Shift the gaze

Supporting appropriate gaze and braking behavior during maneuver confirmation

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Abstract

There are calls requiring drivers to confirm Level 2 (L2) automated maneuvers, such as entering a roundabout, to keep drivers actively engaged. We tested two strategies to support safe and user-friendly maneuver confirmation. First, we tested whether, at maneuver initiation, L2 drivers shift their gaze towards the planned trajectory after checking crossing traffic. This behavior has so far only been studied in manual driving and could potentially be used as an intuitive confirmation signal for L2 maneuvers. Second, to enable drivers to intervene with low effort when an attention-based system initiates a maneuver inappropriately, we tested whether allowing drivers to brake without deactivating the L2 system, in contrast to conventional systems where braking disengages automation, improves anticipatory braking behavior. We conducted a driving simulator study with 124 participants to test both strategies. Eye movements were recorded for a subset of 54 participants. The findings show that participants significantly shifted their gaze towards the trajectory when they intended to continue, and away from it towards potential hazards when they did not intend to continue while the system attempted to proceed. Additionally, we found that an attention-based system especially benefits from allowing drivers to brake without deactivating the L2 system, as reflected in more frequent braking interventions in potentially hazardous situations. All participants responded in case of a system failure. These strategies help ensure that drivers attend to situationally relevant areas and can easily intervene if necessary, thereby potentially supporting safe usage and promoting seamless user-centered interactions.

Keywords: Partially Automated Systems; Level 2 Automation; Maneuver Confirmation; Gaze-Based Interaction; Human-Machine Interaction; Driving Simulator Study; Shared Control

1 INTRODUCTION

1.1 The need to involve the driver in L2 automated driving

In partially automated driving scenarios, also referred to as Level 2 systems (L2 systems), the driver's role transitions to monitoring [37]. These systems can steer and adapt speed, for example, to vehicles in front. Yet they depend on engaged drivers to intervene promptly when necessary. For instance, the driver must intervene to prevent potential safety hazards if the system fails to recognize a priority vehicle at an intersection and attempts to proceed.

L2 systems have the potential to reduce crash risk when they are used appropriately and drivers remain attentive [17,45]. However, in the absence of suitable measures, drivers of L2 systems may fail to monitor sufficiently [4]. They are also more likely to engage in secondary tasks [29] and may show slower reactions to critical situations compared to when driving manually [36,47]. To address the challenge of disengagement, efforts have traditionally focused on strategies that monitor the driver for signs of disengagement [28], implement escalating attention reminders [7,34], and provide cues encouraging drivers to stay alert to forward roadway conditions [6]. Other strategies aim to facilitate driver engagement in the driving task by enabling steering, acceleration, and/or braking without requiring system deactivation [15,26].

There have been increasing calls to explicitly involve drivers in decision-making to ensure that they remain actively in the loop [11,12,41,46]. For example, drivers may be required to confirm their intention to perform a lane change or urban maneuvers like entering a roundabout. This results in a dual demand on the driver, who must first adequately monitor the system and the surrounding environment and then additionally perform an explicit action to confirm their engagement. However, the most elegant solution would be to integrate monitoring behavior and confirmation into a single action. Indeed, drivers prefer to receive automated maneuvers when they are attentive, without the need for explicit confirmation [14]. Moreover, explicit confirmation of a lane change via a touchscreen has been found to reduce monitoring behavior compared to confirmation strategies that incorporate natural driver actions, such as steering input during the lane change [33]. Therefore, confirmation strategies should be considered that effectively combine driver monitoring and intention confirmation into an effortless, natural action, thereby improving both safety and driver acceptance. Gaze patterns represent a promising candidate for achieving this integration. Eye movements, on the one hand, provide a natural indicator of driver intent and situational awareness [20], thereby potentially offering a means to infer the intention to proceed or not. On the other hand, supervisory gaze behavior has been shown to decline during prolonged use of L2 systems [8]. Requiring such natural monitoring behavior as a precondition for automated maneuvers could therefore help counteract this decline and maintain driver engagement.

1.2 Gaze-based maneuver confirmation and the role of shared longitudinal control

During manual driving, drivers tend to focus their gaze mainly along the planned trajectory [21]. The focus typically concentrates approximately 2 seconds ahead. They intermittently check the area nearer to the front of the vehicle to ensure correct lane keeping and further forward along the trajectory for future path planning. Additionally, other scan paths, such as monitoring the scenery and instrument cluster, contribute to their overall visual strategy. Similar scan paths can be observed for assisted driving [27,30]. In more complex situations, such as executing maneuvers at intersections, drivers direct their gaze towards potential collision objects [13] before shifting their focus to the desired direction [1]. For instance, before entering a roundabout when driving manually, drivers assess oncoming traffic and then redirect their gaze towards the intended direction, typically aligning this shift with the moment they accelerate. This gaze shift has also been observed in other traffic participants such as pedestrians crossing intersections or roundabouts right before they start to cross [11]. It aligns with the fundamental visuomotor process of gaze leading action [20]. Gaze is directed toward the planned movement direction prior to the initiation of the movement.

