Effects of directional takeover request interfaces on drivers' gaze behaviour during transitions from automation: A systematic review and meta-analysis

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Highlights:

- Directional TORs indicating hazards' location lead to higher probability and faster hazard detection.
- Hazard visibility moderates the effect of directional TORs on the total fixation duration on hazards: increasing fixation duration for overt hazards but decreasing it for covert hazards.
- Including directional information in TOR displays increases both the frequency and duration of fixations compared to non-directional TORs.
- Directional TORs reduce cognitive workload during takeovers, as indicated by decreased pupil diameter.
- The impact of directional TORs on mirror-checking and road fixations varied with interface modality and location.

Abstract

During SAE Level 2 and 3 automated driving, drivers must resume control when the vehicle reaches the limits of its Operational Design Domain (ODD). Gaze behaviour plays a critical role during this transition, as effective information processing is essential for safely resuming manual control. Directional Takeover Requests (TORs) have been proposed to guide drivers' attention towards safety-critical areas, thereby reducing takeover time and improving takeover quality. However, existing research on the effects of directional TORs on gaze behaviour has found inconsistent results. This systematic review and meta-analysis aimed to clarify effects of directional TORs on drivers' gaze behaviour compared to non-directional TORs during transitions of control. Meta-analyses revealed that incorporating directionality into the visual interface increased both the number and duration of fixations on the TOR display. Directional TORs effectively guided drivers' visual attention towards hazards and reduced cognitive demands, although their effects on mirror-checking and road fixations varied with interface modality and location.

Keywords: Automated vehicles, takeover request, directional interface, gaze behaviour, visual attention

1 Introduction

Although fully autonomous vehicles are still in the early stages of development, the automotive industry continues to make steady progress towards their realisation. Meanwhile, vehicles with intermediate levels of automation (i.e., Levels 2-3) are becoming increasingly pervasive in many parts of the world. For Level 2, drivers are required to continue monitoring the performance of the automated systems, but for Level 3 they have the freedom to engage in Non-Driving Related Tasks (NDRT). However, under these intermediate levels of automation, Automated Driving System (ADS) capabilities are still limited (SAE, 2021). As a result, drivers are required to resume manual control of the vehicle in response to a Request to Intervene (RTI) when the system reaches its operational limits. This operational limitation in L2 and L3 systems raises a major safety concern, as removing drivers from the perceptual-motor control loop (Mole et al., 2019) during the automation may impair their perception and comprehension of the driving environment (Goncalves et al., 2020), potentially leading to poorer performance during transitions of control (Gold et al., 2016; Eriksson and Stanton, 2017; Louw et al., 2017). Since driving is a primarily visual task, and drivers rely on visual information to support motor control, understanding gaze patterns in the context of automation, particularly during transitions of control, can improve our ability to tackle this challenge.

Both on-road and simulator studies have shown that when drivers are not in active physical control of the vehicle, their gaze behaviour changes (Mackenzie and Harris, 2015; Feldhütter et al., 2016; Louw et al., 2017; Louw and Merat, 2017; Schnebelen et al., 2019; Navarro et al., 2019; Gaspar and Carney, 2019; Pipkorn et al., 2024). As the level of automation increases, drivers exhibit a more dispersed gaze pattern (Louw and Merat, 2017), with reduced attention to the road centre (Carsten et al., 2012; Louw et al., 2015; Pipkorn et al., 2024) and fewer glances towards safety-critical areas (Gonçalves et al., 2019). During automation, drivers also tend to shift their gaze further ahead into the road scene (Mackenzie and Harris, 2015) and exhibit greater horizontal gaze dispersion compared to manual driving (Damböck et al., 2013; Louw and Merat, 2017). These dispersed gaze patterns, along with reduced attention to the road ahead, may contribute to drivers becoming out-of-the-loop (OOTL) (Merat et al., 2019), which is linked to diminished SA (Endsley, 1995; Endsley, 2017) and impaired performance during control transitions (Louw et al., 2017). Therefore, without proper visual sampling during the takeover, drivers' control of the vehicle can be dangerous. Research indicates that drivers who were able to avoid a crash after a takeover had significantly different gaze patterns compared to those involved in a crash (Louw et al., 2017; Huang et al., 2023; Goodridge et al., 2025). It is suggested, therefore, that if gaze direction after TOR does affect performance, one would imply that supporting drivers to direct their gaze to the right place could lead to improved safety. A review of twenty-six studies indicates that TORs are more commonly used to re-engage drivers with driving tasks, rather than to direct their attention towards specific, relevant areas (Greatbatch et al., 2020). More recent reviews, however, propose that future warning systems should also emphasise attention guidance by incorporating contextual information into TOR alerts (Liu et al., 2022; Deniel and Navarro, 2023; Kanaan et al., 2024). In this regard, the use of directional TORs has been proposed as an effective way for guiding drivers' attention to the right place at the right time, during transitions of control.

In the context of driving, directional warnings are generally divided into two broad categories: Warning messages that inform drivers about the free lane, helping them to steer away from a potential hazard – which we term "towards-free-lane warning" (Chen et al., 2022; de Winter et al., 2022; Goncalves et al., 2022; Huang and Pitts, 2022; Shi et al., 2022; Arabian et al., 2024; Arabian, C. Goodridge and Merat, 2025; Arabian, C.M. Goodridge and Merat, 2025; Arabian et al., 2026), or they can inform drivers of the location of the hazard (Chen et al., 2022; de Winter et al., 2022; Huang and Pitts, 2022; Shi et al., 2022; Arabian et al., 2024; Arabian, C. Goodridge and Merat, 2025; Arabian, C.M. Goodridge and Merat, 2025; Arabian et al., 2026), assisting them to steer in the opposite direction to the message location, avoiding a collision (which we term "towards-hazard warning"). Towards-free-lane warnings have also been called "ipsilateral" warnings with the towards-hazard warnings also term "contralateral" warnings (Wang et al., 2003; Wang et al., 2007; Straughn et al., 2009; de Winter et al., 2022; Liu et al., 2022; Arabian et al., 2024). Non-directional warnings, on the other hand, are simply used to capture drivers' attention back to the driving task, not necessarily guiding their attention towards specific locations in the driving environment. There is evidence that (when compared to non-directional TORs), directional TORs can guide drivers' visual attention to the right location in preparation for taking over from automated driving, leading to faster reactions (de

Winter et al., 2022; Ma et al., 2023) and improved quality in takeovers (e.g., fewer crashes) (Greatbatch et al., 2020; Huang et al., 2023).

