Transportation Research Part F: Psychology and Behaviour 118 (2026) 103522

Contents lists available at ScienceDirect

Transportation Research Part F: Psychology and Behaviour

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

Now or never: Eye tracking and response times reveal the dynamics of highway merging decisions

Arkady Zgonnikov *, Merijn van Niekerk, Yke Bauke Eisma, Joost de Winter

Department of Cognitive Robotics, Faculty of Mechanical Engineering, Delft University of Technology, Mekelweg 2, Delft, 2628CD, the Netherlands

A R T I C L E I N F O

Keywords:
Driver behavior
Attention
Decision making
Gap acceptance
Time pressure

A B S T R A C T

Merging onto a highway is a safety-critical task resulting in a large number of traffic accidents; fundamental research into merging behavior of human drivers can help reduce this toll. Two cognitive processes critical to merging, attention allocation and decision making, have been extensively studied in real-world and simulated driving scenarios. However, how these processes interact during highway merging remains poorly understood. While the relationship between attention and decision making has been widely examined in cognitive science, this work has largely relied on simple decision-making paradigms involving choices between static items on a computer screen, which limits the understanding of more dynamic and naturalistic decisions such as in driving. To address this gap, we investigated the relationship between attention and decision making in a simplified highway merging task. In a video-based experiment, participants (N = 24) repeatedly made merging gap acceptance decisions based on the dynamic information about the distance and time-to-arrival to the end of the merging lane and the gap to the target-lane vehicle (available in the front view and the side mirror, respectively). Participants' decisions, response times, and eye movements were recorded. We found that decisions to accept a gap were considerably faster than decisions to reject a gap. Decision outcomes and timing depended on the distance to and time-to-arrival of the target-lane vehicle, but also on the time pressure due to approaching the end of the merging lane. Most importantly, under high time pressure, a greater proportion of time spent looking at the side mirror was associated with a lower probability of accepting the gap. This finding indicates that differences in visual information sampling can be closely linked to decision outcomes when time budgets are constrained. Our results provide initial empirical insights relevant for future cognitive modeling of the interplay between decision making and attention during highway merging. This work can inform early-stage exploration of driver monitoring and support systems for partially automated driving.

1. Introduction

Merging onto a highway is a challenging task that often requires a driver to find an appropriate gap between vehicles within a limited amount of available time. This task is safety-critical, resulting in approximately 19,000 accidents per year in the US alone (Sen et al., 2003). Better understanding of human merging behavior can aid in designing improved traffic infrastructure (Zheng and Mcdonald, 2007), development of advanced driver assistance systems (Baumann et al., 2011; Duan et al., 2023; Gonçalves et al.,

* Corresponding author.
E-mail address: a.zgonnikov@tudelft.nl (A. Zgonnikov).

https://doi.org/10.1016/j.trf.2026.103522
Received 3 February 2025; Received in revised form 28 December 2025; Accepted 9 January 2026
Available online 16 January 2026

2022; de Winter et al., 2022) and automated vehicles capable of interacting with human traffic participants (Sadigh et al., 2018; Schwarting et al., 2019; Siebinga et al., 2024b), all of which have potential to reduce accidents related to merging.

Studies of natural human behavior on highways in the presence of another vehicle (or multiple vehicles) in the target lane have found that merging decisions are affected by gap sizes, the speed of the target-lane vehicle, and the distance to the end of the merging lane (Daamen et al., 2010; Marczak et al., 2013). Such studies provide insights into the outcomes of merging maneuvers, but commonly exclude the contribution of human factors, such as situation awareness and cognitive processing, which hinders in-depth understanding of merging decisions.

From a human factors perspective, a more fine-grained understanding of human behavior can be obtained by measuring drivers' eye movements during maneuvers in traffic (Ahlström et al., 2021; Salvucci and Liu, 2002). To make an informed and well-timed merging decision, the driver must allocate their attention between the road ahead (with a decreasing time budget as the driver approaches the end of the merging lane) and the vehicle in the target lane (the gap to which can be assessed, e.g., by glancing at the side mirror). Using eye tracking, previous studies investigated how drivers' visual attention is distributed while merging (Cheng et al., 2016; Mateo et al., 2018; Zheng and Mcdonald, 2007). However, existing literature on merging has predominantly focused either on the outcomes of the merging maneuver (decision making) or drivers' eye movements (attention), but has not explored the link between decision making and attention. An exception is the study by Gonçalves et al. (2022) who investigated how drivers' eye movements and timing of merging decisions are affected by kinematics of the merging situation and the information displayed on the car dashboard. However, more generally, the relationship between attention allocation and decision making dynamics remains unexplored in the context of highway merging despite being relevant for understanding human behavior in traffic. This relationship, however, has been extensively studied in basic and applied cognitive science.

1.1. Interplay between visual attention and decision making

Previous research has highlighted the mutual influences between attention and decision making. The evidence for the influence of attention on choice can be traced back to Zajonc (1968) who demonstrated the mere exposure effect: a stimulus that is attended to more is also preferred more by the decision maker; an effect that has been replicated in various studies since (Orquin and Loose, 2013). However, the mere exposure effect is often conflated with the utility effect, i.e., higher preference towards an option leading to a higher likelihood of visually attending to that option (Fantz, 1964; Orquin and Loose, 2013). Shimojo et al. (2003) hypothesized that the mere exposure effect interacts with the utility effect: the option that is attended to more becomes more preferred, which in turn entails increased likelihood of gazing towards that option, creating a "gaze cascade". The difficulty of disentangling the effects of preference on gaze from the effects of gaze on preference represents a challenge for theories and models that aim to explain the interaction between decision making and attention (Cavanagh et al., 2014; Krajbich et al., 2010; Thomas et al., 2019). However, despite making different assumptions about the mechanisms of gaze–preference interaction, virtually all such theories and models converge on the existence of at least some form of an effect of attention on choice, which has also been illuminated in a recent meta-analysis of empirical literature (Bhatnagar and Orquin, 2022). At the same time, both empirical and theoretical literature on the relationship between decision making and attention is mostly limited to traditional decision-making paradigms which typically display static information about two options in two dedicated areas of interest. It remains unknown whether the findings of such studies generalize to scenarios in which choice options are not associated with any specific area of interest, of which there are plenty in the real world beyond the laboratory — for instance, deciding whether or not to merge onto a highway.

1.2. This study

This study aimed to shed light on the cognitive underpinnings of merging decisions by measuring response timing and eye movements in a video-based paradigm. Using video stimuli allowed us to extend traditional decision-making paradigms from cognitive science to a more naturalistic task context and investigate the relationship between attention and decision making while avoiding confounding effects by disentangling choice options from the visual sources of information.

Our participants observed first-person-view video recordings of a vehicle driving in the merging lane (the *ego* vehicle); the videos were recorded in a driving simulation software. We varied the time-to-arrival and distance to the target-lane vehicle (which participants observed in the side mirror) and the time budget the participants had before the ego vehicle arrived at the end of the merging lane. Participants were asked to judge the situation and make a decision: accept the gap (merge in front of the target-lane vehicle) or reject the gap. Participants pressed either the accept or reject button on a keyboard as soon as they reached their decision, which allowed us to measure the duration of their decision process (response time). Additionally, the recordings of participants' eye movements during the task provided the means to measure how their visual attention was distributed during a decision. With this data at hand, we sought to answer two main research questions.

1.2.1. How does the timing of merging decisions depend on time pressure?

Response times (i.e., how long it takes one to arrive at a decision) can provide valuable insights about, e.g., choice strategy and experienced decision difficulty (Luce, 1986). Previous studies of timing of gap acceptance decisions demonstrated that response times in accept decisions are faster than in reject decisions in left-turn and overtaking decisions (Mohammad et al., 2024; Sevenster et al., 2023; Zgonnikov et al., 2024b). This difference can be attributed to the dynamic nature of the gap acceptance decision (early on in the decision process the evidence in favor of accepting the gap is stronger) and the increased time pressure to make the accept decision (if the gap is not accepted fast, the opportunity to take the gap would be gone). However, these previous studies extracted response times from vehicle trajectory data. This could have introduced systematic differences due to different measurement procedures used for response times in accept and reject decisions. Here we investigated whether this effect is replicated when the response procedure is unified (keyboard button presses).

Duration of the gap acceptance process has also been shown to depend on the kinematics of the vehicles in the scene. This is the case in pedestrian crossing (Pekkanen et al., 2022), left turns across path (Bontje and Zgonnikov, 2024; Zgonnikov et al., 2024a,b), and overtaking (Mohammad et al., 2024; Sevenster et al., 2023). However, response times during merging gap acceptance remain poorly understood. Up to now, gap acceptance response times during merging have only been investigated in a study by Gonçalves et al. (2022). They found that gap acceptance decisions become faster with increasing distance to the target-lane vehicle. However, Gonçalves et al. (2022) have not investigated the effects of other kinematic variables such as time-to-arrival of the target-lane vehicle and the merging lane time budget, which are both critical for gap acceptance decisions (Daamen et al., 2010; Marczak et al., 2013).

Based on the earlier findings in other gap acceptance scenarios, here we hypothesized that response times in accepted gaps will be shorter than in rejected gaps (*H1.1*). We also hypothesized that increasing the time-to-arrival (TTA) of the target-lane vehicle would increase both accept response times (*H1.2*) and reject response times (*H1.3*) due to reduced perceived time pressure for the driver to make the decision (Zgonnikov et al., 2024a). Because distance and TTA were manipulated independently, the distance manipulation would presumably not affect the perceived time pressure, only affecting the perceived size of the gap. The increasing distance would then present stronger evidence for the "accept" decision (and hence faster "accept" responses) but weaker relative evidence for the "reject" decision (and hence slower "reject" responses). We hence assumed that increased distance gaps would lead to reduced accept response times (*H1.4*) and increased reject response times (*H1.5*). Finally, merging is special in that the time budget to make the decision is constrained by the length of the merging lane. We hypothesized that larger time budgets would result in longer response times for both accepted (*H1.6*) and rejected gaps (*H1.7*), for the same reason of reduced time pressure.