To the best of our knowledge, previous research has not examined whether this maneuver-initiating gaze shift, typically observed in manual driving, also occurs during L2 use in urban scenarios. For safe interaction, active gaze strategies under L2 should remain aligned with normal driving behavior, as deviations may indicate reduced supervisory involvement [27]. In a large driving simulator study, we investigated whether this maneuver-initiating gaze shift also occurs when drivers supervise L2 systems in urban scenarios. In a between-subjects design, we compared two systems to examine whether the gaze shift occurs only as a consequence of the confirmation action itself or also naturally during supervision of the L2 system. One system required explicit confirmation via accelerator pedal to confirm that an urban maneuver could be performed, whereas the other system executed maneuvers automatically when drivers showed basic attention.

An attention-based system like the latter is inherently more prone to errors, as it can misinterpret both whether it is possible to proceed and the driver's behavior. To potentially mitigate misinterpretations by the attention-based system, we included shared longitudinal control as an additional between-subjects factor. With shared control, both the human and automation perform a task in a congruent manner [2]. Specifically, fully shared longitudinal control allows drivers to apply braking effortlessly without deactivating the L2 system, in contrast to conventionally shared control, where braking immediately leads to system deactivation. Previous work indicates that fully shared longitudinal control can lead to more frequent [15,18] and earlier braking interventions [15] while also increasing driver acceptance [15,24]. In our study, we therefore contrasted a fully shared longitudinal control system with a conventionally shared control system.

Taken together, the present study pursues two main objectives. First, we examine whether the maneuver-initiating gaze shift, well established in manual driving, also occurs under L2 automation in urban scenarios and can thus serve as a reliable indicator of driver intention. Second, we investigate whether an attention-based confirmation system particularly benefits from fully shared longitudinal control, by providing drivers with an effortless way to intervene without deactivating the L2 system. Ultimately, the natural gaze shift could serve as an intuitive confirmation input. Combined with shared control, it may help maintain driver engagement and address intensifying calls for meaningful driver involvement in L2 automated driving.

2 METHOD

2.1 Participants

A total of 135 BMW employees were recruited from the company's internal participant pool to take part in the study, with the condition that only individuals not involved in the development of automated functions were eligible for participation. Participants were required to have prior experience with both adaptive cruise control and lane centering assistance to qualify for the study. This criterion was set because behavior during initial exposure might significantly differ from long-term usage [10,25], and the focus was not on first-time interactions with automated driving systems. Data from 9 participants were omitted due to motion sickness, and 4 participants were excluded because of technical issues. The final sample comprised 124 participants (*M* = 41.39 years, *SD* = 9.99, *range* = 25-65 years), including 23 persons identifying as women. On average, participants had held a driver's license for 23.97 years (*SD* = 10.05, *range* = 5-48 years). Due to technical constraints, eye tracking data were collected only for 54 participants (*M* = 40.73 years, *SD* = 10.04, *range* = 25-60 years), including 10 persons identifying as women. On average, these participants had held a driver's license for 23.56 years (*SD* = 10.05, *range* = 6-43 years).

2.2 Study design and driver assistance

A between-subjects design was utilized, varying the type of maneuver confirmation (attention-based vs. explicit) and the level of shared longitudinal control (fully vs. conventionally). Participants were randomly assigned to one of the four experimental groups, with randomization stratified by gender to obtain similar gender proportions across conditions. Participants operated a vehicle equipped with distance control and lane centering, classifying it as an L2 system that requires drivers to monitor the system at all times and intervene when necessary. The vehicle also featured a traffic light assistant, enabling it to respond to traffic lights. Driver confirmation was necessary for executing maneuvers in specific scenarios: at yield signs, when approaching roundabouts, and at traffic lights when the vehicle came to a standstill at the designated stopping line in response to a red light. Confirmation options became available once the relevant traffic situation was visible. Additionally, the automated system allowed for lateral shared control, enabling drivers to influence lateral movement through the steering wheel without deactivating the automated features.

Level of shared longitudinal control. In the group with conventionally shared longitudinal control, participants could accelerate without deactivating the system; however, braking would deactivate the automation. In contrast, the fully shared longitudinal control group additionally allowed drivers to brake without turning off the automated features.

Type of maneuver confirmation. The explicit confirmation system required drivers to manually initiate maneuvers using the accelerator or a button on the steering wheel. Without such confirmation, the system would halt the vehicle at the designated stopping line for the specific use case. Conversely, the attention-based system initiated maneuvers based on two criteria: the system's assessment of a situation as clear and the driver's demonstration of appropriate gaze behavior. Predetermined gaze behaviors for each scenario required participants to focus their attention on specific directions—left, straight ahead, and/or right—depending on potential crossing traffic. The sequence of these gaze directions was flexible. For instance, when navigating roundabouts, participants needed to observe both the left and front zones for incoming vehicles. Detailed descriptions of necessary gaze directions for each use case are available in the supplementary material. The experimenter followed a predefined decision protocol to ensure consistent triggering of maneuvers across participants. They authorized vehicle maneuvers once the required gaze behavior was exhibited and the situation was deemed clear. The study included scenarios in which the experimenter intentionally withheld maneuver confirmation even when the required gaze behaviors were displayed, in order to realistically simulate possible system misclassifications and the resulting need for driver intervention in a gaze-controlled interface. If participants failed to exhibit the required gaze behavior and did not confirm a maneuver by using the accelerator, the system would stop the vehicle at the designated stopping line for the scenario.