Given the potential benefits of directional warnings in guiding visual attention, several studies have recently examined how the directionality feature of TORs influence drivers' gaze behaviour during transitions of control (Borojeni et al., 2018; Eriksson et al., 2018; Wright et al., 2018; Gruden et al., 2022; Jing et al., 2022; Weidner and Broll, 2022; Fathiazar et al., 2023; Ma et al., 2023; Han et al., 2024; A. Huang et al., 2024; Rodrigues, 2024; W.-C. Huang et al., 2024; Shi et al., 2024; Yu et al., 2025; Arabian et al., 2026). Previous studies consistently show that directional TORs, which indicate the location of a hazard, lead to faster fixation towards the hazard (Fathiazar et al., 2023; Ma et al., 2023; Han et al., 2024; Arabian et al., 2026). However, findings on their effect on fixation duration on hazards are less consistent. Yu et al. (2025) and Huang et al. (2024) reported that directional TORs reduced total fixation duration on the hazard, whereas A. Huang et al. (2024) and Ma et al. (2023) observed an increase. Evidence regarding mirror-checking behaviour during lane changes is similarly mixed. Rodrigues, (2024) reported that directional TORs increased both the number and duration of fixations on mirrors compared to non-directional TORs, whereas Shi et al. (2024) found a negative effect, and Borojeni et al. (2018) observed no significant differences. Directional TORs have also been associated with a greater number and longer duration of fixations on the TOR display compared to non-directional warnings (Weidner and Broll, 2022), whereas Borojeni et al. (2016, 2018) reported no significant differences. Together, these inconsistencies lead to a lack of understanding of the actual effects of directional warnings on drivers' gaze behaviour. Therefore, an overarching aim of this systematic review and meta-analysis is to synthesise the available evidence to determine how directional TORs influence drivers' gaze behaviour and to identify the underlying reasons for the observed inconsistencies. The findings of the current systematic review and meta-analysis will contribute to the development of more effective driver assistance systems in automated vehicles.

2 Methods

This systematic review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analysis) guidelines (Moher et al., 2009). The protocol for the review was registered on the Open Science Framework on 20^{th} of January 2024, and can be accessed at https://doi.org/10.17605/OSF.IO/Y925K.

2.1 Search strategy

Since 2014 coincides with the first publication of the SAE levels of driving automation, the time interval of the search strategy was selected from 1^{st} of January 2014, until 30^{th} of June 2025. The original search was done in August 2023, and a follow-up search was conducted in July 2025, along with forward and backward citation searches. To ensure a comprehensive exploration for relevant studies, we conducted a search of studies published in different databases (following guidelines from (Chandler et al., 2019) and (Mathew, 2024)) such as: Scopus, Web of Science, ProQuest, and Google Scholar databases. The databases were searched using a combination of terms which are detailed in

Gaze Keywords (OR)	**AND**	**Vehicle Automation Keywords (OR)**	**AND**	**Takeover Request Keywords (OR)**
"look", "eye*", "blink", "pupil", "visual exploration", "attention", "fixation", "eye movements", "eye track*", "eye-tracking",		"automated car*", "autonomous car*", "selfdriving", "self-driving", "self driving", "driverless", "vehicle automation", "automated driving", "autonomous		"warning", "advisory warning", "multimodal", "auditory", "tactile", "vibrotactile", "haptic", "visual", "cue*", "alert*", "modality", "modalities", "ARHUD", "AR-HUD", "ambient light", "augmented reality head-up display", "head-up display", "HUD", "LED light", "take-over request", "takeover request", "TOR

"gaze", "glance", "visual attention"	vehicle*", "automated vehicle*"	signal", "TOR", "human-machine interaction", "human machine interface*", "human-machine-interface*", "interface design", "user interface*", "human automation interaction", "HMI", "human-machine interface*"

Table 1. Following the guidelines by Keele, (2007), an initial search was conducted to scan titles, abstracts, and keywords of core articles and relevant systematic reviews to extract main keywords. Supplementary appendix A provides the search syntax used for Scopus, which was modified to align with the syntax requirements of other databases.

Table 1. Search terms used for the systematic literature review.

Gaze Keywords (OR)	AND	Vehicle Automation Keywords (OR)	AND	Takeover Request Keywords (OR)
"look", "eye*", "blink", "pupil", "visual exploration", "attention", "fixation", "eye movements", "eye track*", "eye-tracking", "gaze", "glance", "visual attention"		"automated car*", "autonomous car*", "selfdriving", "self-driving", "self driving", "driverless", "vehicle automation", "automated driving", "autonomous vehicle*", "automated vehicle*"		"warning", "advisory warning", "multimodal", "auditory", "tactile", "vibrotactile", "haptic", "visual", "cue*", "alert*", "modality", "modalities", "ARHUD", "AR-HUD", "ambient light", "augmented reality head-up display", "head-up display", "HUD", "LED light", "take-over request", "takeover request", "TOR signal", "TOR", "human-machine interaction", "human machine interface*", "human-machine-interface*", "interface design", "user interface*", "human automation interaction", "HMI", "human-machine interface*"

2.2 Inclusion and exclusion criteria

To be included in this review, studies had to:

1- Be written in the English language.

2- Include the interaction between participants and a simulated or on-road vehicle with driving automation levels 2 and/or 3, as described by the SAE taxonomy (SAE, 2021).

3- Involve a transition of control in response to a 'take-over request' (TOR). That is, we only included "mandatory automation initiated driver-in-control (AIDC) transitions" as defined by Lu et al., (2016).

4- Include variations in TOR directionality as an independent variable.
5- Include at least one eye metric as a dependent variable measured through an eye-tracking device.

Furthermore, all publications including conference papers, journal articles, and dissertation documents were used to minimise publication bias (Rothstein et al., 2005).

2.3 Study selection and data extraction

A total of 3882 papers were extracted from the four databases. After removing the duplicates by Endnote (version 21.2) software, this number was reduced to 2776 articles and entered for the initial screening (Title and Abstract). To determine whether the remaining articles met the inclusion criteria, two authors (AA and YTL) independently screened the titles and abstracts of these articles. The full-text of the remaining 146 articles were screened for eligibility (AA and YTL) and disagreements were resolved in consultation with a third reviewer (CMG). As a consequence, a final sample of 16 studies were obtained via database search (for more details, see Figure 1). Forward and backward citation searches of 16 included studies also identified an additional 6 eligible studies, bringing the total number of eligible articles to 22. For each study, we examined how directionality of the message affected gaze metrics. Furthermore, the following information was extracted from each article: (i) bibliographic details (title of the study, authors, publication year, country), (ii) study characteristics (study design, theoretical framework), (iii) participant demographics (e.g., age, gender), (iv) details of the experiment (participant sample size, characteristics of the driving scenario, SAE automation level, simulator fidelity according to (Wynne et al., 2019), and presence of NDRT).