1.2.2. Does attention distribution correlate with the outcome of the merging decision?

If a driver making a merging decision fails to see the target-lane vehicle, their merging decision would not depend on the kinematics of the target-lane vehicle. On the other hand, if one's attention is fully on the target-lane vehicle, they would presumably judge the gap to this vehicle accurately but would be unaware of their own proximity to the end of the merging lane. Between these two unlikely extremes are a multitude of different spatiotemporal attentional patterns. For instance, if a driver only looks at the target-lane vehicle for a fraction of a second, would their decision be the same as if they looked at it ten times as long?

Here we hypothesized that naturally occurring differences in attention allocation (as quantified by the total duration of fixations on the target-lane vehicle) are associated with differences in decision outcomes (i.e., the gap acceptance likelihood) (*H2*). This would imply that in conditions with relatively large gaps to the target-lane vehicle, whenever drivers look more at the side mirror, they would be more likely to accept the gap (since the information in the mirror contributes to the evidence that the gap is safe to accept). Conversely, in conditions where information in the side mirror (distance and TTA) favors rejecting the gap, greater attention to the mirror would be associated with lower gap acceptance rate. This hypothesis is grounded in theories and empirical studies of downstream effects of attention on decision making in simpler paradigms (Bhatnagar and Orquin, 2022; Krajbich et al., 2010; Orquin and Loose, 2013; Zajonc, 1968). Motivated by these findings, here we investigated whether participants' merging decisions would be correlated with where they look, and if so, under what circumstances.

2. Methods

2.1. Participants

A total of 24 (9 female, 15 male) volunteers participated in the experiment. Our key hypotheses concerned functional relationships at the individual participant level, hence we chose to collect a large number of observations per participant (Smith and Little, 2018). The number of participants was thus determined based on practical feasibility while keeping it above 20, a number previously shown to yield high levels of statistical power (given the large number of measurements per participant) for a variety of response time study designs (Miller, 2024). Simulation-based post-hoc power analysis of our experiment design for our key hypothesis (*H2*) revealed that the study was adequately powered to detect effects with magnitudes similar to the one observed (95% confidence interval for power $(0.89, 1.0)$ based on 30 simulations). Details and source code of power analysis simulations are available in online supplementary information.

The age of the participants ranged from 22 to 60 years (all but one of the participants were between 22 and 28 years old), with a mean age of 26.6 years and a standard deviation of 7.3 years. All participants provided written informed consent. The experimental protocol was approved by the TU Delft Human Research Ethics Committee.

2.2. Apparatus

The experiment was conducted using a 24.5-inch BENQ XL2540-B monitor, with a display resolution of 1920×1080 pixels. The video stimuli were recorded at 20 frames per second in the driving simulation software Prescan 2019.3.0. Eye movements of the participants were recorded using an SR Research EyeLink 1000 Plus eye tracker. Stimulus presentation, data recording, and experiment flow were controlled using SR Research Experiment Builder. To maximize data quality and minimize the amount of data loss, all participants used head support. The monitor was situated 100 cm from the head support. The experimenter used an adjacent computer to control the experiment. A photo of the setup is shown in Fig. 1.

Fig. 1. Experimental setup. Experimenter's computer is on the left-hand side.

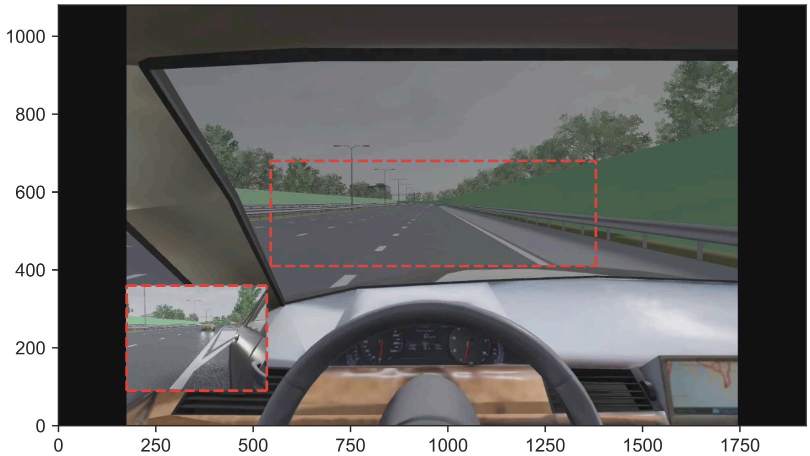

Fig. 2. Participant's view of the task. Red rectangles indicate areas of interest (side mirror and front view) used for data analysis and were not visible to the participants.

2.3. Task and stimuli

On each trial, a participant observed a first-person perspective recording of a simulated ego vehicle driving in the merging lane (referred to as "acceleration lane" in instructions to participants) while another vehicle drove in the target lane on the highway (Figs. 2 and 3). The target-lane vehicle was visible in the side mirror. The video stimuli were recorded at 20 frames per second using the driving simulator Prescan 2019.3.0. The participant's task was to press one of the two keyboard buttons depending on whether they thought the current situation represents a good opportunity for the ego vehicle to merge in front of the target-lane vehicle (LSHIFT) or not (RSHIFT). Importantly, this was not intended to reduce the real-world merging process to a discrete decision detached from continuous vehicle control; instead, the binary response procedure was used to obtain a well-defined temporal marker of decision commitment, allowing us to measure the timing of the perceptual-decisional process.

After the participant pressed one of the two buttons, the video playback continued until the ego vehicle reached the end of the merging lane, after which the next trial commenced. This was done to enable the measurement of eye movements after rejecting a gap. To elicit naturalistic responses despite the artificial nature of the button-press reporting procedure and the lack of visual feedback after a decision, we framed the task as providing guidance to an automated vehicle during highway merging. At the same time, we encouraged participants to make decisions as they would in real traffic by instructing them to respond as soon as they reached a decision and to judge gaps just as they would when driving on a real road.

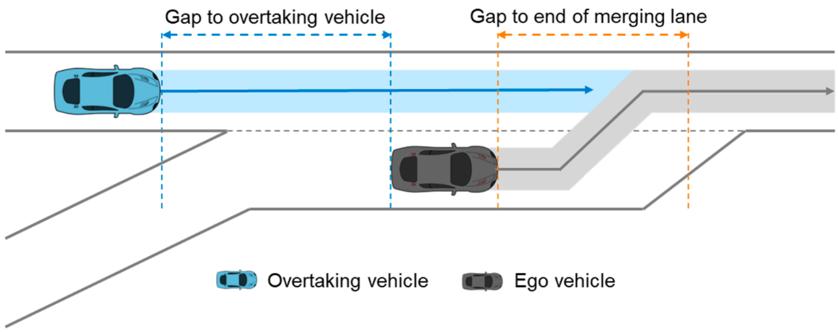

Fig. 3. Top-down view of the merging interaction.

Table 1
Overview of the experimental conditions. The three independent variables are denoted by an asterisk (*). The remaining variables were either held constant or varied directly with the independent variables. Distance to and time-to-arrival of the target-lane vehicle are relative to the ego vehicle.

	Distance to end of merging lane (m)	Time budget in merging lane (s)*	Speed of ego vehicle (m/s)	Distance to target-lane vehicle (m)*	Time-to-arrival of target-lane vehicle (s)*	Speed of target-lane vehicle (m/s)	Relative speed of target-lane vehicle (m/s)
Video 1	132	**4**	33	**20**	**4**	38.0	5.0
Video 2	132	**4**	33	**20**	**6**	36.3	3.3
Video 3	132	**4**	33	**30**	**4**	40.5	7.5
Video 4	132	**4**	33	**30**	**6**	38.0	5.0
Video 5	132	**4**	33	**40**	**4**	43.0	10.0
Video 6	132	**4**	33	**40**	**6**	39.7	6.7
Video 7	132	**6**	22	**20**	**4**	27.0	5.0
Video 8	132	**6**	22	**20**	**6**	25.3	3.3
Video 9	132	**6**	22	**30**	**4**	29.5	7.5
Video 10	132	**6**	22	**30**	**6**	27.0	5.0
Video 11	132	**6**	22	**40**	**4**	32.0	10.0
Video 12	132	**6**	22	**40**	**6**	28.7	6.7

The exact task instructions were as follows: *"Imagine you are an expert driver whose job is to teach an autonomous vehicle (AV) how to handle merging situations on a highway. You will view multiple videos of an AV driving in an acceleration lane. You will see that another car is already driving on a highway. Your task is to instruct the AV which situations represent a good opportunity to merge onto a highway, depending on the distance to that car and its speed. Your task is to press LSHIFT if you would like the AV to merge in front of the approaching car on the highway. Alternatively, press RSHIFT if you do not want the AV to merge in front of the approaching car. Please decide just like you would decide when driving on a real road. Press one of the keys as soon as you arrive at your decision. Keep in mind that in the videos, the AV will not actually merge but will stay on the acceleration lane. Keep looking at the video and assess the situation until the video ends."*

Here, the instruction to decide "*just like you would decide when driving on a real road*" was critical as it was intended to elicit experience-based judgments. Indeed, participants were shown dynamic visual scenes from the driver's perspective and asked to judge whether a gap was acceptable for merging; the task required them to evaluate the situation in real time, without guidance or constraints from an automated system. As such, the task was designed to elicit key perceptual and decision-making processes involved in merging behavior during manual driving, rather than abstract supervisory judgments.

2.4. Study design

The experiment followed a 2 × 2 × 3 within-subject design with three independent variables: 2 values of the time budget in the merging lane (i.e., the time it takes the ego vehicle to arrive at the end of the merging lane) × 3 values of the distance gap to the target-lane vehicle × 2 values of the time-to-arrival of the target-lane vehicle (with respect to the ego vehicle). The distance gap between the vehicles and time-to-arrival of the target-lane vehicle were manipulated independently by varying the relative speed of the target-lane vehicle with respect to the ego vehicle (Table 1). Because TTA is defined as the ratio of distance to speed, we were able to present the same TTA using different distances by adjusting the target-lane vehicle's (relative) speed accordingly. For example, a TTA of 4 s could correspond to a distance of 20, 30, or 40 m if the relative speed of the target-lane vehicle was set to 5, 7.5, or 10 m/s, respectively. This approach allowed us to decouple the effects of distance and TTA in participants' gap acceptance decisions.