2.3 Apparatus, materials and procedure

Simulator. A high-fidelity dynamic simulator was utilized for the experiments (Figure 2), featuring a full-scale mockup. This simulator is equipped with a hexapod system that offers six degrees of freedom and is mounted on an additional rail system for both the X and Y axes. To achieve a comprehensive 360° horizontal field of view, the setup utilizes fifteen projectors, each delivering a resolution of 2560 x 1600 pixels. Integrated displays within the authentic vehicle mirrors provide realistic rear visibility.

Figure 1: Illustration of the utilized dynamic high-fidelity simulator.

Driving scenarios. The participants drove a typical commuting route from a small town via a country road to a large city and back, set in a Central European environment (Figure 3). They encountered a variety of traffic regulations and situations, including traffic lights, roundabouts, crosswalks and intersections requiring the driver to yield (Figure 4). At crosswalks, heightened attention was necessary due to the proximity of pedestrians; however, no intervention from the participants was needed as the pedestrians did not cross the crosswalk. In general, the simulation was designed to realistically reflect the performance of an L2 system. It could execute maneuvers like roundabouts, but was also programmed to make errors. Therefore, incorrect interpretation of three red lights (use case identifier: 6TS, 23TS & 42TS), one green light (31TS), and four lateral control failures were incorporated for both systems. In the attention-based condition, the system performed a maneuver when the driver carried out necessary control glances and the situation was deemed clear by the system. To create a realistic experience of the capabilities of the attention-based system, one roundabout (10RS) and a yielding situation (37PL) were included where the system performed a maneuver even though the situation was not clear when the participant showed necessary control glances. Hence, participants had to brake. For a more detailed description of the situations and their categorization, please refer to the supplementary material. For ethical reasons, the system was programmed to initiate an emergency brake if the participant failed to respond in time.

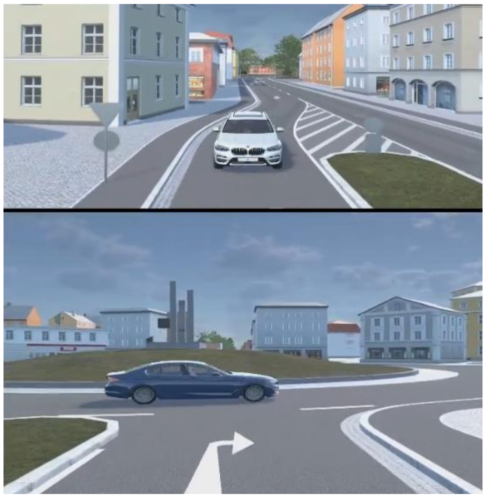

Figure 2: Example of approaching a roundabout illustrating the simulated study environment. The first image provides a frontal view of the participant's vehicle, while the second image offers a view from the perspective of the participants. This roundabout represented the use case 18RS. The automated system performed the maneuver upon receiving the driver's confirmation, which varies based on the experimental condition. Without confirmation, the vehicle stopped at the roundabout's designated stopping line.

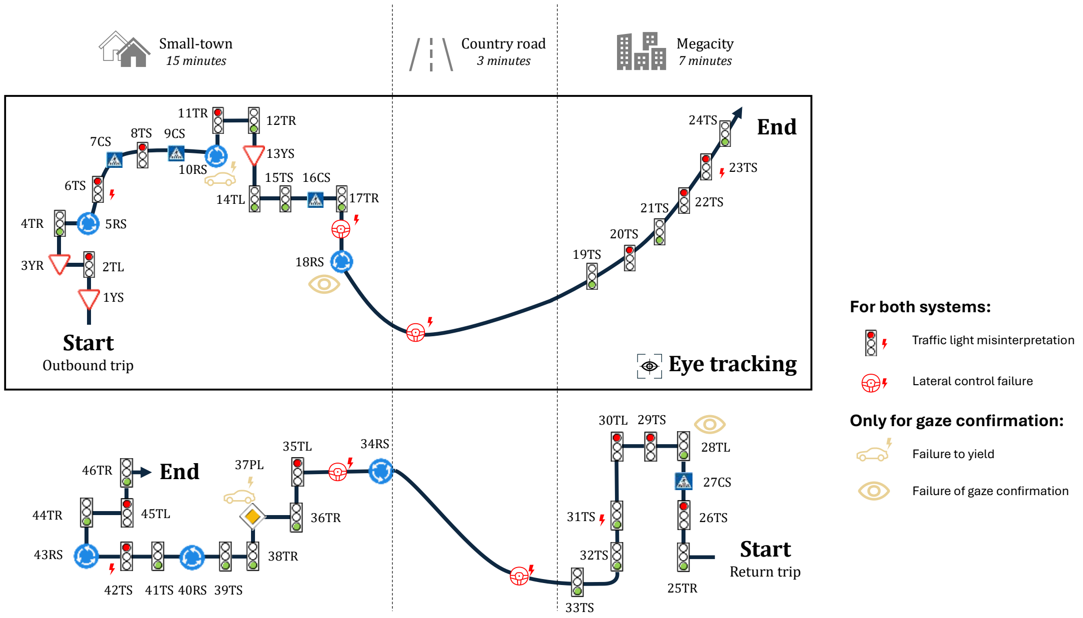

Figure 4: Overview of the use cases of the outbound and return trip. See supplementary material for a detailed description of each use case. Eye tracking data was only collected during the outbound trip.