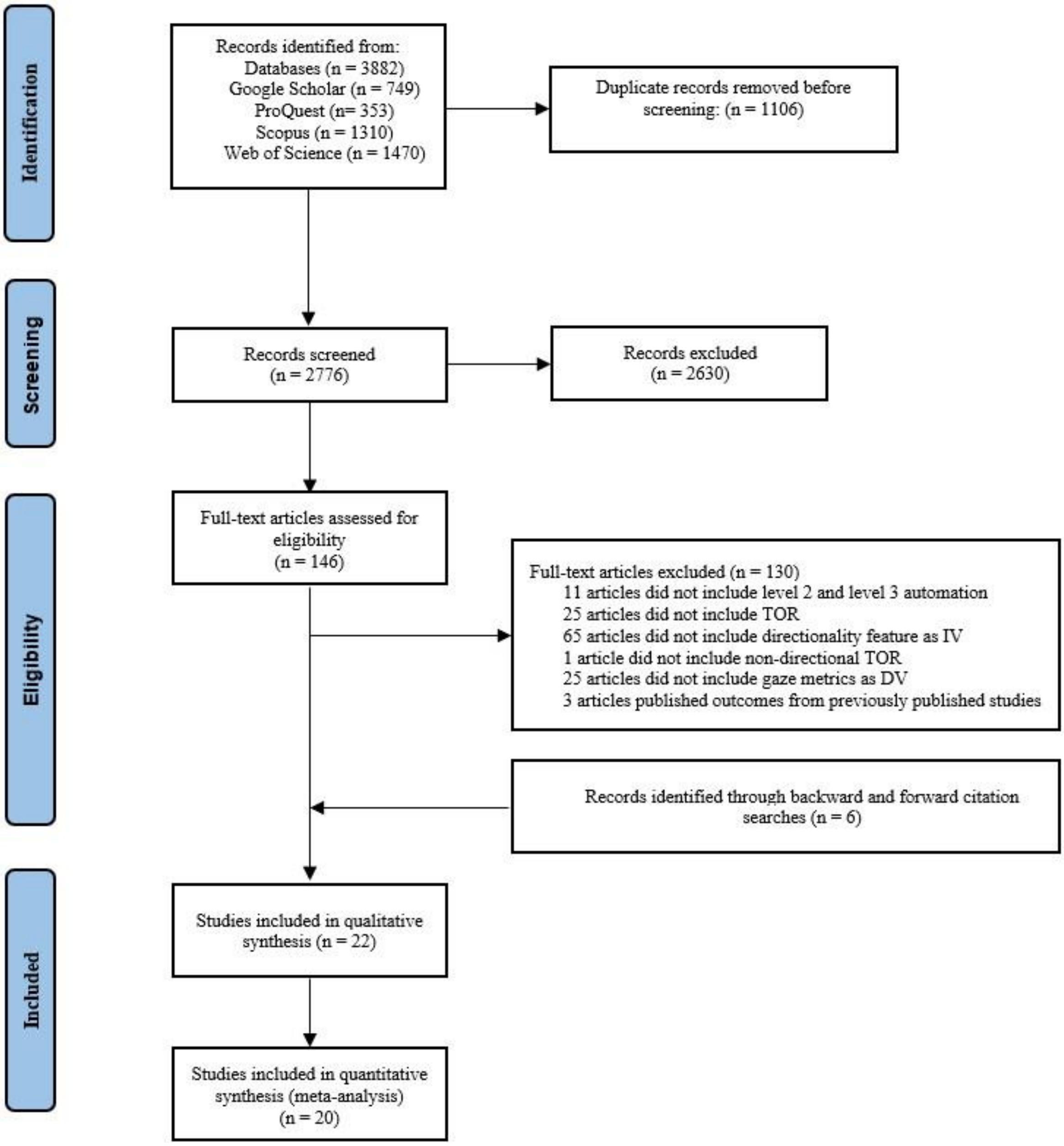

Figure 1. Systematic literature review process based on the PRISMA method.

2.4 Risk of bias assessment

Risk of bias was assessed using the Risk of Bias In Non-randomized Studies of Interventions (ROBINS-I) tool (Sterne et al., 2016). We analysed study bias across seven domains: confounding, sample selection, classification of interventions, missing data, measurement of outcomes and selection of the reported results. According to ROBINS-I tool, each domain can be designated "low," "moderate," "serious," or "critical" to obtain an overall assessment of bias. For assessing overall risk of bias, studies were classified as low risk of bias if all individual domains were rated as low risk. If studies had low or moderate risk of bias across all domains, they were categorised as moderate risk of bias. Studies were considered at serious risk of bias if at least one domain was rated as serious, but none were rated as critical. Finally, studies with a critical risk of bias in at least one domain were classified as having a critical risk of bias. Two reviewers (AA and RCG) independently completed the risk of bias assessments. Disagreements were resolved in consultation with the third reviewer (RC).

2.5 Data synthesis

For the meta-analysis, 11 gaze metrics were extracted from the selected studies. To enhance clarity and support easier interpretation of the findings, all metrics were classified into five distinct categories: (i) *gaze metrics associated with hazard*, (ii) *gaze metrics associated with TOR display*, (iii) *gaze metrics associated with mirror-checking behaviour*, (iv) *gaze metrics associated with road environment*, and (v) *gaze metrics associated with cognitive workload*. For example, time to first fixation to hazard, the probability of fixation to hazard, and the total fixation duration on hazard were grouped under the category of gaze metrics associated with hazard. Table 2 shows the definition of each metric, as reported in the included studies, together with the corresponding hypotheses regarding the effects of directional TORs.

Table 2. Gaze metrics included in the meta-analysis, with definitions and hypothesised effects of directional TORs.

Gaze metrics categorisation	**Metrics**	**Study**	**Definition**	**Hypothesis (in comparison with non-directional TORs)**
Gaze metrics associated with hazard	Time to first fixation to hazard	(Fathiazar et al., 2023; Ma et al., 2023; Han et al., 2024; Huang et al., 2024; Arabian et al., 2026)	The time from the occurrence of the takeover alert to the first fixation to hazard.	Directional TORs that indicate hazards' location are hypothesised to draw drivers' visual attention to the right place (the location of the hazard), facilitating faster fixations to hazard.
	Probability of fixation to hazard	(Wright et al., 2017; Detjen et al., 2022; Fathiazar et al., 2023)	Whether or not drivers were able to detect the hazard (i.e., fixation to hazard) during the takeover time budget.	Directional TORs that indicate hazards' location are hypothesised to draw drivers' visual attention to the right place (the location of the hazard), facilitating an increase in the probability of fixation to hazard.
	Total fixation duration on hazard	(A. Huang et al., 2024; Huang et al., 2024; Ma et al., 2023; Yu et al., 2025)	It was defined as the sum of all fixation durations directed towards the hazard during the takeover time budget.	It is hypothesised that directional TORs that provide drivers with information about the hazard's location would facilitate earlier awareness of the hazard before fixation on it, thereby reducing the time required for hazard processing (i.e., shorter fixation duration on hazard).
Gaze metrics associated with TOR display	Number of fixations to TOR display	(Borojeni et al., 2016; Borojeni et al., 2018; Weidner and Broll, 2022; Yu et al., 2025)	Total number of fixations to the TOR display during the takeover time budget.	Directional visual TOR displays that include additional information about hazards' location or free lane are hypothesised to increase number of fixations to the TOR displays.
	Total fixation duration on TOR display	(Borojeni et al., 2016, 2018; Huang et al., 2024; Shi et al., 2024; Weidner & Broll, 2022; Yu et al., 2025)	It was defined as the sum of all fixation durations directed towards the TOR display during the takeover time budget.	Directional visual TOR displays that include additional information about hazards' location or free lane are hypothesised to increase total fixation duration on TOR displays. This is because incorporating directionality features add more visual elements to a visual TOR display. As a result, as the number of elements in visual TOR display increases, drivers may spend longer fixation duration on them.
Gaze metrics associated with mirror-checking behaviour	Time to first fixation to mirrors	(Lorenz et al., 2014; Arabian et al., 2026)	The time from the occurrence of the takeover alert to the first fixation to mirrors.	It is hypothesised that directional TORs are associated with faster fixations to mirrors.
	Number of fixations to mirrors	(Borojeni et al., 2018; Rodrigues, 2024)	Total number of fixations to the free-lane wing mirror during the takeover time budget.	Directional TORs are hypothesised to decrease number of fixations to mirrors.
	Total fixation duration on mirrors	(Borojeni et al., 2018; Rodrigues, 2024; Shi et al., 2024)	It was defined as the sum of all fixation durations directed towards the free-lane wing mirror during the takeover time budget.	Directional TORs are hypothesised to reduce total fixation duration on mirrors.
Gaze metrics associated with road environment	Time to first fixation to the road	(Forster et al., 2017; Eriksson et al., 2018; Gruden et al., 2022; Weidner and Broll, 2022; Zhu et al., 2024)	The time from the occurrence of the takeover alert to the first fixation to the road.	Directional TORs are hypothesised to have no impact on time to first fixation to the road.
	Total fixation duration on the road	(Jing et al., 2022; Merlhiot and Yousfi, 2024; Zhu et al., 2024; Shi et al., 2024)	It was defined as the sum of all fixation durations directed towards the road during the takeover time budget.	Directional TORs are hypothesised to increase total fixation duration on the road.
Gaze metrics associated with cognitive workload	Pupil diameter	(Ma et al., 2023; Yu et al., 2025)	Pupil diameter is an objective physiological indicator of cognitive workload that can be used to measure workload effectively during the takeover process.	Directional TORs are hypothesized to enhance drivers' recognition and processing of road information, thereby reducing cognitive workload.