Each of the resulting 12 conditions (Table 1) was repeated 30 times for each participant, leading to a total of 360 trials per participant. The number of repetitions per condition per participant was chosen to enable reliable estimation of response times as well as to allow future studies to use our data for cognitive process modeling (Bachmann and Maanen, 2024). The order of the trials was randomized within blocks of 60 trials, such that each block comprised five repetitions of each condition.

Time budget in the merging lane, time-to-arrival and distance to the target-lane vehicle were chosen as independent variables based on previous studies of naturalistic human merging behavior which highlighted these as the key factors influencing gap acceptance (Daamen et al., 2010; Marczak et al., 2013). Other variables that affect gap acceptance include accelerations of the ego vehicle and target-lane vehicle, as well as distance to the leading vehicle (if it is present on the highway) and its velocity. These were not included in this study for reasons of simplicity and to keep the number of observations per condition per participant as high as possible.

The levels of independent variables — time budget: 4 s or 6 s; distance to the target-lane vehicle: 20 m or 30 m or 40 m; TTA: 4 s or 6 s — were chosen (and calibrated in a pilot study) in such a way that the condition with the highest proportion of accepted gaps (hypothetically: time budget 4 s, distance 40 m, TTA 6 s) would mostly result in “accept gap” decisions but also occasionally elicit “reject gap” responses. Similarly, the condition with lowest time pressure (time budget 6 s) and smallest gap (distance 20 m, TTA 4 s) was intended to lead to the gap rejected most of the time but still occasionally accepted. This was done to enable the measurement of response times and attention distribution in “rare” decisions — small gaps that were still accepted and large gaps which were nevertheless rejected.

2.5. Experimental procedure

At the start of the experiment, the participants were briefed on the objective of the experiment, i.e., to gain insight into the decision-making behavior of human drivers, and that such information could prove valuable in improving the decision-making behavior of automated vehicles. Participants then experienced an interactive demonstration comprising ten trials. In each of these demo trials, a video of merging (Video 12, Table 1) was played for 2 s, followed by a text instruction on the screen prompting participants to press either the LSHIFT or RSHIFT key. Upon pressing a key, another video was played in which the ego vehicle would either merge in front of or behind the target-lane vehicle, based on the pressed key. The purpose of this demo was to familiarize participants with the specific maneuver associated with each instruction, since such feedback was not provided during the main experiment.

Following the demo, participants were presented with the task instructions (see the text above), followed by 20 practice trials. The practice trials were conducted using Videos 1, 6, 7, and 12, each repeated five times. During the practice trials, the experimenter observed the participants to ensure they comprehended the task correctly. If required, additional verbal instructions were provided to clarify the task.

Following the practice sessions, the participants were informed that for the remaining duration of the experiment, they had the option to take a break (to alleviate fatigue) and lift their heads from the head support after every set of 60 trials. Additionally, participants were instructed that they could look away from the screen every ten trials, while still maintaining their head in the head support. After these final instructions were presented, a nine-point eye-tracker calibration was initiated. After calibration, the main experiment (360 trials) began. After every trial, a fixation cross was displayed at the center of the screen for 0.3 s. After every set of 60 trials, if a participant opted to lift their head from the head support, the eye-tracker calibration was performed before the subsequent set.

2.6. Data preprocessing and analysis

The raw data recorded during the experiment included participants’ gaze positions of the left and right eyes (in pixels, recorded at 1000 Hz), the *decision outcome* (based on the button pressed: LSHIFT — accept the gap; RSHIFT — reject the gap) and *response time* (the time between the start of video playback and the moment the participant pressed one of the response buttons). Before the analysis, the gaze data for the two eyes were averaged to obtain the mean gaze position, and downsampled to 100 Hz to facilitate data visualization. Six trials with no indicated decision were excluded from the analysis, resulting in 8634 trials analyzed across 24 participants.

We defined two areas of interest on the screen (Fig. 2): the side mirror (containing the information on the target-lane vehicle) and the front view (containing the information on the remaining space in the merging lane). For every trial, we then calculated the *relative dwell time on the mirror* — the percentage of trial time (until the response button was pressed) the participant spent looking at the side mirror. As an example, if the response time was 2 s and the participant in total spent 1.2 s looking at the mirror (after the video started but before they pressed the button), the relative dwell time on the mirror would be $1.2\ \mathrm{s}/2\ \mathrm{s} = 0.6$.

The trial-level metrics obtained from pre-processed data thus included the decision outcome (accept the gap (merge) or reject the gap (not merge)), response time, and relative dwell time on the mirror.

Mixed-effect models coded in pymer4 (Jolly, 2018) were used for statistical analyses, with maximum interaction and random effects structure permitting model convergence. Decision outcomes were coded as 0 (reject) and 1 (accept). All other variables were z-scored for the purpose of regression analyses. For the response time model, we computed the Type III sum-of-squares ANOVA table using the Satterthwaite approximation of degrees of freedom, and performed post-hoc tests to analyze marginal effects for the two decision outcomes separately. “Accept” was set as a reference level for the decision outcome factor in the response time model.

3. Results

3.1. Validity checks

Laboratory studies using simplified, video-based driving tasks have previously been shown to provide valid and informative measures of driver behavior, particularly for perceptual and decisional processes that precede vehicle control. For example, early

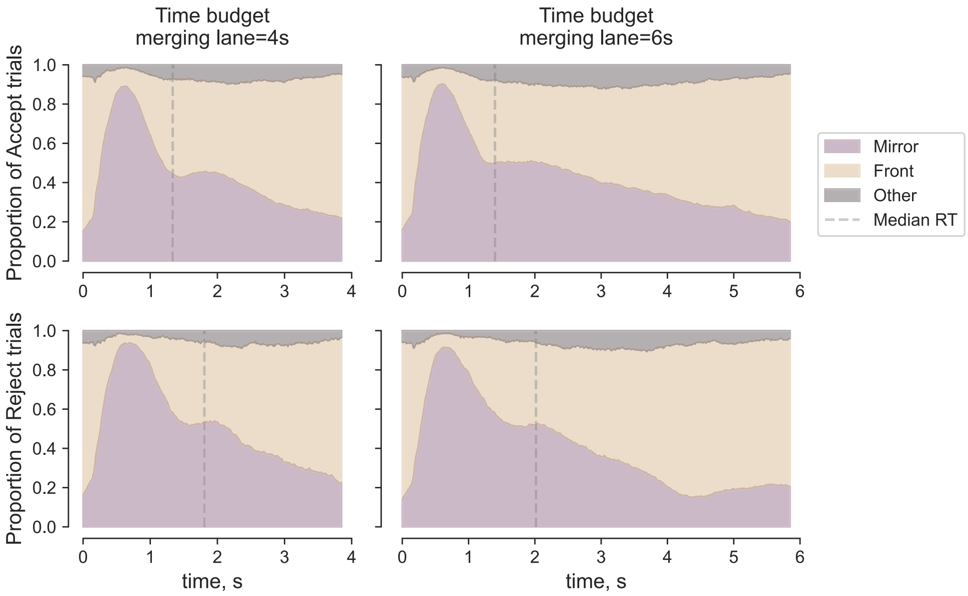

Fig. 4. Average attention distribution over time in accept (top row) and reject (bottom row) decisions: Proportion of trials in which participants looked at the areas of interest (mirror, front view, other) over time. Duration of each trial was equal to the time budget in the merging lane. Median RT is indicated for reference.

work demonstrated that dynamic video stimuli are sufficient to elicit attentive behavior characteristic of real driving, even in the absence of active vehicle control: "*the absence of a driving task has no substantial effect on attentive behaviour suggesting that the visual information presented by the movie film is sufficient to generate attentive processes characteristic of driving*" (Hughes and Cole, 1986). More recent video-based and non-interactive laboratory studies have successfully examined lane-changing and merging-related judgments (Eisma et al., 2022; Jokhio et al., 2024). They revealed systematic effects of surrounding traffic configuration on drivers' decisions and response timing that are consistent with findings from more interactive simulator studies. Together, these studies indicate that video-based paradigms can capture core aspects of driver perception and decision making when the relevant visual and temporal cues are preserved.

In line with this literature, participants' behavior in the present study exhibited patterns that closely match those reported in studies of gap acceptance during real-world merging and high-fidelity simulated driving. Specifically, the temporal dynamics of gaze behavior observed in the present experiment were consistent with prior eye-tracking studies of merging and lane-change maneuvers. Participants typically directed their gaze forward at the start of the trial, followed by glances toward the side mirror to assess the target-lane vehicle, and subsequently returned their gaze to the forward view as the decision progressed (Fig. 4). Similar gaze sequences—characterized by an initial focus on the road ahead, followed by mirror checks during gap assessment—have been reported in simulator and on-road studies of merging and lane changing (Cheng et al., 2016; Mateo et al., 2018; Salvucci and Liu, 2002; Tijerina et al., 2005). While the spatial layout of mirrors in our task is necessarily simplified, the temporal structure of information sampling appears consistent with naturalistic merging. This correspondence suggests that the simplified visual scene was sufficient to evoke naturalistic patterns of visual information sampling during merging decisions.

Furthermore, the probability of accepting a gap increased with both the distance gap and the time-to-arrival (TTA) of the target-lane vehicle, and decreased with the time budget provided by the merging lane (Fig. 5a, b and Table 2). This is consistent with empirical observations from instrumented vehicles, roadside measurements, and simulator studies (Daamen et al., 2010; Kondyli and Elefteriadou, 2012; Marczak et al., 2013). Moreover, the distribution of accepted gap sizes in our data was quantitatively consistent with empirical observations from real-world merging. Across the two TTA conditions, distance gaps of 20 m were approximately equally likely to be accepted or rejected, whereas distance gaps of 40 m were accepted in the majority of trials, similar to the distribution of accepted/rejected gaps reported for naturalistic merging data by Marczak et al. (2013).