Human-machine interface. The vehicle featured a panoramic display, located at the lower part of the windshield, which served as the digital instrument cluster directly in the driver's line of sight (Figure 5). In its manual setting, this display showed the vehicle's current speed, the prevailing speed limits, and directional navigation cues. When the vehicle operated in L2 mode, additional information was presented, including the applicable right of way rule and a green steering wheel symbol flanked by hands, all within a green lane outline. When confirmation for a maneuver was required, a message appeared above these icons prompting the driver's input. Upon deactivation of the L2 system, the system immediately switched to the manual driving mode display. Activation of the L2 system was achieved through a dedicated button, located to the left of the steering wheel's airbag cover, when the steering wheel was oriented in the neutral position. To deactivate the system, the participant could press this button once more.

Figure 5: Figure 4: Visualization of the utilized BMW Neue Klasse interior. The BMW Panoramic Vision display, positioned at the lower windshield, showcases the Human-Machine Interface while in park mode. The central information display was not used.

Questionnaires and procedure. The study was conducted in German. At the beginning of the study, participants completed an informed consent form and attended a safety briefing on using the simulator. They engaged in a 5-minute instruction drive to become familiar with the simulator's motion cueing and the automated system they would be using, which could assist with distance and lateral control. Participants were informed that although the system provides assistance, they must remain prepared to intervene at any time. Initially, participants drove manually before activating the automated system using a button on the steering wheel. During the instruction drive, they encountered three crossings with traffic lights, performing one straight crossing, one right turn, and one left turn. They were advised that, if the situation allowed and they felt comfortable, they should use the automated system as much as possible during the study. Participants were instructed to steer, accelerate, and brake consecutively. The level of shared control was not explained. Prior to each simulator drive, participants were briefed on the maneuver confirmation methods of the automated systems and assessed their initial trust using the LETRAS-G questionnaire [19]. After the test drive, participants completed the LETRAS-G questionnaire again, the User Experience Questionnaire (UEQ) [22], the System Acceptance Scale [43], and a single-item measure of cognitive workload [16]. Each test drive lasted approximately 50 minutes in total, with the outbound and return journeys each taking 25 minutes. Overall, participation in the study lasted about 120 minutes.

Eye tracking. A prototypical eye tracking system captured data at 12 frames per second. It tracked both horizontal (yaw) and vertical (pitch) gaze orientations using a camera mounted on the interior rearview mirror. Due to technical constraints and storage limitations, eye tracking was conducted exclusively for participants in the fully shared longitudinal control group utilizing both explicit and attention-based confirmation systems, but not for those in the conventionally shared longitudinal control group. The accuracy tests indicated that the eye tracking system achieved a root mean square error (RMSE) of 5°, representing the average deviation from the true gaze direction.

2.4 Pilot study

An initial pilot study was conducted to examine eye tracking data, focusing on identifying gaze shifts during explicit confirmations. The goal was to assess the presence of these shifts and determine where participants look when focusing on the trajectory to proceed, providing insights for the larger study analysis. The pilot study involved 25 participants who drove only the small city portion of the outbound journey using the explicit confirmation system. Gaze behavior was recorded using Tobii Pro Glasses 2, and manually labeled for three scenarios— a right turn at a yield situation (3YR), a roundabout (10RS), and a right turn at a traffic light (11TR) —using Tobii Pro Lab. Labeling covered a time window from 1 second before to 1 second after confirmation, categorizing gaze every 20 milliseconds into trajectory, intersecting road, traffic light, or other. The driving simulator, vehicle, and user interface employed were consistent with those used in the larger study detailed in this paper. The simulator session lasted 15 minutes. A linear mixed model analysis revealed a significant tendency for participants to shift their gaze towards the trajectory during confirmation. For further details, please refer to the supplementary material.

2.5 Data Analysis

Data preparation. The assumptions for the tests and models were thoroughly checked. We identified and excluded outlier responses from the questionnaires to mitigate bias and maintain the power of our statistical analyses [5]. Specifically, for each combination of the factors confirmation type and level of shared longitudinal control, responses more than 2.5 standard deviations away from the group-specific mean were considered outliers and removed. For questionnaires that were administered multiple times (e.g., the LETRAS-G), we first calculated the mean score across both measurements within each participant before performing outlier detection on the group level.

Gaze shift analysis. To analyze gaze shifts, a period from 4 seconds before to 4 seconds after confirmation was examined, following the methodology used in analyses of manual driving at roundabouts [1]. Initially, all gazes directed vertically above or below the windshield or side-windows were filtered out to identify driving-related gazes. Subsequently, horizontal gaze data was utilized to differentiate between gazes towards the planned trajectory and other areas. The relevant degree range of the trajectory was determined based on the geometry of the intersections and maximum gaze orientations during gaze shifts within the pilot study. The following horizontal degree ranges were ultimately used to identify a trajectory gaze (positive degree = left): Straight-ahead (15° to -15°), roundabout (0° to -40°), right turn (0° to -58°), left turn (0° to 58°), right turn at traffic lights (5° to -66°), left turn at traffic lights (-5° to 66°). We focused on scenarios requiring driver confirmation to examine gaze shifts with the intention to proceed for both confirmation types, excluding automated situations like green light crossings and crosswalk encounters. 11 urban maneuver situations of the outbound trip were included in this analysis: two roundabout entries, three yielding situations, and six traffic-light-controlled intersections. For attention-based confirmation, situation 10RS was analyzed separately, as in this case there was no intention to proceed and driver intervention was required.