2.5.1 Meta-analysis

The R package version 1.1.456, RStudio, Inc. (R Core Team, 2020) with the "meta" package (Balduzzi et al., 2019) was used for the meta-analysis. We conducted a meta-analysis for each gaze metric that was reported in at least two studies. Given the need for a conclusion, Valentine et al., (2010) showed that synthesising two studies through meta-analysis is more transparent and more likely to be valid compared to other synthesis techniques, such as narrative synthesis. This is because meta-analysis explicitly quantifies the size and precision of effects using a reproducible statistical framework, whereas narrative approaches rely on subjective judgment and are less defensible and replicable. In this study, effect sizes were reported as mean differences (MD) or standardised mean differences (SMD), each with a 95% confidence interval. The MD was used when continuous variables were inherently comparable or can be converted to a similar unit (Andrade, 2020; Jing & Lin, 2024). In contrast, the SMD was applied when outcomes were reported in different units. For example, time to first fixation on the hazard was consistently reported in seconds across studies, and thus MD was calculated. However, total fixation duration on the hazard was reported either in seconds or as a percentage of total fixation time; therefore, SMD was calculated as a measure of the effect size. To calculate the effect size for each gaze metric in each study, the sample size, mean, and standard deviation (SD) were extracted. When means and SDs were reported in graphs and charts, the Web Plot Digitizer application (https://automeris.io/) was used to extract the values. If means and SDs could not be directly extracted, they were estimated using the methods described by Wan et al. (2014). Additionally, SD values were generated by converting standard errors (SEs) or confidence intervals (CIs), using formulas provided in the Cochrane Handbook (section 6.5.2.2) (Chandler et al., 2019).

The fixed effects model is considered appropriate when the number of studies included in a meta-analysis is less than five (Murad et al., 2015; Tufanaru et al., 2015). When at least five studies were available, we assessed methodological heterogeneity to determine the appropriate model. A random-effect model was applied in the presence of methodological diversity, while a fixed-effect model was used when studies were methodologically comparable (Tufanaru et al., 2015; Chandler et al., 2019). The inconsistency index (I^2) was also calculated to determine statistical heterogeneity across the studies. Low, moderate, and high levels of heterogeneity were defined by I^2 outcomes of 25%, 50%, and 75%, respectively (Borenstein et al., 2021). Significant effects were determined by a p value <0.05. In the case of high and significant heterogeneity, subgroup analyses and sensitivity analysis by sequentially excluding one study from the analysis (i.e., leave-one-out approach) were conducted to identify the sources of heterogeneity, and the potential effects on the results are discussed. For meta-analyses with only two studies, we also narratively interpreted results rather than relying solely on pooled effect sizes.

3 Results

3.1 Study characteristics

Table 3 provides a summary of the studies included in this review. The 22 studies reported below recruited a total of 846 participants, aged between 18 and 69 with a mean of 27.66 years old. The mean percentage of female participants across studies was 39.81%, ranged from a minimum of 16.67% to a maximum of 70%. Regarding driving simulation, eight studies used low fidelity, 11 studies used medium fidelity, and three studies utilised high fidelity driving simulator. Of the included studies, 19 were conducted using conditionally automated vehicles (Level 3), and the remaining 3 utilized a partially automated vehicle (Level 2). More than half of the selected studies (n = 13) employed a within-participants design, while the remaining studies recruited either a between-participants design (n = 5) or a mixed-design (n = 4).

Table 3. Characteristics of included studies.