Finally, response times in our data varied systematically with TTA and distance (Fig. 5c–f and Table 3), similar to earlier findings from interactive simulator studies of merging and lane-change maneuvers (Gonçalves et al., 2022) as well as from related gap acceptance tasks such as left turns and overtaking (Bontje and Zgonnikov, 2024; Mohammad et al., 2024; Sevenster et al., 2023; Zgonnikov et al., 2024a,b). Importantly, our response times were of a similar order of magnitude as those reported in simulated interactive gap acceptance by Bontje and Zgonnikov (2024), Mohammad et al. (2024), Zgonnikov et al. (2024b): approx. 1 s in accepted gaps and approx. 2 s in rejected gaps. The presence of well-established functional dependencies and similarity of absolute response time values suggest that our simplified task elicited decision timing patterns consistent with those observed in more naturalistic settings.

Table 2
Standardized coefficients of the mixed-effects logistic regression describing the final decision. All effects were modelled as random slopes per participant: `decision ~ 1 + distance + TTA + time budget + (1 + distance + TTA + time budget) | participant`.

	β	SE	z	p
(Intercept)	1.30	0.26	4.90	< 0.001
distance	0.54	0.11	4.97	< 0.001
TTA	1.84	0.12	15.71	< 0.001
time budget	-0.42	0.10	-4.26	< 0.001

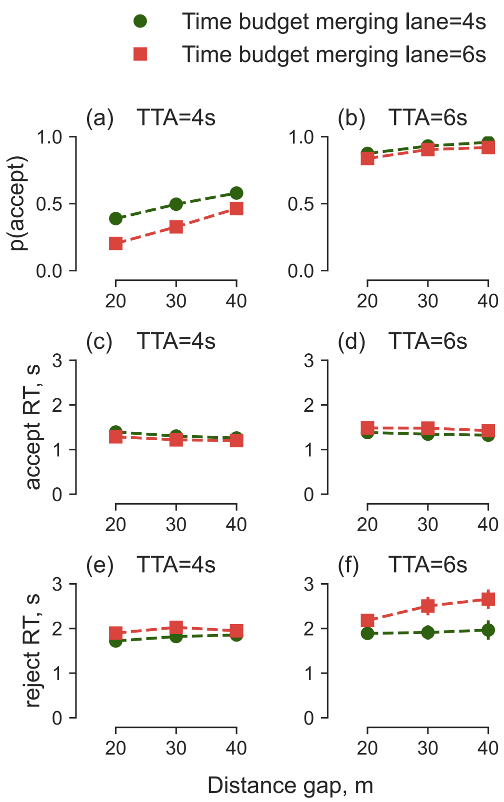

Fig. 5. Probability of accepting the gap (a and b) and mean response times in accepted (c and d) and rejected gaps (e and f) as a function of time-to-arrival (TTA) and distance gap to the target-lane vehicle and merging lane time budget. Error bars reflect 95% confidence intervals, and are smaller than marker size in most conditions.

3.2. How does the timing of merging decisions depend on time pressure?

We hypothesized that response times in accept decisions would be lower than in reject decisions (*H1.1*); we found that this was indeed the case ($\Delta = 0.69$ s, $t = 11.4$, $p < 0.001$, Table 3, Fig. 5c–f). This difference can be attributed to two factors: a) “accept” decision being a “cognitive default” in a merging situation (as the driver would normally merge in the target lane eventually, even after rejecting the gap), and b) evidence in favor of accepting the gap being strongest early on in the decision process; the longer the driver deliberates, the smaller the gap becomes, making slow accept decisions unlikely.

In accordance with our hypothesis *H1.2*, accept response times were slightly shorter in trials with shorter TTA ($\beta = 0.04$, $t = 3.8$, $p < 0.001$, Fig. 5c and d), confirming previous observations that time pressure imposed by the closing gap leads to faster decisions. Confirming *H1.4*, accept response times slightly decreased with distance ($\beta = -0.04$, $t = -3.9$, $p < 0.001$, Fig. 5c and d).

Finally, the time budget provided by the merging lane increased accept response times (as hypothesized in *H1.6*), but only in trials with the larger time-to-arrival of the target-lane vehicle (marginal effects $\beta = 0.01$, $t = 0.76$, $p = 0.22$ for TTA = 4 s, $\beta = 0.1$, $t = 9.27$, $p < 0.001$ for TTA = 6 s, Fig. 5c and d; see also interaction effect TTA:time budget in Table 3).

Table 3
Standardized coefficients of the mixed-effects linear regression describing response times. Random slope of decision was included per participant: `RT ~ 1 + decision*(TTA*time budget + distance) + (1 + decision) | participant`. "Accept" was set as a reference level for the decision outcome factor. Degrees of freedom were estimated using the Satterthwaite approximation.

	β	SE	DF	t	p
(Intercept)	-0.26	0.12	23.08	-2.19	0.039
decision	1.08	0.09	23.99	11.38	< 0.001
distance	-0.04	0.01	8579.89	-3.94	< 0.001
TTA	0.04	0.01	8589.92	3.76	< 0.001
time budget	0.06	0.01	8579.98	5.69	< 0.001
TTA:time budget	0.04	0.01	8579.08	4.42	< 0.001
decision:distance	0.09	0.02	8591.99	5.67	< 0.001
decision:TTA	0.28	0.02	8599.40	12.95	< 0.001
decision:time budget	0.13	0.02	8583.27	6.18	< 0.001
decision:TTA:time budget	0.04	0.02	8581.32	1.98	0.048

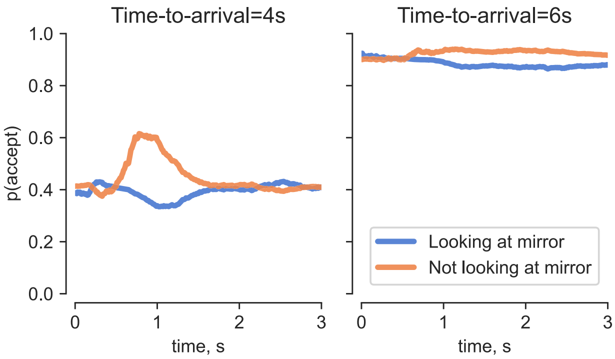

Fig. 6. Proportion of accepted gaps in trials where participants looked (or did not look) at the mirror at a given time t. To obtain the plot in each panel, for each time point t, we split all trials into two groups: those in which participants were looking (blue) or not looking (orange) at the side mirror at time t. We then calculated the proportions of accepted gaps in both these groups. This was repeated for all t between 0 s and 3 s, with the step of 10 ms. As an example, the proportion of accepted gaps in TTA = 4 s trials (left panel) in which a participant was not looking at the side mirror (orange line) at $t = 1$ s was 0.59. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We observed that response times in reject decisions increased with the TTA ($\beta = 0.28$, $t = 13$, $p < 0.001$), distance ($\beta = 0.09$, $t = 5.7$, $p < 0.001$), and time budget ($\beta = 0.13$, $t = 6.2$, $p < 0.001$) (Fig. 5e and f). This confirmed *H1.3*, *H1.5*, and *H1.7*, respectively.

Overall, we found that response times in accept decisions are much shorter than those in reject decisions, and that in both decisions response times tend to be shorter in the presence of time pressure (smaller TTA/time budget) and in the absence of visual cues disfavoring that decision (such as larger distances for rejected gaps). At the same time, the observed effects of the kinematic variables on accept response times were small while reject response times were affected stronger, especially by the TTA.

3.3. Does the distribution of attention correlate with the outcome of the merging decision?

We observed that eye movements during the initial stage of the decision process have little to no predictive power regarding the decision outcome (Fig. 6, 0 to approx. 0.5 s). At the same time, trials in which participants did not look at the mirror around 1 s were associated with a substantially increased likelihood of accepting the gap in the TTA = 4 s condition (Fig. 6, left panel, 0.5 to approx. 1.5 s). However, this association could be a direct consequence of the baseline differences in response times between accepted and rejected gaps: participants would inevitably look at the mirror for a longer time (or more often) if they did not accept the gap early on (Fig. 4).

To disentangle the association between decision outcomes and gazing behavior from the potential confounding effect of response time, we analyzed the probability of gap acceptance as a function of relative dwell time on the mirror while controlling for response time. We found that participants' probability of accepting the gap was negatively associated with the proportion of decision time they spent looking at the side mirror (Table 4 and Fig. 7). This association seemed to be present on average across all trials ($\beta = -0.32$, $z = -4.9$, $p < 0.001$). However, a closer inspection revealed that this effect was mostly limited to trials with lower time budget provided by the merging lane (interaction between time budget and relative dwell time on the mirror: $\beta = 0.24$, $z = 4.8$, $p < 0.001$), thereby only partially confirming *H2*.