Analyses. Data analyses were conducted using R version 4.3.1 with the packages lme4, lmerTest and ez. A p-value of less than 0.05 was set as the threshold for statistical significance in all analyses. Effect sizes are interpreted as small (d = 0.2; η_G^2 = 0.02), medium (d = 0.5; η_G^2 = 0.13), or large (d = 0.8; η_G^2 = 0.26) [3,9,32]. To compare shifts in gaze behavior towards or away from the trajectory, Linear Mixed Models (LMM) were applied.

3 RESULTS

3.1 Safety and driving behavior

Throughout the study, there were no safety-critical incidents due to the appropriate actions taken by participants. Participants intervened during scenarios where the system misinterpreted the traffic light or when lateral control failed. However, critical situations (10RS, 37PL) where a vehicle with the right of way was disregarded only occurred in the attention-based confirmation condition. These situations were resolved by the intervention of all participants.

3.2 Analysis of trajectory gaze dynamics: Explicit vs. attention-based confirmation

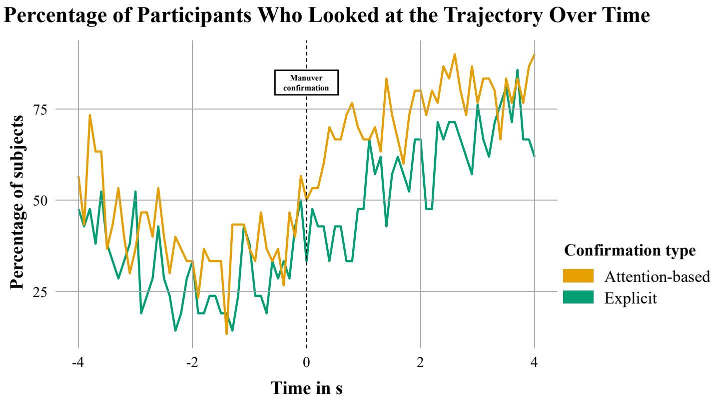

Figure 6: Line graph illustrating the percentage of participants observing the trajectory over time, segmented by confirmation type. The data was centralized by aligning the confirmation event as time point 0 for each participant.

We employed an LMM to analyze the percentage of participants gazing at the trajectory over time, considering the effects of confirmation type (explicit vs. attention-based confirmation). The analysis included a total of 5149 observations from 51 participants. Three participants in the explicit confirmation condition could not be included because no valid gaze data were available for them in any of the relevant maneuver time windows. The model included fixed effects for time, confirmation type, and their interaction, as well as a random intercept for each participant to account for individual variability. The model was estimated using Restricted Maximum Likelihood (REML) and was specified as follows: Trajectory gaze ~ Time × Confirmation type + (1 | Participant)

There was a significant main effect of confirmation type, indicating a higher percentage of trajectory gaze for attention-based confirmation (*M* = 57.7%) than for explicit confirmation (*M* = 44.8%), $\beta = 0.12$, *SE* = 0.05, *t*(49) = 2.54, *p* = .014. On average, the percentage of trajectory gaze (57.7%) was higher with attention-based confirmation compared to explicit confirmation (44.8%). A significant main effect for time, with a coefficient of 0.05, *SE* < 0.01, *t*(5096) = 13.61, *p* < 0.001, indicates that the percentage of gaze directed at the trajectory increased over time. Time was coded in 0.1-s units, so this coefficient corresponds to an increase of 0.05 (i.e., 5 percentage points) in the estimated proportion of participants looking at the trajectory per 0.1 s. The interaction between time and confirmation type was not significant, coefficient < 0.01, *SE* < 0.01, *t*(5096) = 0.11, *p* = 0.91. This suggests that the increase in trajectory gaze over time does not differ significantly between gaze and explicit confirmation.

The random effects showed a variance of 0.03 (*SD* = 0.16) for the participant intercepts. The residual variance was 0.20 (*SD* = 0.45). The Intraclass Correlation Coefficient (ICC) was 0.14, indicating that approximately 13.38% of the total variance in trajectory gaze was attributable to differences between participants.

The variance explained by fixed effects (marginal R^2) was 0.102, while the variance explained by both fixed and random effects (conditional R^2) of the model was 0.22. The scaled residuals range from -2.31 to 2.35, with a median close to zero (0.26).

Exploratory analysis focused on a narrow time frame of -1 to +1 seconds surrounding the confirmation event—a potentially critical window where the system should detect the driver's intention to proceed. By ensuring timely automated confirmation via a gaze shift, unnecessary delays in system response can be minimized. The analysis specifically examined whether participants executed a gaze shift towards the trajectory and maintained fixation for at least 200 milliseconds, which has been applied as the minimum duration for a valid fixation in driver behavior studies [1]. During attention-based confirmation, it was found that 96.7% of participants maintained fixation on the trajectory for at least 200 milliseconds, a result that was statistically significant compared to random chance (exact binomial test, *n* = 30, *p* < 0.001). In contrast, scenarios involving explicit confirmation revealed that participants maintained trajectory fixation for a minimum of 200 milliseconds in 76.2% of instances, which also showed a significant deviation from chance (exact binomial test, *n* = 21, *p* = 0.027). A direct comparison using Fisher's exact test indicated that the proportion of trials with such fixations did not differ significantly between gaze and explicit confirmation (p = 0.070).