Study	Study design	Country	N	Age: Range, Mean (SD)	Gender (No of Females)	Simulator fidelity	Level of automation	Driving scenario
(Arabian et al., 2026)	Within-participants	UK	48	24-69, 41.94 (13.04)	23	Low	2	97 km/h, three-lane highway
(Borojeni et al., 2016)	Within-participants	Germany	21	26.33 (4.02)	11	Medium	3	Three-lane highway
(Borojeni et al., 2018)	Within-participants	Germany	18	20-35, 27.94 (4.95)	9	Medium	3	100 km/h, two-lane highway with light traffic density
(Detjen et al., 2022)	Within-participants	Germany	12	22-32, 25.83 (3.56)	2	Low	3	30 km/h, two-lane road in a suburban area
(Eriksson et al., 2018)	Within-participants	UK	25	19-36, 25.7 (3.9)	11	Medium	3	110 km/h, two-lane highway
(Fathiazar et al., 2023)	Within-participants	Germany	10	19-36, 24.8 (5.4)	7	High	3	Various traffic scenarios on three-lane highway
(Forster et al., 2017)	Within-participants	Germany	17	22-56, 29.0 (8.12)	7	High	3	130 km/h, three-lane highway
(Gruden et al., 2022)	Mixed design	Slovenia	36	18-45, 26.58 (6.96)	12	Medium	3	110 km/h, foggy three-lane highway with low traffic
(Han et al., 2024)	Within-participants	United States	12	25.8 (4.4)	6	Low	3	56 km/h, urban area
(Huang et al., 2024)	Within-participants	China	26	22-28, 24.5	11	Medium	3	30 km/h, complex urban traffic
(A. Huang et al., 2024)	Between-participants	Germany	157	25.63 (9.54)	53	Low	2	Mountain road, city road, country road, and highway road
(Jing et al., 2022)	Between-participants	China	36	18-31, 22.7 (3.1)	12	Low	2	Urban scenarios
(Lorenz et al., 2014)	Between-participants	Germany	46	20-54, 31.7 (10.1)	10	High	3	120 km/h, three-lane highway
(Ma et al., 2023)	Within-participants	China	24	22-41, 27.8 (5.4)	5	Medium	3	50 km/h, two-lane curve scenario
(Merlhiot and Yousfi, 2024)	Mixed design	France	35	26-65, 43.09 (10.81)	16	Medium	3	130 km/h; three-lane highway
(Shi et al., 2024)	Mixed design	China	30	19-23, 20.5	15	Low	3	90 km/h; three-lane highway
(Rodrigues, 2024)	Within-participants	Portugal	12	19-45, 28.83 (8.16)	2	Low	3	Two-lane highway
(Weidner and Broll, 2022)	Mixed design	Germany	52	19-63, 31.9 (10.6)	18	Low	3	120 km/h, three-lane highway
(Wright et al., 2017)	Between-participants	United States	57	18-26, 21.17 (2.20)	-	Medium	3	Various scenarios (rural, urban, suburban, highway)
(Wu et al., 2023)	Between-participants	China	80	18-26, 21.81 (1.91)	32	Medium	3	90 km/h, three-lane road
(Yu et al., 2025)	Within-Participants	China	56	19-64, 27.31 (8.63)	28	Medium	3	50 km/h, urban traffic
(Zhu et al., 2024)	Within-participants	China	36	18-50	15	Medium	3	40-50 km/h, urban bidirectional four-lane and two-lane roads

3.2 Risk of bias assessment

We used the ROBINS-I tool to assess the quality of the included studies. As illustrated by Figure 2, confounding appeared as the common source of potential bias. Eighteen out of the 22 studies included at least one confounding variable (e.g., age, gender, or driving experience). Moreover, 10 studies had bias due to deviations from intended interventions. The main reason for this bias was participants' misunderstanding of the interventions (directional TOR) or controls (non-directional TOR) due to their visual attributes such as the shape or colour of the TOR cue. For example, while the study reported in (Borojeni et al., 2016) used directional LED displays to indicate the free lane, the colour of this LED was red, which is commonly associated with danger or hazard. As a result, participants might have perceived the directional LED as an indicator of hazard instead of the free lane, which could lead to deviations from the intended intervention. Some studies also reported missing data due to technical failures (Borojeni et al., 2018), glances to the road before the TOR (Lorenz et al., 2014), or because the automation system was not deactivated during the TOR (Forster et al., 2017). Figure 2 shows domain-specific and overall distribution of all studies, based on their risk-of-bias rating. Seventeen of the 22 studies (77.27%) were considered to have an overall moderate risk of bias, four studies (18.18%) were categorised as having serious overall risk of bias, and one study (4.55%) was assessed as having a critical overall risk of bias.

3.3 Results of the systematic review and meta-analysis

Table 4 summarises the review findings on the effects of directional TORs on various gaze metrics. Thirteen studies examined towards-hazard and non-directional TORs, two assessed towards-free-lane and non-directional TORs, and three compared directional TOR (i.e., a single TOR with simultaneously presenting both towards-hazard and towards-free-lane) and non-directional ones. The remaining four studies investigated all three towards-hazard, towards-free-lane, and non-directional TORs but reported heterogeneous gaze measures, preventing direct comparisons between towards-hazard and towards-free-lane TORs. As a results, this review focuses on the broader distinction between directional and non-directional TORs. The following sub-sections present the results of how directional TORs influence gaze behaviour.

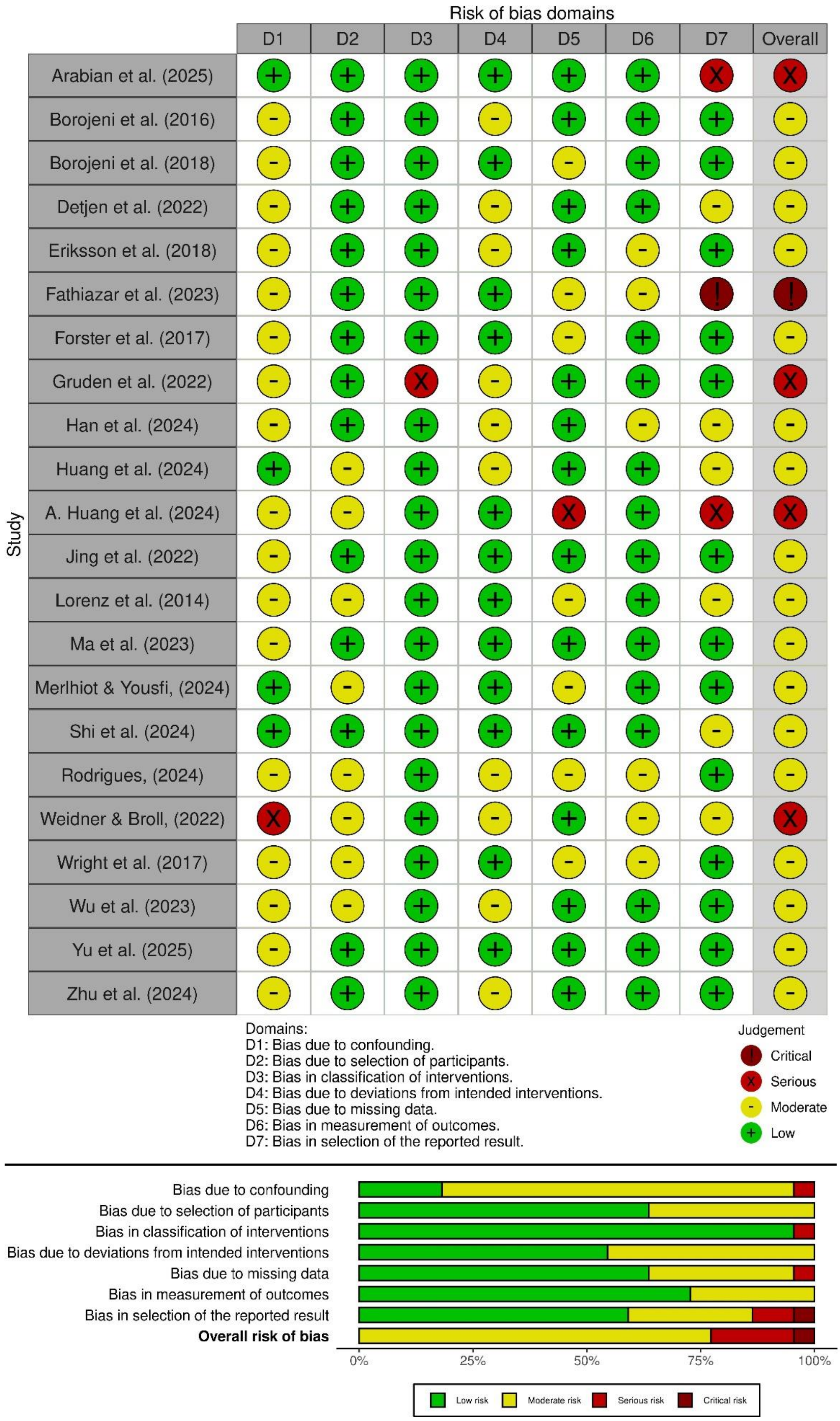

Figure 2. Risk of bias graph and summary.