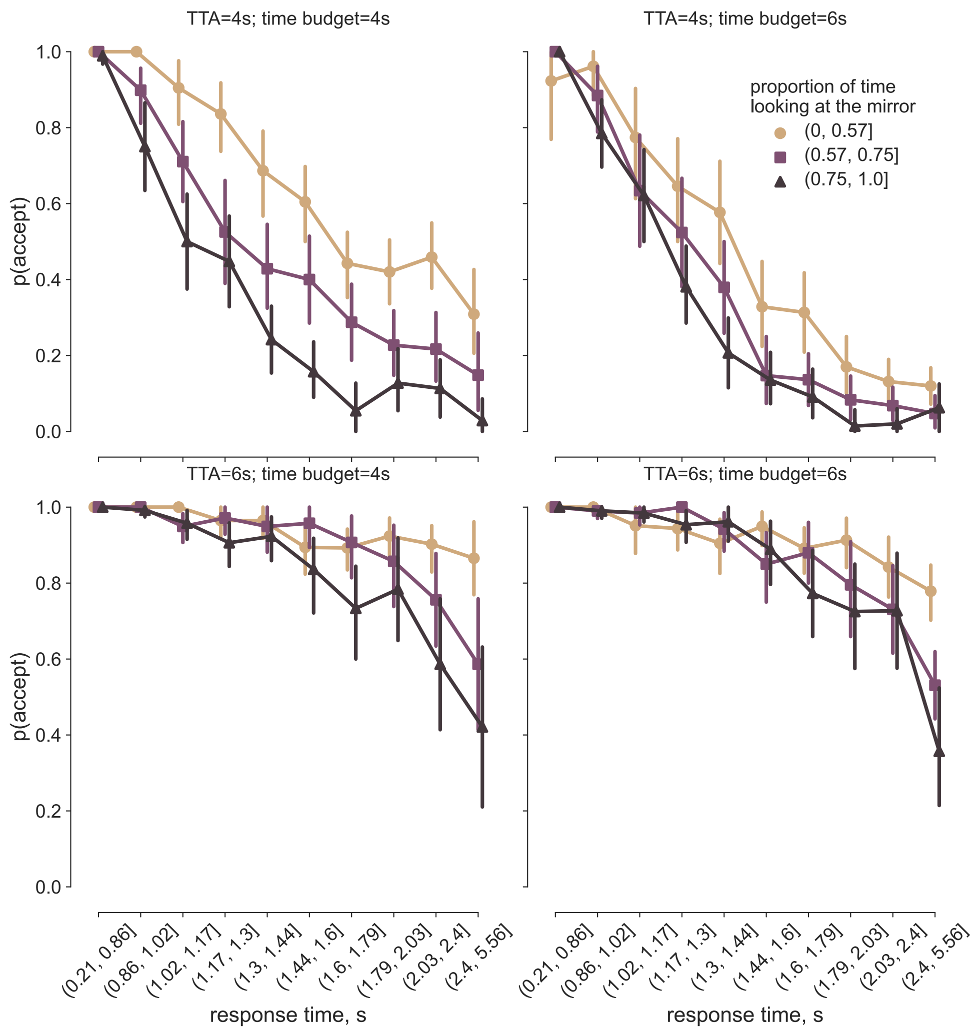

Fig. 7. Relationship between the proportion of time participants spent looking at the side mirror and the probability of accepting the gap, controlling for response time. For visualization purposes, response time and dwell time values were discretized into ten and three equal-sized bins, respectively. Error bars: 95% confidence intervals.

Table 4
Standardized coefficients of the mixed-effects logistic regression describing the decision outcome as a function of kinematic variables, response time, and relative dwell time. Random slopes of distance and TTA to the overtaking vehicle and the time budget provided by the merging lane were included per participant: `decision ∼ 1 + RT + (distance + TTA + time budget) * % dwell time mirror) + (1 + distance + TTA + time budget) | participant`.

	β	SE	z	p
(Intercept)	1.77	0.33	5.41	< 0.001
distance	0.51	0.12	4.15	< 0.001
TTA	2.24	0.16	13.59	< 0.001
time budget	-0.28	0.08	-3.61	< 0.001
% dwell time mirror	-0.32	0.07	-4.86	< 0.001
RT	-1.97	0.06	-30.90	< 0.001
distance:% dwell time mirror	-0.15	0.05	-2.82	0.005
TTA:% dwell time mirror	0.13	0.06	2.02	0.044
time budget:% dwell time mirror	0.24	0.05	4.83	< 0.001

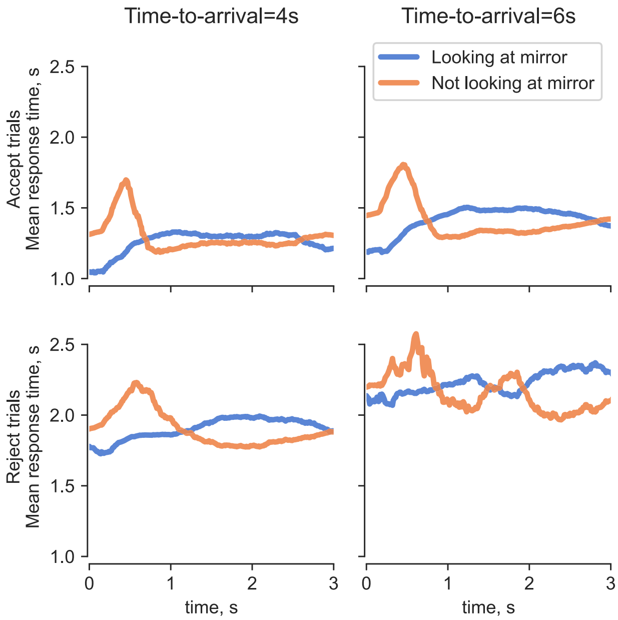

Fig. 8. Mean response time for trials in which participants looked (or did not look) at the mirror at a given time. To obtain the plot in each panel, for each time point t, we split all trials into two groups: those in which participants were looking (blue) or not looking (orange) at the side mirror at time t. We then calculated the mean response times in both these groups. This was repeated for all t between 0 s and 3 s, with the step of 10 ms. As an example, mean response time in TTA = 4 s accept trials (top left panel) in which a participant was not looking at the side mirror (orange line) at $t = 1$ s was 1.2 s. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The negative relationship between dwell time on the side mirror and decision outcome is especially striking for TTA = 4 s, time budget = 4 s — the most ambiguous condition for the participants across the three distance gap levels (as suggested by Fig. 5a). For instance, in trials with response times ranging from 1.3 s to 1.44 s, participants accepted most of the gaps (about 70%) if they looked at the mirror less than 57% of total trial time so far, but rejected most of the gaps (about 25% gap acceptance rate) if they looked at the mirror more than 75% of the trial time (Fig. 7, top left panel). This suggests that in trials with comparable response times, differences in attention allocation could be associated with major differences in decision outcomes.

In trials with the larger time budget, the association between the decision outcome and dwell times was less pronounced. This suggests that with less time pressure, differences in drivers' attention allocation patterns were less strongly associated with decision outcomes. Interestingly, despite differences suggested by Fig. 7, there was only weak evidence for an interaction between dwell time on the mirror and TTA ($\beta = 0.13$, $z = 2.0$, $p = 0.044$). There was however an interaction of dwell time with the distance to the target-lane vehicle, suggesting that the negative association between dwell time and decision outcome was more pronounced at larger distances ($\beta = -0.15$, $z = -2.8$, $p = 0.005$).

To illuminate the dynamics of participants' decision-making over time, we examined mean response times depending on whether participants were looking at the mirror. We found that if participants looked at the mirror early on, they were more likely to reach a decision swiftly, regardless of which decision was eventually made (Fig. 8). This could be observed already within the first half-second after the start of the trial (that is, well before the decision was indicated in most trials), especially in accept trials. If a participant kept looking at the mirror from 1 s onward, this was associated with slower decision making.

To further investigate the complex relationship between decisions, response times, and gaze behavior, we analyzed individual differences between participants (Fig. 9). There was no evidence that looking at the mirror early correlated with participants' gap acceptance probability ($r = 0.07$, $p = 0.74$ and $r = -0.04$, $p = 0.85$, for TTA = 4 s and TTA = 6 s, respectively). Participants who were more likely to look at the mirror 0.3 s after the video started were also quicker to arrive at a decision ($r = -0.53$, $p = 0.008$ and $r = -0.65$, $p < 0.001$ for TTA = 4 s and TTA = 6 s, respectively). In other words, participants' mirror-looking behavior can, to a certain extent, be used to predict individual differences in speed at which participants make their decisions. Yet, one's tendency to look at the mirror early does not provide a reliable prediction regarding how likely they are to accept gaps on average.

4. Discussion

By probing response timing and eye movements of participants, we scrutinized the cognitive dynamics of merging gap acceptance decisions. Our data revealed that variables that have long been known to affect the outcome of gap acceptance decisions — the size of the gap and the time pressure — also affect the timing of these decisions. Most importantly, we demonstrated that under time pressure, the duration of glances at the side mirror can correlate with the outcome of the gap acceptance decisions.

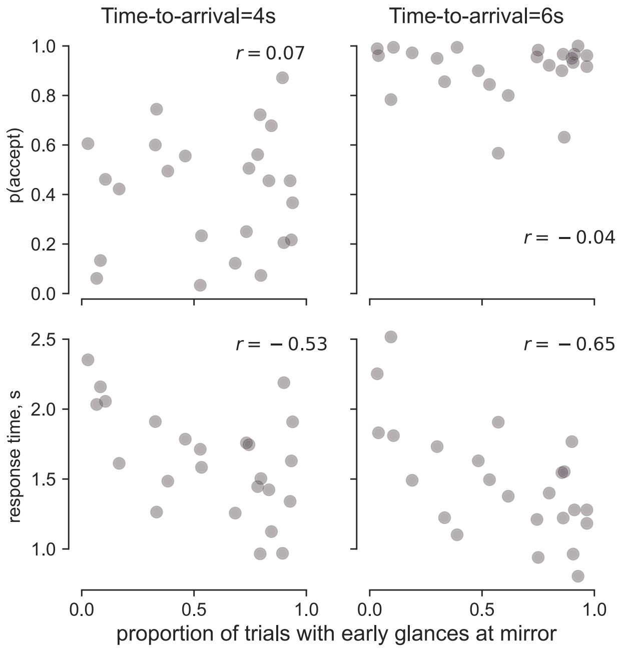

Fig. 9. Relationship between within-participant average probability of accepting the gap (top row) and response time (bottom row) and proportion of trials with at least one early glance at the mirror (within 0.3 s after the start of the decision). Each data point represents one participant.