3.3 Analysis of trajectory gaze dynamics: intention vs. no intention to proceed

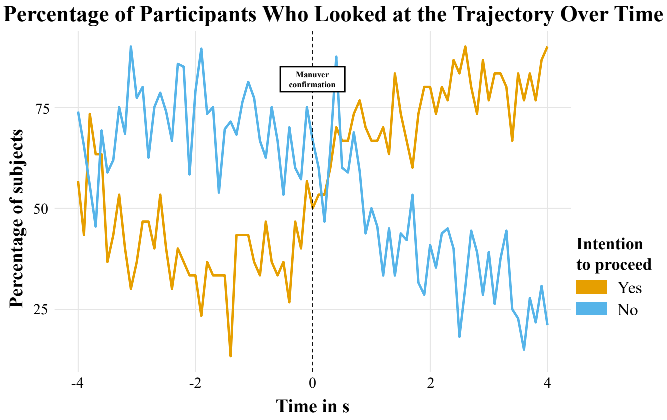

Figure 7: Line graph illustrating the percentage of participants observing the trajectory over time, segmented by whether they actually intended to continue or not. The data was centralized by aligning the confirmation event as time point 0 for each participant.

We employed an LMM to analyze the percentage of gazes directed at the trajectory of participants over time, considering the effects of intention to proceed (yes vs. no). The analysis included a total of 3,887 observations from 30 participants in the attention-based confirmation condition. Unintended confirmations could not occur in the explicit confirmation condition, so those participants were not included in this analysis. The model comprised fixed effects for time, intention, and their interaction, as well as a random intercept for each participant to account for individual variability. The model was estimated using Restricted Maximum Likelihood (REML) and was specified as follows: Trajectory gaze ~ Time × Intention + (1 | Participant)

The main effect of intention was not significant, with a coefficient of -0.12, *SE* = 0.05, $t(49) = -1.84$, $p = 0.067$. On average, the percentage of trajectory gaze for intention (57.7%) did not differ significantly from no intention to proceed (55.3%). A significant main effect for time, with a coefficient of 0.06, $SE < 0.01$, $t(3854) = 16.84$, $p < 0.001$, indicates that the percentage of gaze directed at the trajectory increased over time. Time was coded in 1-s units, so this corresponds to an increase of about 6 percentage points per second. The interaction between time and intention was significant, coefficient of -0.13, $SE < 0.01$, $t(3854) = -20.89$, $p < .001$. This finding suggests that the effect of time on trajectory gaze differs significantly between intention and no intention. For intention, the percentage of participants looking at the trajectory increased by 6.49% per second, whereas for no intention, it decreased by 6.59% per second.

The random effects showed a variance of 0.03 ($SD = 0.16$) for the participant intercepts. The residual variance was 0.2 ($SD = 0.44$). The Intraclass Correlation Coefficient (ICC) was 0.12, indicating that approximately 11.58% of the total variance in trajectory gaze was attributable to differences between participants.

The variance explained by fixed effects (marginal R^2) was 0.1, while the variance explained by both fixed and random effects (conditional R^2) of the model was 0.2. The scaled residuals range from -2.39 to 2.16, with a median close to zero (0.25).

3.4 Brake frequency

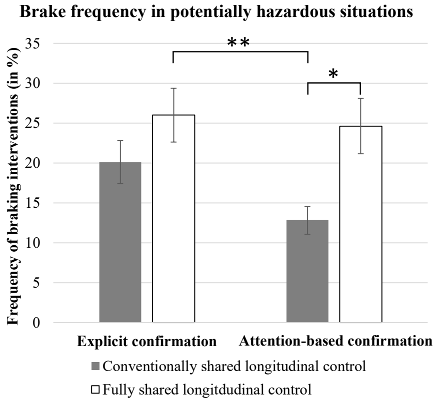

Figure 8. Frequency of braking interventions in potentially hazardous situations per confirmation variant across the levels of shared longitudinal control. Error bars indicate standard error of the means. * p < .05, ** p < .01.

To investigate whether the attention-based confirmation system benefits particularly from fully shared longitudinal control compared to conventionally shared control, we conducted an ANOVA followed by a post-hoc test for potentially hazardous situations. These situations were defined as use cases where anticipatory intervention was not mandatory but advisable for prompt reactions to potential sudden changes, such as the presence of pedestrians adjacent to a crosswalk [15].

The analysis revealed a significant main effect of the level of shared longitudinal control, $F(1, 114) = 9.39$, $p = 0.003$, $\eta_G^2 = 0.08$. Participants using fully shared longitudinal control showed a significantly higher intervention frequency (M = 25.33%, SD = 18%) compared to those using conventionally shared longitudinal control (M = 16.49%, SD = 12.57%). The main effect of the confirmation variant was not significant, $F(1, 114) = 2.19$, $p = 0.141$, $\eta_G^2 = 0.02$, nor was the interaction between the level of shared longitudinal control and the confirmation variant, $F(1, 114) = 1.06$, $p = 0.31$, $\eta_G^2 = 0.01$.