Table 4. *Summary of results.*

Study	Time budget	NDRT	Directional TOR			TOR direction	Non-directional TOR			Gaze metrics
			Modality	Classes	Location		Modality	Classes	Location	
(Arabian et al., 2026)	3 s	-	Auditory	D-Speech	Headphones	Hazard	Auditory	Speech	Headphones	▼ Probability of fixation to mirrors ▼ Time to first fixation to hazard ◆ Time to first fixation to mirrors
				D-Speech	Headphones	Free lane				▼ Probability of fixation to mirrors ◆ Time to first fixation to hazard ▼ Time to first fixation to mirrors
(Borojeni et al., 2016)	5 s	N-back task	Auditory; Visual	D-Earcon (Beep); D-Abstract (LED)	Speakers; Dashboard	Free lane	Auditory; visual	Earcon (Beep); Abstract (LED)	Speakers; Dashboard	◆ Number of fixations to TOR display ◆ Total fixation duration on TOR display
(Borojeni et al., 2018)	-	Reading span task (Recalling words after 3 sentences)	Auditory; Visual	D-Earcon (Beep) _ D-Abstract (LED)	Speakers; Dashboard	Free lane	Auditory; Visual	Earcon (Beep); Abstract (LED)	Speakers; Dashboard	◆ Number of fixations to TOR display ◆ Total fixation duration on TOR display ◆ Number of fixations to mirrors ◆ Total fixation duration on mirrors
(Detjen et al., 2022)	5 s	Span task	Auditory; Visual	N-Earcon (Beep); D-Abstract (Bounding box)	VR setup	Hazard	Auditory	Earcon (Beep)	VR setup	▲ Probability of fixation to hazard
(Eriksson et al., 2018)	12 s	Playing game (Angry Birds)	Vibrotactile; Visual	N-Vibrotactile; D-Abstract (Sphere)	Seat; AR-HUD	Hazard	Vibrotactile	Vibrotactile	Seat	◆ Time to first fixation to the road
			Vibrotactile; Visual	N-Vibrotactile; D-Symbol (Carpet)	Seat; AR-HUD	Free lane				◆ Time to first fixation to the road
			Vibrotactile; Visual	N-Vibrotactile; D-Symbol (Arrow)	Seat; AR-HUD	Free lane				◆ Time to first fixation to the road
(Fathiazar et al., 2023)	-	Question & Answer task	Visual	D-Abstract (Circle)	AR-HUD	Hazard	-	-	-	▼ Time to first fixation to hazard ▲ Probability of fixation to hazard
(Forster et al., 2017)	20 s	Reading	Auditory	D-Speech; N-Earcon (Beep)	Vehicle sound system	Hazard	Auditory	Earcon (Beep)	Vehicle sound system	◆ Time to first fixation to the road
(Gruden et al., 2022)	6 s	Playing game (Tetris)	Auditory; Visual	D-Earcon (Beep); D-Abstract (LED)	Speakers; Dashboard (One-way)	Hazard	Auditory; Visual	Earcon (Beep); Abstract (LED)	Speakers; Dashboard (Two-way)	◆ Time to first fixation to the road
			Vibrotactile; Visual	D-Vibrotactile; D-Abstract (LED)	Seat; Dashboard (One-way)	Hazard	Vibrotactile; Visual	Vibrotactile; Abstract (LED)	Seat; Dashboard (Two-way)	◆ Time to first fixation to the road

(Han et al., 2024)	4 s	Tetris game	Auditory; Visual	N-Alert; D-Abstract (Bounding box)	Sound system; Hazard-lane wing mirror	Hazard	Auditory	Alert	Sound system	♦ Time to first fixation to hazard
(Huang et al., 2024)	7s	Playing game (Merge Fruit)	Auditory; Visual	N-Earcon (Tone); N-Text (Takeover); D-Symbol (Triangular warning)	Vehicle sound system; Instrument cluster	Hazard (it was visible in front view of vehicle, overt)	Auditory; Visual	Earcon (Tone); Text (Takeover)	Vehicle sound system; Instrument cluster	▲ Total fixation duration on TOR display ♦ Time to first fixation to hazard ▲ Total fixation duration on hazard
			Auditory; Visual	N-Earcon (Tone); N-Text (Takeover); D-Symbol (Triangular warning)	Vehicle sound system; Instrument cluster; Instrument cluster	Hazard (it was covert)				▲ Total fixation duration on TOR display ▼ Time to first fixation to hazard ▼ Total fixation duration on hazard
(A. Huang et al., 2024)	-	No task	Auditory; Visual	N-Speech; D-Abstract (Bounding box)	VR setup	Hazard	Auditory	Speech	Headphones	▲ Total fixation duration on hazard
(Jing et al., 2022)	-	No task	Visual	D-Abstract (Arrow pointing); N-Symbol	AR-HUD; Instrument cluster	Hazard	Visual	Symbol	Instrument cluster	▲ Total fixation duration on the road
(Lorenz et al., 2014)	7 s	Surrogate Reference Task	Auditory; Visual	D-Symbol (Carpet); N-Earcon (Beep); N-Abstract (Red icon)	AR-HUD; Speaker; Instrument cluster	Hazard	Auditory; Visual	Earcon (Beep); Abstract (Red icon)	Speaker; instrument cluster	♦ Time to first fixation to mirrors
				D-Symbol (Carpet); N-Earcon (Beep); N-Abstract (Red icon)	AR-HUD; Speaker; Instrument cluster	Free lane				♦ Time to first fixation to mirrors
(Ma et al., 2023)	7 s	Watching videos	Auditory	D-Earcon (Beep)	6 speakers around the driver	Hazard	Auditory	Earcon (Beep)	Centre speaker	▼ Time to first fixation to hazard ▲ Proportion of fixation duration on hazard ♦ Pupil diameter
(Merlhiot and Yousfi, 2024)	7 s	Answering a question in an email	Auditory; Visual	N-Earcon (Beep); N-Symbol (Vehicle); N-Text (Takeover request); D-Symbol (Triangle warning)	Vehicle sound system; Dashboard; Dashboard; AR-HUD	Hazard	Auditory; Visual	N-Earcon (Beep); N-Symbol (Vehicle); N-Text (Takeover request)	Vehicle sound system; Dashboard; Dashboard	▲ Percentage of fixation duration on the road
(Shi et al., 2024)	7 s	Tetris game	Auditory; Visual	N-Earcon (Beep); D-Icon (Red line and green line indicating hazard and free lanes, respectively)	Vehicle sound system; Instrument panel	Hazard; Free-lane	Auditory; Visual	Earcon (Beep); Icon (Hands on steering wheel)	Vehicle sound system; Instrument panel	▼ Percentage of fixation duration on the road ▼ Percentage of fixation duration on mirrors ▲ Percentage of fixation duration on TOR display
			Auditory; Visual	N-Earcon (Beep); D-Icon (Red line and green line	Vehicle sound system; HUD	Hazard; Free-lane	Auditory; Visual	Earcon (Beep); Icon (Hands on steering wheel)	Vehicle sound	▲ Percentage of fixation duration on the road