4.1. Response times characterize the time course of merging gap acceptance decisions

In cognitive psychology, the duration of the decision making process has proved to be a valuable measure providing a high-level insight into the dynamics of cognitive processing (Luce, 1986). In driver behavior, response times have been extensively studied in the context of take-over requests (Zhang et al., 2019), but until recently have been left out of investigations of tactical decision making, including merging. Our study contributes to the emerging body of literature demonstrating that timing of gap acceptance decisions depends on the characteristics of the gap size. Our results are consistent with the finding of Gonçalves et al. (2022) that response times in accepted gaps decrease with distance — the effect that has also been reported for overtaking (Mohammad et al., 2024; Sevenster et al., 2023) but not left-turn gap acceptance (Bontje and Zgonnikov, 2024; Zgonnikov et al., 2024a). Furthermore, our data generalize the results of Gonçalves et al. (2022) in multiple ways. First, the positive effect of the time-to-arrival of the target-lane vehicle on response time has been reported earlier in overtaking (Mohammad et al., 2024) and left-turn gap acceptance (Bontje and Zgonnikov, 2024; Zgonnikov et al., 2024a,b); here we showed that it also applies to merging. Second, we analyzed response times not only in accepted but also rejected gaps, revealing that larger distance gaps lead to longer reject response times. Third, among the gap acceptance tasks, merging is unique in that reaching the end of the merging lane imposes an additional time constraint for making the decision; we found evidence that increasing this time budget leads to increased response times in both accept and reject decisions.

In addition to the relationship between kinematic variables and response times, we found that the speed at which a decision was made was strongly associated with the decision outcome: accept decisions were substantially faster than reject decisions. An explanatory factor of this asymmetry in response times can be found in the limited time available to make a decision, where the longer one waits, the more critical the situation becomes. Accepting the gap requires a certain level of boldness, i.e., a liberal decision threshold, whereas a reject decision can be preceded by a phase of accumulating information about the traffic situation to assure oneself that the gap is indeed too small; taking more time will only reinforce this decision.

These assertions are consistent with prior research which focused on response times for accept and reject decisions in left-turn gap acceptance (Zgonnikov et al., 2024b) and overtaking maneuvers (Mohammad et al., 2024; Sevenster et al., 2023) in the presence of an oncoming vehicle. In those studies, it was posited that the response times for accepted gaps were quicker than for rejected gaps due to the early evidence favoring accepting the gap, as well as the urgency associated with accepting a gap. This aligns with an extensive body of research examining the speed at which drivers regain control from an automated vehicle as a function of time budget until a collision (Zhang et al., 2019): the empirical evidence indicates that take-over times tend to be quicker when the time budget is shorter (Eriksson and Stanton, 2017; Zhang et al., 2019). In comparison, when a larger time budget exists, drivers are inclined to first evaluate the situation, and increase situational awareness before making a decision. In summary, a plausible explanation for the faster response times for accept decisions compared to reject decisions is the limited time budget: prompt action is required to accept the gap. We believe that the asymmetry in accept/reject response times can be informative for studies on reaction times in cognitive psychology at large, particularly concerning individual differences in response criteria.

4.2. Implications of the association between decision making and attention in merging

4.2.1. Implications for the study of human cognition

In simple binary choice (for example, between two food items), the longer one looks at a choice option, the more likely they are to choose it (see Bhatnagar and Orquin, 2022; Orquin and Loose, 2013, for review). Krajbich et al. (2010) proposed that this can be due to a causal effect of attention allocation on decision making. At the same time, there is no consensus in the literature on this explanation, as these observations could often be explained by the utility effect — “better” choice options are naturally looked at more often (Orquin and Loose, 2013; Shimojo et al., 2003). This hampers theorizing about the interplay between attention and decision making (Bhatnagar and Orquin, 2022; Orquin and Loose, 2013). Furthermore, current findings on the link between decision making and attention are mostly limited to static tasks in which each choice option is inherently represented by a spatial area of interest (typically, an image or a text description of the option). However, in many real-world tasks, choice options do not necessarily map onto visual areas of interest, making a direct replication of this effect difficult.

In our merging task, the two choice options (accept or reject the gap) are not mapped to any particular location in the visual scene. This goes beyond experimental paradigms traditionally used to study the role of attention in decision making by disentangling the choice options from the sources of information, eliminating the possibility of utility effect and correspondingly the gaze cascade effect (Fantz, 1964; Shimojo et al., 2003). Still, we found evidence for an association between attention allocation and decision making in this task, which is in line with the previous evidence from more basic tasks. We thus believe that tasks with naturalistic stimuli like ours can contribute to advancing the understanding of underlying cognitive mechanisms by providing a novel kind of testbed for process models of the interplay of attention and decision making.

While existing models have yet to be adapted to the dynamic nature of such tasks to allow for quantitative testing, some of these models are inherently more suitable for dynamic tasks than others. For instance, the mere exposure effect (Zajonc, 1968) and the gaze cascade hypothesis (Shimojo et al., 2003) imply that longer gaze at an option would increase the likelihood of choosing that option no matter its value. This implication is difficult to interpret in the context of our task: even if our choice options could hypothetically be represented by some values, they are not per se represented by any areas of interest, hence the theories that attribute interaction of attention and decision making to these effects would not apply to such scenarios. On the other hand, the models which integrate visual attention and evidence accumulation (Cavanagh et al., 2014; Krajbich et al., 2010; Thomas et al., 2019) postulate that longer fixations on an option would increase the likelihood of choosing that option if the value of that option is relatively high, and decrease it if the value is relatively low. Translated to our task, this would imply that the likelihood of gap acceptance should increase with the proportion of time the information favoring the “accept gap” is attended to, and decrease with the dwell time on the information that supports rejecting the gap. Our findings are in principle consistent with this implication. For instance, the effect of dwell time on the mirror on gap acceptance likelihood and its interaction with the kinematic conditions (Table 4 and Fig. 7) could result from gaze-contingent evidence accumulation process. However, we expect that such models would predict stronger interaction of dwell time with TTA rather than with time budget (because the effect of the former on the decision outcome is much stronger), while we observed the opposite. Furthermore, we observed negative association between dwell time on the mirror and gap acceptance probability even in conditions where the mirror presented evidence in favor of accepting the gap (e.g., TTA = 4 s, time budget = 6 s). Hence, rigorous interpretation of our results in the context of existing models of gaze-choice interaction necessitates further research into adapting and testing such models against our data.

4.2.2. Relevance for applications in traffic safety and driving automation

Besides contribution to the fundamental understanding of human cognition, our findings may have potential safety implications: for small gaps that are unsafe to accept, short glances on the mirror might not provide the driver with enough evidence to reject the gap, especially when the time budget before reaching the end of the merging lane is small. Previous studies demonstrated that educating drivers on gap acceptance strategies can improve their driving outcomes (e.g. Hunt et al., 2011); our findings point to attention allocation as a potential target for future investigations into driver training interventions. Furthermore, our observations may offer an additional perspective on how driver distraction could affect gap acceptance behavior. Past research highlighted that distracted drivers fail to factor in important aspects of the road situation in their gap acceptance decisions at intersections (Choudhary and Velaga, 2019; Cooper and Zheng, 2002) and roundabouts (Haque et al., 2016). However, both intersection crossing and roundabout scenarios are simpler compared to merging in that they typically do not require the driver to use the side mirror. The need for the driver to take into account at least two separate sources of information therefore makes merging particularly vulnerable to detrimental effects of driver distraction, warranting more detailed investigations on the effect of distraction on attention distribution.

We found that early mirror glancing on its own hardly allowed reliable predictions of gap acceptance (Fig. 6). However, conditioned on the kinematic conditions and response time, glancing behavior over the whole duration of the decision can be strongly associated with the gap acceptance outcome (Fig. 7). This opens an avenue for future research exploring whether associations between gaze behavior and decision making could be leveraged in the design of partially automated driving systems, for example, in exploratory studies of attention-aware driving support strategies.

4.3. Limitations and future directions

Our study provides several illuminating insights, yet the simplifications of our experimental paradigm warrant caution in generalizing our results to real-world merging.

4.3.1. Task simplifications and their consequences

First, our task was not interactive whereas in real-world merging, drivers can accelerate or decelerate while making the decision, thereby effectively increasing or decreasing the size of the available gap. Furthermore, the oncoming vehicle in our paradigm had constant speed, while merging drivers often interact with other vehicles (e.g. Kondyli and Elefteriadou, 2012; Siebinga et al., 2024a), including the phenomenon of 'anticipation' by the new follower (Chen et al., 2023) and 'relaxation' after the lane change has occurred (Zheng et al., 2013). The latter entails that drivers sometimes tolerate small gaps, knowing that these gaps will soon expand again (Daamen et al., 2010). Therefore, the merging driver's gap acceptance decision and its timing used here as key behavioral metrics only provide a surface-level description of the merging interaction. The intrinsically interactive nature of real-world merging requires using more advanced behavioral metrics which need to capture the dynamics of the interaction of two (and possibly more) drivers, covering tactical and operational characteristics of their behavior (Siebinga et al., 2024b).

Second, our task did not provide participants with any feedback on their decisions. In particular, if a participant made a decision that would result in a collision, they did not experience any consequences, much unlike real-life merging. For this reason, had our participants been asked to perform real-life merging under the same kinematic conditions, they would have probably exhibited less risky behavior, resulting in lower probabilities of accepting a given gap (compared to Fig. 5). However, such a difference in the baseline gap acceptance probability would likely not have impacted any of our conclusions regarding the relationships between the kinematic variables, decision outcomes, response times, and gaze allocation.

Third, our participants had a much simplified visual representation of the information relevant for the merging decision. Importantly, they did not have an option to look over their shoulder or in the rear-view mirror. Furthermore, the shape, size, and location of the side mirror in our task was different from that in a real vehicle. These differences mean that our findings on attention distribution (e.g., Fig. 4) cannot be directly translated to real-world merging. At the same time, while including the rear-view mirror, a more realistic side mirror, or the ability to look over one's shoulder would have improved the ecological validity of our setup, this would likely not have introduced fundamentally new task-relevant state information (as the information on the distance to and TTA of the target-lane vehicle was already available in the side mirror), although it may have reduced uncertainty or provided redundant cues.