A post-hoc analysis using the Tukey-HSD method showed that participants using the attention-based confirmation system intervened significantly more often when using fully shared longitudinal control (M = 24.64%, SD = 18.4%) compared to conventionally shared longitudinal control (M = 12.85%, SD = 9.5%), with a p-value adjusted to $p_{adj} = 0.024$, $d = 0.81$.

3.5 Exploratory analyses

Exploratory analyses of questionnaires assessing trust in automation, cognitive workload, user experience, and acceptance were conducted to evaluate differences in potential user adoption and safe usage. This overview highlights the central findings, focusing primarily on significant results and a general interpretation of score magnitudes. For complete results and descriptive analyses, please refer to the supplementary material.

For trust in automation there was no main effect of the level of shared control, $F(1, 119) = 0.194$, $p = 0.660$, $\eta_G^2 < 0.01$, nor of the type of attention-based confirmation, $F(1, 119) = 0.003$, $p = 0.955$, $\eta_G^2 < 0.001$. The main effect of time was significant, $F(1, 119) = 47.44$, $p < 0.001$, $\eta_G^2 = 0.11$. Descriptive statistics revealed that trust scores decreased from the pre-simulator measurement (M = 4.37, SD = 0.81) to the post-simulator measurement to a medium level (M= 3.66, SD = 1.23). Interactions were not significant ($p > .05$).

The analysis of hedonic qualities of the UEQ revealed a significant main effect of the confirmation type, $F(1, 114) = 4.96$, $p = 0.028$, $\eta_G^2 = 0.04$. Participants using attention-based confirmation showed higher hedonic quality scores (M =

1.29, *SD* = 0.64) compared to those using explicit confirmation (*M* = 1.03, *SD* = 0.77). The main effect of the level of shared control was not significant, $F(1, 114) = 0.04$, $p = 0.846$, $\eta_G^2 < 0.001$. The interaction between the confirmation type and the level of shared control was significant, $F(1, 114) = 4.55$, $p = 0.035$, $\eta_G^2 = 0.04$. For fully shared longitudinal control, gaze (*M* = 1.18, *SD* = 0.7) and explicit confirmation (*M* = 1.17, *SD* = 0.84) showed similar scores, while attention-based confirmation with conventionally shared longitudinal control (*M* = 1.45, *SD* = 0.51) had the highest scores with substantial differences to explicit confirmation (*M* = 0.87, *SD* = 0.66).

There was no main effect of confirmation type or level of shared control nor was there a significant interaction of both factors for cognitive workload, acceptance and the subscales of attractiveness and hedonic qualities of the UEQ. All groups had medium scores for cognitive workload and positive acceptance scores. Except for explicit confirmation with conventionally shared longitudinal control, all systems were evaluated according to the UEQ benchmarks as good, placing them in the upper 25% of products across all three scales of hedonic and pragmatic qualities as well as attractiveness [39].

4 DISCUSSION

This study examined whether drivers of L2 systems, similar to manual drivers, show a gaze shift back to the planned trajectory at the moment of maneuver initiation in urban settings. Additionally, it investigated whether allowing braking without deactivating the L2 system supports drivers' anticipatory behavior. These research questions were motivated by the need to develop confirmation strategies that keep drivers meaningfully involved in decision-making, while maintaining both safety and user-friendliness.

Indeed, when drivers intended to proceed, they shifted their gaze towards the planned trajectory at the moment of maneuver confirmation. This pattern was similar for manual confirmation and for automatic confirmation based on a clear situation (i.e., no object remains on or approaching the planned trajectory) and basic visual attention. Accordingly, drivers shifted their gaze towards the trajectory during maneuver confirmation not only when they actively confirmed the maneuver themselves, but also when they merely supervised the system while it confirmed the maneuver automatically. This is in line with the assumption that learned visual control is used not only for manual driving but also for monitoring automated driving systems [27] and with the general gaze pattern that drivers tend to look along the planned trajectory to guide a vehicle [21]. Importantly, our findings reveal that drivers shift their gaze away from the trajectory when the system intends to continue but they do not. This pattern differed significantly from situations where drivers actually intended to proceed, underscoring that gaze shifts can discriminate between situations in which drivers intend to proceed and those in which they do not. This is in line with findings that drivers focus on potential hazards [13] before shifting their gaze towards the planned direction to continue when driving manually [1].

In sum, a gaze shift towards the trajectory that occurs as the urban scenario becomes clear may serve as a promising indicator of the driver's intention to proceed. If used to confirm maneuvers, it both builds on drivers' natural visual checking behavior in these situations and requires that, at maneuver initiation, their gaze is directed towards the path in which the vehicle will continue, thereby helping to harness the safety potential of L2 systems. At the same time, because it is based on the natural behavior observed in manual and L2 driving, this would offer an intuitive interaction, in line with user-centric approaches that adapt system design to natural user behavior to increase appeal [31,42]. It is especially important to develop safe and user-friendly interaction strategies since underutilized technology causes substantial economic loss [23]. Indeed, in our study, even with the basic visual-attention-based system, without an explicit implementation of gaze-shift confirmation, drivers intervened in time in all critical system failures, and the system received good user experience and acceptance ratings.