				indicated hazard and free lanes, respectively)					system; HUD	▼ Percentage of fixation duration on mirrors ▲ Percentage of fixation duration on TOR display
			Auditory; Visual	N-Earcon (Beep); D-Abstract (LED strips placed at the left and right frames along with above dashboard. Red and and green LEDs at left or right frames indicated hazard and free lanes, respectively)	Vehicle sound system; Vehicle's frames	Hazard; Free-lane	Auditory; Visual	Earcon (Beep); Abstract (LED strips placed at the left and right frames along with above dashboard. All three LEDs became red as a takeover request)	Vehicle sound system; Vehicle's frames	▲ Percentage of fixation duration on the road ▼ Percentage of fixation duration on mirrors ♦ Percentage of fixation duration on TOR display
(Rodrigues, 2024)	15 s	Watching videos	Visual	N- Earcon (Beep); N-Text and Icon (Takeover soon and Hands on steering wheel); D-AR_HUD (Bounding box around mirrors and Arrows flowing from left to right)	VR setup; Tablet; AR-HUD	Hazard; Free-lane	Visual Visual	N- Earcon (Beep); Icon (Hands on steering wheel); Text (Takeover soon); Text (Check for hazards, or take the upcoming exit)	VR setup; HUD; HUD; Centre console	▲ Number of fixations to mirrors ♦ Total fixation duration on mirrors
(Weidner and Broll, 2022)	5 s	N-back task	Auditory; Visual	N-Earcon (Beep); D-Symbol (Stereoscopic 3D visual TOR with exclamation mark on hazard)	Speaker; Instrument cluster	Hazard	Auditory; Visual	Earcon (Beep); Symbol (Stereoscopic 3D visual TOR with hands on steering wheel)	Speaker; Instrument cluster	▲ Time to first fixation to the road ▲ Number of fixations to TOR display ▲ Total fixation duration on TOR display
(Wright et al., 2017)	4 s	Reading task	Auditory	D-Speech	Vehicle sound system	Hazard	Auditory	Speech	Vehicle sound system	▲ Probability of fixation to hazard
(Wu et al., 2023)	5 s	Playing game (Spot the difference)	Auditory; Visual	N-Earcon (Beep); N-Symbol (Hands on steering wheel); D-Symbol (Exclamation mark)	Vehicle sound system; Centre console; AR-HUD	Hazard	Auditory; Visual	Earcon (Beep)-Symbol (Hands on steering wheel)	Vehicle sound system; Centre console	♦ Gaze distribution across AOIs
			Auditory; Visual	N-Earcon (Beep); N-Symbol (Hands on steering wheel); D-Symbol (Arrow)	Vehicle sound system; Centre console; AR-HUD	Free lane				♦ Gaze distribution across AOIs

			Auditory; Visual	N-Earcon (Beep); N-Symbol (Hands on steering wheel); D-Symbol (Red rectangular); D-Symbol (Green rectangular)	Vehicle sound system; Centre console; AR-HUD	Hazard; Free-lane				▲ Gaze distribution across AOIs
(Yu et al., 2025)	8 s	Texting on a phone	Auditory; Visual	N-Speech (Please take over); D-symbols (Cross mark and red arrow indicated hazard; check mark and green arrow indicated free lane)	HUD (projected onto the driver's central field of vision)	Hazard; Free-lane	Auditory	Speech (Please take over)	Vehicle sound system	▼ Pupil diameter ▼ Percentage of fixation duration on hazard ▲ Percentage of fixation duration on TOR display ▼ Number of fixations to hazard ▲ Number of fixations to TOR display
(Zhu et al., 2024)	7s	Playing games	Auditory; Visual	N-Earcon (Beep); D-Abstract (Bounding box around the main hazard)	Vehicle sound system; AR-HUD	Hazard	Auditory	Earcon (Beep)	Vehicle sound system	♦ Time to first fixation to the road ▲ Total fixation duration on the road

▲ = There was an increase in this gaze metric when a directional TOR was presented, compared to when a non-directional TOR was presented.

▼ = There was a decrease in this gaze metric when a directional TOR was presented, compared to when a non-directional TOR was presented.

♦ = There was no difference in this gaze metric when a directional TOR was presented, compared to when a non-directional TOR was presented.

D = Directional

N = Non-directional

3.3.1 *The effect of directional TORs on gaze behaviour to hazard*

The pooled results from five studies found that there was a significant reduction in time to first fixation on the hazard when drivers received a directional TOR, indicating the hazard location, compared to a non-directional one (n = 234, MD = -0.41, 95% CI [-0.72; -0.10], p = 0.01, Table 5). There was a significant difference in statistical heterogeneity between the five studies (I2 = 84%, p < 0.001). Sensitivity analysis using a leave-one-out approach showed that excluding the study by Arabian et al. (2026) resulted in a more pronounced effect, with more faster hazard fixation in response to towards-hazard directional TORs compared to non-directional ones. Omitting this study also reduced heterogeneity between studies to a negligible level (I^2 = 0%), indicating that this study had a significant influence on the overall result (Figure 3).

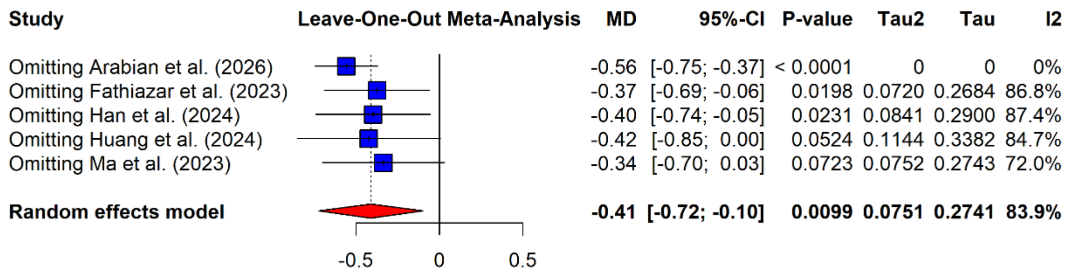

Figure 3. Leave-one-out sensitivity analysis for the meta-analysis comparing the effect of directional vs. non-directional TORs on the time to first fixation to hazards.