We acknowledge that the process of decision making in our task is different from real-world merging in many regards. At the same time, it was not our intention to capture all intricacies of real-world merging in this study. Our goal was rather to distill the real-world task to such an extent that we can examine in close detail one key aspect of it. Specifically, the fundamental feature of the real-world merging gap acceptance task that our setup does replicate is the presence of at least two distinct sources of task-relevant information. In our simplified merging task, the information about the target-lane vehicle is available only in the side mirror, and the information on the end of the merging lane is available in the front view. Our participants thus needed to sample visual information from more than one source in order to make an informed decision — this is the main aspect of the real-world merging task that our experimental paradigm aimed to capture. The goal of our somewhat extreme simplification was therefore to enable rigorous measurement and analysis of the association between attention and decision making. Had the merging task been replicated with all its real-world nuances, it would have hampered our ability to measure and understand this association.

This trade-off between mundane realism and the ability to rigorously control the perceptual experiences of participants and directly measure the cognitive processes of interest is inherent to studies of human behavior in traffic (see, e.g., the discussion by Eisma et al., 2022; Jokhio et al., 2024). Given that the present results reproduced key dependencies observed in real-world driving and high-fidelity simulated driving (see Section 3.1), the main limitations concern how these effects would scale quantitatively in interactive and real-world contexts.

4.3.2. Generalization to real-world driving

Our research questions and main claims in this study concerned functional relationships, i.e., the qualitative effect our manipulations (distance, TTA, time budget) have on decision outcomes and response times, as well as the relationship between these measures with the gaze-based metrics. Hence, our experimental paradigm was designed with the intention to capture these qualitative effects while sacrificing the mundane realism required to accurately reflect these effects quantitatively.

As a result, the *quantitative* aspects of our results are unlikely to generalize outside of the narrow task we considered. Specifically, the characteristic values (intercepts) of our dependent variables (gap acceptance probability, response times) and magnitude of the effects we found are likely to be affected by multiple factors that were excluded or simplified in our study. The differences in perceptual characteristics of the stimuli (e.g., due to the size and shape of the side mirror, narrow field of view, the lack of opportunity to look over one's shoulder), the interactive nature of the task (e.g., accelerating while making the decision vs constant speed of the ego vehicle in our task), the presence of other sources of potentially relevant information (e.g., the rear-view mirror) — all of this means that if one were to measure our variables of interest in the real-world analogue of our task, the effect sizes would very likely be different.

At the same time, based on the above considerations, we expect that the *qualitative* relationships observed in our study are likely to generalize to real-world driving. In particular, we expect the *directions* of the following effects in real-world driving to be consistent with our study: the effect of distance, TTA, and time budget on response times (Fig. 5, Tables 2 and 3) and the relationship between dwell time on the side mirror and decision outcome (Fig. 7, Table 4). Of course, to validate these predictions, in the real-life task the measures of attention and decision-making should be designed differently. For instance, to characterize the amount of time the driver perceives the information about the distance and TTA to the target-lane vehicle in real life, the dwell time on the side mirror would need to be augmented with the duration of glancing over the shoulder and possibly on the rear-view mirror. Similarly, the gap acceptance decision (as well as its timing) is more difficult to define in real life, as it could involve, e.g., gaps that were accepted but then aborted due to reassessment of the situation. Still, based on our results, we hypothesize that if these variables were measured in real-life merging while accounting for additional complexities, the qualitative relationships between them would remain similar. The necessary next step is then to validate our qualitative insights in interactive simulated driving and in real-world merging.

More practically, our statistical models cannot be directly used for applications in designing driving automation and driver assistance systems due to the fundamental differences between our task and real driving. Instead, our contribution to the design of such systems lies in the increased understanding of the relationship between gaze behavior and decision making. Specifically, the observed association between side-mirror glancing behavior and decision outcomes highlights a relationship that could be explored in future research on attention-aware driver support systems. That said, if one were to directly implement, e.g., a statistical model quantifying the association between gaze and gap acceptance into the design of such a system, such a model would first need to be calibrated on the data collected in the circumstances directly capturing the context of operation of the system.

4.3.3. *Other limitations*

Besides the general considerations related to simplifications of our video-based task, an important limitation of our experimental setup is the lack of control over participants' gaze behavior in the beginning of the trial. The fixation cross was displayed in between the trials for 0.3 s; although we instructed participants to look at the cross, several participants still adopted a strategy of ignoring the cross and gazing at the mirror area of interest in between the trials. This behavior was characterized also by large values of relative dwell time on the mirror, potentially affecting our interpretation of the main findings. In particular, this could have led to differences in the probability of gap acceptance for different dwell times (Fig. 7) if the same participants who adopted this strategy also happened to show increased tendency to accept gaps. However, based on Fig. 9, this was not the case, which indicates that the relationship between relative dwell time on the mirror and decision outcome is unlikely to result from individual differences between participants. Replicating our experiment with gaze-contingent fixation cross in between the trials can help future studies avoid this potential pitfall.

Our main measures of attention and decision making (eye movements, response times, and decision outcomes) are not independent from each other, and are known to interact in a non-linear way even in less dynamic tasks (Orquin and Loose, 2013). Therefore, any interpretation of our results is bound to be limited to statistical associations rather than causal relationships. Next steps in interpreting our results should necessarily involve modeling cognitive processes underlying the gap acceptance task during merging. This can allow one to test alternative process-level explanations of the observed associations, providing a means of interpreting the data in light of competing theories of cognition. We believe that evidence accumulation models in particular would be useful here, as such models have already been used in modeling human behavior in traffic (Bontje and Zgonnikov, 2024; Markkula et al., 2023; Mohammad et al., 2023, 2024; Pekkanen et al., 2022; Zgonnikov et al., 2024a,b) and also naturally lend themselves to interactions between attention and decision-making (Krajbich et al., 2010; Thomas et al., 2019).

4.4. *Conclusion*

Our study bridges applied studies on driver behavior and fundamental research on the interplay between attention and decision making. We highlighted that gap acceptance during merging is a dynamic process (rather than an instantaneous decision) which can play out differently depending on where a driver looks; this in turn suggests that duration of glancing at the side mirror could impact the outcome of the merging decision. These findings contribute to ongoing efforts aimed at understanding and ultimately reducing merging-related accidents, as well as informing research on advanced driver assistance systems.

Declarations

Ethics approval and consent to participate

All participants provided written informed consent. The experimental protocol was approved by the TU Delft Research Ethics Committee.

Consent for publication

All authors approved this manuscript for publication.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

CRediT authorship contribution statement

Arkady Zgonnikov: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization; **Merijn van Niekerk:** Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Data curation; **Yke Bauke Eisma:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization; **Joost de Winter:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Formal analysis, Data curation, Conceptualization.

Availability of data and materials

Online supplementary information, data, and code required to replicate our analyses are publicly available at https://osf.io/43bng/.

References

Ahlström, C., Kircher, K., Nyström, M., Wolfe, B., 2021. Eye tracking in driver attention research-how gaze data interpretations influence what we learn. *Frontiers in neuroergonomics 2*, 778043. https://doi.org/10.3389/fnrgo.2021.778043

Bachmann, D., Maanen, L.V., 2024. Towards the application of evidence accumulation models in the design of (semi-)autonomous driving systems - an attempt to overcome the sample size roadblock. *International Journal of Human-Computer Studies 185*, 103220. https://doi.org/10.1016/j.ijhcs.2024.103220

Baumann, M., Steenken, R., Kassner, A., Weber, L., Lüdtke, A., 2011. Effects of situational characteristics on drivers' merging into freeway traffic. In: Cacciabue, P.C., Hjälmdahl, M., Luedtke, A., Riccioli, C. (Eds.), *Human modelling in assisted transportation*. Springer, pp. 343–351. https://doi.org/10.1007/978-88-470-1821-1_37

Bhatnagar, R., Orquin, J.L., 2022. A meta-analysis on the effect of visual attention on choice. *Journal of Experimental Psychology: General 151*, 2265–2283. https://doi.org/10.1037/xge0001204

Bontje, F., Zgonnikov, A., 2024. How sure is the driver? Modelling drivers' confidence in left-turn gap acceptance decisions. *Computational Brain & Behavior 7*, 437–456. https://doi.org/10.1007/s42113-024-00207-7

Cavanagh, J.F., Wiecki, T.V., Kochar, A., Frank, M.J., 2014. Eye tracking and pupillometry are indicators of dissociable latent decision processes. *Journal of Experimental Psychology: General 143(4)*, 1476–1488. https://doi.org/10.1037/a0035813

Chen, K., Knoop, V.L., Liu, P., Li, Z., Wang, Y., 2023. How gaps are created during anticipation of lane changes. *Transportmetrica B: Transport Dynamics 11*, 958–978. https://doi.org/10.1080/21680566.2022.2152129

Cheng, Y., Gao, L., Zhao, Y., Du, F., 2016. Drivers' visual characteristics when merging onto or exiting an urban expressway. *PLOS ONE* Vol. 11, e0162298. https://doi.org/10.1371/journal.pone.0162298

Choudhary, P., Velaga, N.R., 2019. Gap acceptance behavior at unsignalized intersections: Effects of using a phone and a music player while driving. *Traffic Injury Prevention 20* 372–377. https://doi.org/10.1080/15389588.2019.1591619

Cooper, P.J., Zheng, Y., 2002. Turning gap acceptance decision-making: The impact of driver distraction. *Journal of Safety Research 33*, 321–335. https://doi.org/10.1016/S0022-4375(02)00029-4

Daamen, W., Loot, M., Hoogendoorn, S.P., 2010. Empirical analysis of merging behavior at freeway on-ramp. *Transportation Research Record: Journal of the Transportation Research Board* Vol. 2188, 108-118. https://doi.org/10.3141/2188-12

Duan, K., Yan, X., Li, X., Hang, J., 2023. Improving drivers' merging performance in work zone using an in-vehicle audio warning. *Transportation Research Part F: Traffic Psychology and Behaviour 95*, 297–321. https://doi.org/10.1016/j.trf.2023.04.004