An attention-based system is inherently more prone to errors, as it can misinterpret both whether it is possible to proceed and the driver's behavior. To potentially mitigate such misinterpretations, we additionally examined whether the attention-based system benefits when drivers can brake without deactivating the system. Compared to a state-of-the-art system where braking completely deactivates L2, this approach leads to significantly more frequent braking in potentially hazardous situations when using an attention-based system. This aligns with other findings that suggest it can generally result in more braking interventions in such situations [15]. Instead of penalizing a driver for anticipatory driving, this approach actually rewards them, which can promote appropriate driver engagement in the long term [28]. This also provides the driver with an effortless intervention option, should they unintentionally trigger a confirmation by shifting their gaze in the direction of the planned trajectory. To additionally mitigate such false positives, it is sensible that maneuvers are promptly initiated when the situation is clear after the gaze shift, giving the driver the feeling that they actively initiated the execution of the maneuver. This could boost the feeling of responsibility and might be easily understood, which is especially helpful as the development of meaningful mental models is crucial [35]. It may also address observations that drivers of L2 systems sometimes do not intervene even though they look at the hazard [44], because they now feel actively responsible. For the explicit confirmation system, no such differences were found, indicating that it is particularly the attention-based system that benefits from an easy intervention option. This is most likely because the explicit confirmation system stops in the absence of driver confirmation, making braking interventions less often necessary. When braking did not deactivate the system, explicit confirmation and the attention-based system did not differ significantly in braking frequency in potentially hazardous situations.

Taken together, the present findings show that the maneuver-initiating gaze shift, well established in manual driving, also occurs under L2 automation in urban settings. Hence, it can potentially serve as a confirmation strategy that combines safety and user-friendliness. In addition, allowing drivers to brake without deactivating the system can further enhance safe usage, helping to harness the safety potential of L2 systems.

5 LIMITATIONS

Our study's insights into gaze shifts during maneuver initiation in urban L2 automated driving are subject to limitations that future research should address. First, based on the pilot study, maneuver-initiating gaze shifts were identified using horizontal gaze orientation only. In addition, a vertical filter was applied to exclude non-driving-related gazes (e.g., looking down into the footwell). Moreover, due to technical constraints, eye tracking was only conducted in the fully shared longitudinal control condition, in which braking did not deactivate the L2 system. As a result, the gaze-based findings may not generalize directly to conventionally shared longitudinal control, and comparisons across control modes rely primarily on behavioral rather than gaze measures. Future studies should aim to link gaze data directly with environmental information, allowing for a more fine-grained distinction of what drivers are actually looking at and for a more comprehensive assessment across different shared-control configurations.

Additionally, research should now aim to implement a system that immediately initiates maneuvers following a driver's gaze shift to assess safety implications and determine whether this strategy fosters an intuitive, user-centric interaction that enhances system appeal and boosts its adoption. Building on existing advancements, gaze-based interfaces have already demonstrated success in utilizing head or gaze rotation for vehicle steering [38,40], highlighting promising prospects for implementing gaze shifts as an interaction strategy.

6 CONCLUSION

This simulator study examined whether the maneuver-initiating gaze shift, well established in manual driving, also occurs when drivers supervise L2 automation in urban scenarios, and whether allowing braking without deactivating the system supports anticipatory driver behavior. Across yield, roundabout, and traffic light situations, drivers reliably shifted their gaze towards the planned trajectory when they intended to proceed. This pattern emerged both when drivers explicitly confirmed maneuvers and with an attention-based system that executed maneuvers automatically based on basic visual attention, suggesting that learned visuomotor control strategies from manual driving are preserved under L2 automation. When drivers did not intend to proceed while the system attempted to do so, they instead shifted their gaze away from the trajectory towards potential obstacles, indicating that gaze behavior can differentiate between intention to continue and the lack thereof.

These findings suggest that a gaze shift towards the planned trajectory, occurring as the situation becomes clear, can serve as a natural and potentially precise indicator of the driver's intention to proceed. Using this gaze shift as a confirmation input would integrate environmental monitoring and maneuver confirmation into a single, intuitive action and may help maintain driver engagement while addressing calls for meaningful driver involvement in L2 driving. In addition, allowing braking without deactivating the L2 system increased braking interventions in potentially hazardous situations, particularly for the attention-based confirmation system. This provides an effortless intervention channel that supports anticipatory behavior and may mitigate safety risks associated with misinterpretations of the environment or driver state. Overall, implementing gaze-shift-based confirmation in combination with braking that does not deactivate L2 offers a promising pathway towards interaction concepts that keep drivers meaningfully in the loop, promote acceptance, and help harness the safety potential of L2 driving in urban environments.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION PROCESS.

During the preparation of this work, the authors used ChatGPT 4.1 mini to optimize the code for data analysis. After utilizing this tool, the authors carefully reviewed and edited the content as necessary and take full responsibility for the content of the published article.

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

The datasets generated and analyzed during the current study are not publicly available due to corporate confidentiality restrictions but are available from the corresponding author on reasonable request.

AUTHOR CONTRIBUTIONS

Johannes Illgner: Conceptualization, data analysis, methodology, writing – original draft; Nataša Miličić: Conceptualization, methodology, supervision, writing – review and editing; Martin Baumann: Conceptualization, methodology, supervision, writing – review and editing.

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