator affects participants' ability to sense lateral car movements, a factor worth exploring in future research. It would be valuable to investigate differences in lane crossings and OTs when these cues are on versus off.

Fixed speed was employed in this study to isolate the investigation on lateral vehicle control, minimizing noise in the data from longitudinal control. While drivers may utilize longitudinal control for lateral adjustment, our focus was primarily on lateral control for the purposes of our analyses. However, exploring longitudinal vehicle control within the same setting remains a potential avenue for future research. Furthermore, the possible use of mental arithmetic or other explicit cognitive processing on OTs is a subject for future inquiry; participants may have mentally counted the duration of their occlusion, which might represent ecologically invalid behavior due to the experimental design.

The observed TLC distributions had a long tail in comparison to the OT distributions. The long TLC values were a result of a coincidence of almost perfectly aligned steering angle in respect to the road geometry at the end of occlusion. While the very long TLC values (>70 s) were filtered before the analyses, these differences in the TLC and OT distributions might have affected the linear models. Here, TLC also assumes that the driver would have kept the same trajectory if they would have stayed occluded. Additionally, it should be noted that residuals in some models were not normally distributed, a factor to bear in mind when assessing the validity of the statistical models.

An additional avenue for future research is exploring the impact of participants' risk-taking tendencies on OTs. Ensuring a balanced representation of both low and high risk-takers in future occlusion studies may help to mitigate the possible influence of this tendency on experiment results.

6 Conclusions

In this study, we investigated the situational dynamics of visual information sampling in lateral vehicle control and compared subjective and objective spare visual capacity in driving. Drawing from a participant group of $N = 30$, our findings indicate that situational variables – such as speed, lane position and TLC of the car when the occlusion starts, and steering during occlusion – significantly influence spare visual capacity in lane keeping, as estimated by TLC.

Drivers appear capable of making small adjustments to their subjective estimates of this spare visual capacity (measured by OT) based on the same situational variables affecting TLC. However, their situational OT adjustments seem only gradual, and their OT choices appear to be primarily determined by individual preference level, possibly rooted in a personal uncertainty tolerance threshold or the rate of uncertainty growth while occluded. This level showed no association with driving experience or driver's general instability in lateral control, the latter suggesting that the drivers may not be fully aware of their steering skill level in the lane-keeping task. The unexplained inter-individual variability in OT, as a measure of subjective estimates of spare visual capacity, appears considerably larger than in TLC (objective spare visual capacity), potentially making it more challenging to predict. This was evident with the OT models' ICCs being 6–11 times as large as the TLC models' ICCs. Furthermore, the driver's general instability in lateral control emerged as the strongest predictor of lane crossing probability in continuous intermittently occluded driving. Together, these findings offer valuable insights into the situational dynamics of drivers' visual information sampling in lateral vehicle control and the available spare visual capacity in various situations, as well as drivers' adaptation and subjective estimates of this capacity. These results have a number of potential practical implications, especially in the development of personalized and contextually intelligent driver attention monitoring and warning systems.

CRediT authorship contribution statement

Hilkka Grahn: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Tuomo Kujala:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization, Formal analysis. **Toni Hautaoja:** Writing – review & editing, Formal analysis. **Dario D. Salvucci:** Writing – review & editing, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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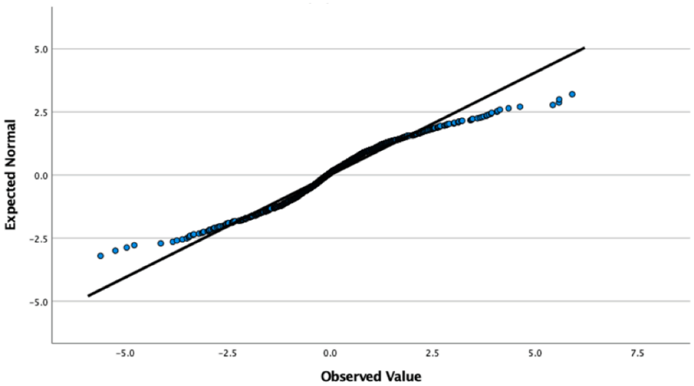
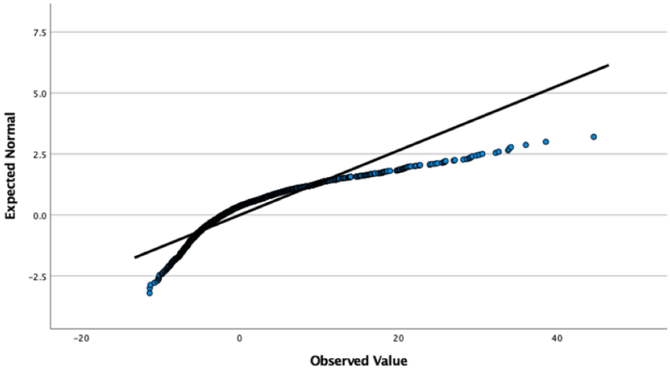
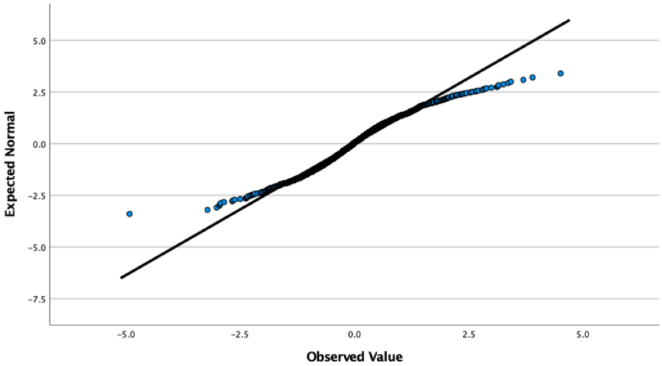
Appendix A



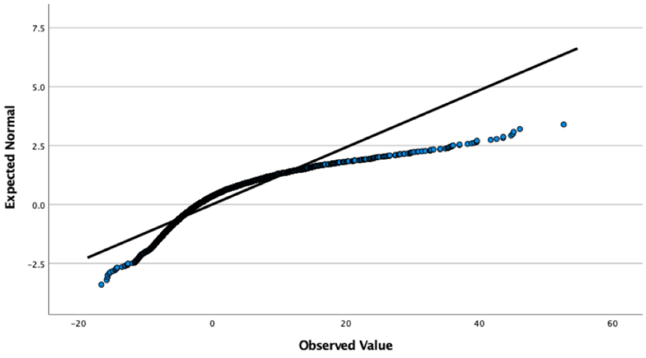
Normal Q-Q plot of residuals of OT in single-occlusion trials (Model 1).



Normal Q-Q plot of residuals of TLC in single-occlusion trials (Model 2).



Normal Q-Q plot of residuals of OT in multiple-occlusion trial (Model 3).



Normal Q-Q plot of residuals of TLC in multiple-occlusion trial (Model 4).

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