Eisma, Y.B., Eijssen, D.J., Winter, J.C.F.D., 2022. What attracts the driver's eye? Attention as a function of task and events. *Information 13*, 333. https://doi.org/10.3390/info13070333

Eriksson, A., Stanton, N.A., 2017. Takeover time in highly automated vehicles: Noncritical transitions to and from manual control. *Human Factors: The Journal of the Human Factors and Ergonomics Society* Vol. 59(4), 689-705. https://doi.org/10.1177/0018720816685832

Fantz, R.L., 1964. Visual experience in infants: Decreased attention to familiar patterns relative to novel ones. *Science 146* 668–670. https://doi.org/10.1126/science.146.3644.668

Gonçalves, R.C., Louw, T.L., Madigan, R., Quaresma, M., Romano, R., Merat, N., 2022. The effect of information from dash-based human-machine interfaces on drivers' gaze patterns and lane-change manoeuvres after conditionally automated driving. *Accident Analysis & Prevention 174*. https://doi.org/10.1016/j.aap.2022.106726

Haque, M.M., Oviedo-Trespalacios, O., Debnath, A.K., Washington, S., 2016. Gap acceptance behavior of mobile phone-distracted drivers at roundabouts. *Transportation Research Record: Journal of the Transportation Research Board* Vol. 2602. https://doi.org/10.3141/2602-06

Hughes, P.K., Cole, B.L., 1986. What attracts attention when driving? *Ergonomics 29*, 377–391. https://doi.org/10.1080/00140138608968272

Hunt, M., Harper, D.N., Lie, C., 2011. Mind the gap: Training road users to use speed and distance when making gap-acceptance decisions. *Accident Analysis & Prevention 43*, 2015–2023. https://doi.org/10.1016/j.aap.2011.05.020

Jokhio, S., Dürr, M., Bärgman, J., Baumann, M., 2024. Influence of surrounding traffic on lane change dynamics: Insights from a video-based laboratory study. *Transportation Research Part F: Traffic Psychology and Behaviour 105*, 87–98. https://doi.org/10.1016/j.trf.2024.06.025

Jolly, E., 2018. Pymer4: Connecting r and python for linear mixed modeling. *Journal of Open Source Software 3*, 862. https://doi.org/10.21105/joss.00862

Kondyli, A., Elefteriadou, L., 2012. Driver behavior at freeway-ramp merging areas based on instrumented vehicle observations. *Transportation Letters 4* 129–142. https://doi.org/10.3328/TL.2012.04.03.129-141

Krajbich, I., Armel, C., Rangel, A., 2010. Visual fixations and the computation and comparison of value in simple choice. *Nature Neuroscience 13*, 1292–1298. https://doi.org/10.1038/nn.2635

Luce, R.D., 1986. Response times: Their role in inferring elementary mental organization. Oxford University Press.

Marczak, F., Daamen, W., Buisson, C., 2013. Key variables of merging behaviour: Empirical comparison between two sites and assessment of gap acceptance theory. *Procedia - Social and Behavioral Sciences 80*, 678–697. https://doi.org/10.1016/j.sbspro.2013.05.036

Markkula, G., Lin, Y.S., Srinivasan, A.R., Billington, J., Leonetti, M., Kalantari, A.H., Yang, Y., Lee, Y.M., Madigan, R., Merat, N., 2023. Explaining human interactions on the road by large-scale integration of computational psychological theory. *PNAS Nexus 2(6)*, pgad163 https://doi.org/10.1093/pnasnexus/pgad163

Mateo, S.S., Perez-Moreno, E., Jiménez, F., Naranjo, J.E., Flores, C.G.P., Teruel, J.A., 2018. Study of a driver assistance interface for merging situations on highways. In: *2018 IEEE International conference on vehicular electronics and safety (ICVES)*, pp. 1–5. https://doi.org/10.1109/ICVES.2018.8519495

Miller, J., 2023. How many participants? How many trials? Maximizing the power of reaction time studies. *Behavior Research Methods* 56, 2398–2421 https://doi.org/10.3758/s13428-023-02155-9

Mohammad, S.H., Farah, H., Zgonnikov, A., 2023. Modeling gap acceptance in overtaking: A cognitive process approach. In: *2023 IEEE 26th International conference on intelligent transportation systems (ITSC)*, pp. 5925–5931. https://doi.org/10.1109/ITSC57777.2023.10422576.iSSN:2153-0017

Mohammad, S.H.A., Farah, H., Zgonnikov, A., 2024. In the driver's mind: Modeling the dynamics of human overtaking decisions in interactions with oncoming automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour 107*, 562–577. https://doi.org/10.1016/j.trf.2024.09.020

Orquin, J.L., Loose, S.M., 2013. Attention and choice: A review on eye movements in decision making. *Acta Psychologica 144*, 190–206. https://doi.org/10.1016/j.actpsy.2013.06.003

Pekkanen, J., Giles, O.T., Lee, Y.M., Madigan, R., Daimon, T., Merat, N., Markkula, G., 2022. Variable-drift diffusion models of pedestrian road-crossing decisions. *Computational Brain & Behavior 5*, 60–80. https://doi.org/10.1007/s42113-021-00116-z

Sadigh, D., Landolfi, N., Sastry, S.S., Seshia, S.A., Dragan, A.D., 2018. Planning for cars that coordinate with people: leveraging effects on human actions for planning and active information gathering over human internal state. *Autonomous Robots 42* 1405–1426. https://doi.org/10.1007/s10514-018-9746-1

Salvucci, D.D., Liu, A., 2002. The time course of a lane change: Driver control and eye-movement behavior. *Transportation Research Part F: Traffic Psychology and Behaviour 5*, 123–132. https://doi.org/10.1016/S1369-8478(02)00011-6

Schwarting, W., Pierson, A., Alonso-Mora, J., Karaman, S., Rus, D., 2019. Social behavior for autonomous vehicles. *Proceedings of the national academy of sciences 116(50)*, 24972–24978. https://doi.org/10.1073/pnas.1820676116

Sen, B., Smith, J.D., Najm, W.G., John, A., 2003. Volpe national transportation systems center. Technical Report HS-809 571. Technical Report. U.S. Analysis of lane change crashes. https://rosap.ntl.bts.gov/view/dot/6180.

Sevenster, A., Farah, H., Abbink, D., Zgonnikov, A., 2023. Response times in drivers' gap acceptance decisions during overtaking. *Transportation Research Part F: Traffic Psychology and Behaviour 94*, 329–340. https://doi.org/10.1016/j.trf.2023.03.003

Shimojo, S., Simion, C., Shimojo, E., Scheier, C., 2003. Gaze bias both reflects and influences preference. *Nature Neuroscience 6*, 1317–1322. https://doi.org/10.1038/nn1150

Siebinga, O., Zgonnikov, A., Abbink, D.A., 2024a. Human merging behavior in a coupled driving simulator: How do we resolve conflicts? *IEEE Open Journal of Intelligent Transportation Systems 5*, 103–114. https://doi.org/10.1109/OJITS.2024.3349635

Siebinga, O., Zgonnikov, A., Abbink, D.A., 2024b. A model of dyadic merging interactions explains human drivers' behavior from control inputs to decisions. *PNAS Nexus 3*, pgae420. https://doi.org/10.1093/pnasnexus/pgae420

Smith, P.L., Little, D.R., 2018. Small is beautiful: In defense of the small-n design. *Psychonomic Bulletin & Review 25* 2083–2101. https://doi.org/10.3758/s13423-018-1451-8

Thomas, A.W., Molter, F., Krajbich, I., Heekeren, H.R., Mohr, P.N.C., 2019. Gaze bias differences capture individual choice behaviour. *Nature Human Behaviour* Vol. 3, 625–635. https://doi.org/10.1038/s41562-019-0584-8

Tijerina, L., Garrott, W.R., Stoltzfus, D., Parmer, E., 2005. Eye glance behavior of van and passenger car drivers during lane change decision phase. *Transportation Research Record: Journal of the Transportation Research Board* Vol. *1937(1)*, 37–43. SAGE Publications Inc. https://doi.org/10.1177/0361198105193700106

de Winter, J., Hu, J., Petermeijer, B., 2022. Ipsilateral and contralateral warnings: Effects on decision-making and eye movements in near-collision scenarios. *Journal on Multimodal User Interfaces 16*, 303–317. https://doi.org/10.1007/s12193-022-00390-6

Zajonc, R.B., 1968. Attitudinal effects of mere exposure. *Journal of Personality and Social Psychology* Vol. *9(2)*, 1–27. https://doi.org/10.1037/h0025848

Zgonnikov, A., Abbink, D., Markkula, G., (2024a). Should i stay or should i go? Cognitive modeling of left-turn gap acceptance decisions in human drivers. *Human Factors 66*, 1399–1413. https://doi.org/10.1177/00187208221144561

Zgonnikov, A., Beckers, N., George, A., Abbink, D., Jonker, C., 2024. Nudging human drivers via implicit communication by automated vehicles: Empirical evidence and computational cognitive modeling. *International Journal of Human-Computer Studies 185*, 103224. https://doi.org/10.1016/j.ijhcs.2024.103224

Zhang, B., Winter, J.D., Varotto, S., Happee, R., Martens, M., 2019. Determinants of take-over time from automated driving: A meta-analysis of 129 studies. *Transportation Research Part F: Traffic Psychology and Behaviour 64*, 285–307. https://doi.org/10.1016/j.trf.2019.04.020

Zheng, P., Mcdonald, M., 2007. Evaluation of effects of ramp metering on merging operations. *Transportation Research Record: Journal of the Transportation Research Board 2012*, 105–112. https://doi.org/10.3141/2012-12

Zheng, Z., Ahn, S., Chen, D., Laval, J., 2013. The effects of lane-changing on the immediate follower: Anticipation, relaxation, and change in driver characteristics. *Transportation Research Part C: Emerging Technologies 26*, 367–379. https://doi.org/10.1016/j.trc.2012.10.007