The meta-analysis of three studies showed a significant positive effect of towards-hazard directional TORs on the likelihood of fixation to the hazard, compared to non-directional TORs, with a pooled mean difference of 0.14 (n = 67, 95% CI [0.03; 0.24], p = 0.01, I^2 = 0%, Table 5). However, the pooled results indicated no significant difference in the total fixation duration on hazard (k = 4, n = 291, SMD = -0.06, 95% CI [-0.29; 0.17], p = 0.61, Table 5) between towards-hazard directional TORs and non-directional TORs. Due to the high heterogeneity across studies comparing directional and non-directional TORs (I2 = 79%, p = 0.002), subgroup analysis was conducted to identify the potential moderator. Hazard visibility emerged as a plausible moderating factor, as previous findings indicate that directional TORs enhance fixation duration on salient hazards visible within the driver's forward field of view (i.e., overt hazards), whereas they may reduce fixation duration when hazards are covert and difficult to spot (Huang et al., 2024). The hazard visibility appeared to differentially affect the primary outcome, change in fixation duration on hazard. When the hazard was covert, directional TORs had a significant negative effect on fixation duration on the hazard (k = 2, n = 164, SMD = -0.33, 95% CI [-0.64, -0.02]; Figure 4), indicating that directional TORs significantly reduced total fixation duration compared with non-directional TORs. In contrast, when the hazard was overt, directional TORs showed a positive effect on fixation duration (Figure 4). The overt subgroup also demonstrated low heterogeneity across studies ($I^2 = 0\%$).

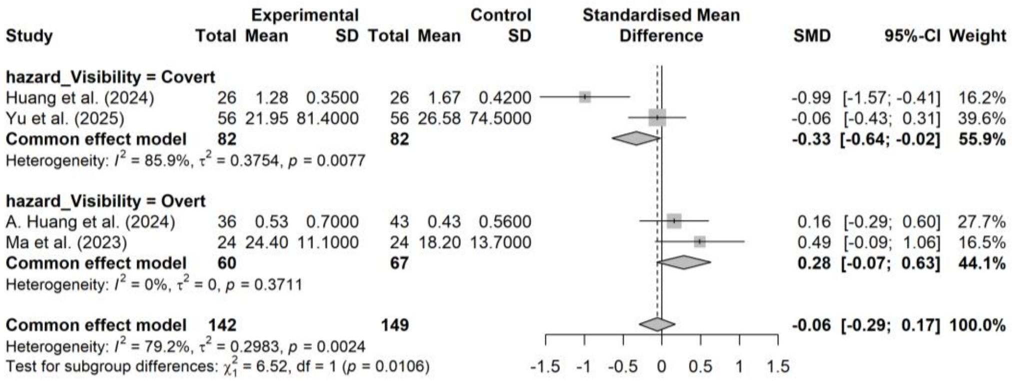

Figure 4. Subgroup analysis of the effect of directional TORs on total fixation duration on the hazard, classified by hazard visibility (overt vs. covert).

Overall, results reported that drivers were more likely to fixate on hazards, and did so more quickly following towards-hazard directional TORs compared to non-directional TORs. Hazard visibility acted as a moderating factor in the relationship between TOR directionality and fixation duration on the hazard, with directional TORs reducing fixation duration for covert hazards while increasing it for overt hazards.

3.3.2 *The effect of directional TORs on gaze behaviour to the TOR display*

The pooled results revealed that directional TORs not only increased the frequency of fixations to the TOR displays (k = 4, n = 216, MD = 1.04, 95% CI [0.50; 1.58], $p < 0.001$, $I^2 = 63\%$, Table 5) but also extended the total duration of fixations on them (k = 6, n = 298, SMD = 0.51, 95% CI [0.28; 0.74], $p < 0.001$, $I^2 = 35\%$, Table 5**Error! Reference source not found.**), when compared to non-directional TORs. Overall, visual TORs that included directional information, indicating the location of the hazard or the free lane, led to an increase in both the number and duration of fixations on the TOR display.

Table 5. Meta-analysis results of the effect of directional takeover requests on gaze behaviour outcomes.

Outcome	**No. of studies**	**Total N (Exp/Control)**	**Pooled MD/SMD [95% CI]**	***p*-value**	**Heterogeneity (I², %)**	**Model Used (Fixed/Random Effect)**
Time to first fixation to hazard	5	234 (117/117)	MD = -0.41 [-0.72; -0.10]	0.01	84%	Random
Probability of fixation to hazard	3	67 (33/34)	MD = 0.14 [0.03; 0.24]	0.01	0%	Fixed
Total fixation duration on hazard	4	191 (142/149)	SMD = -0.06 [-0.29; 0.17]	0.61	79%	Fixed
Number of fixations to TOR display	4	216 (108/108)	MD = 1.04 [0.50; 158]	< 0.001	63%	Fixed
Total fixation duration on TOR display	6	298 (149/149)	SMD = 0.51 [0.28; 0.74]	< 0.001	35%	Fixed
Time to first fixation to mirrors	2	123 (65/58)	MD = -0.11 [-0.26; 0.04]	0.16	39%	Fixed
Number of fixations to mirrors	2	60 (30/30)	MD = 1.84 [-0.27; 3.95]	0.09	81%	Fixed
Total fixation duration on mirrors	3	90 (45/45)	SMD = -0.21 [-0.63; 0.21]	0.34	49%	Fixed
Time to first fixation to the road	5	218 (109/109)	MD = 0.59 [-0.14; 1.32]	0.12	90%	Random
Total fixation duration on the road	4	150 (75/75)	SMD = 1.51 [1.11; 1.90]	< 0.001	92%	Fixed
Pupil diameter	2	160 (80/80)	MD = -0.15 [-0.30; -0.01]	0.03	0%	Fixed

3.3.3 *The effect of directional TORs on mirror-checking behaviour*

Pooled analyses revealed no significant differences between directional and non-directional TORs in time to first fixation to mirrors (k = 2, n = 123, MD = -0.11, 95% CI [-0.26; 0.04], $p = 0.16$, $I^2 = 39\%$, Table 5), number of fixations to mirrors (k = 2, n = 60, MD = 1.84, 95% CI [-0.27; 3.95], $p = 0.09$, $I^2 = 81\%$, Table 5), and total fixation duration on mirrors (k = 3, n = 90, SMD = -0.21, 95% CI [-0.63; 0,21], p = 0.34, I^2 = 49%, Table 5). Due to the significant and high heterogeneity observed across studies examining the number of fixations to mirrors (I^2 = 81%, p = 0.02), a narrative review was also conducted. The forest plots indicated that the study by Rodrigues (2024) reported a positive effect on the number of fixations to mirrors, whereas the study by Borojeni et al. (2018) reported a negative effect. See supplementary appendix B for graphical representation of meta-analyses. This discrepancy may be attributable to differences in display location, with Borojeni et al. (2018) presenting directional LEDs on the vehicle dashboard, while Rodrigues (2024) implemented visual displays (bounding boxes) directly around the mirrors.

3.3.4 The effect of directional TORs on gaze behaviour to the road environment

Data pooling from five studies indicated no significant difference in the time to first fixation to the road, between directional and non-directional TORs (n = 218, MD = 0.59, 95% CI [-0.14, 1.32], p = 0.12, I^2 = 89%, Table 5**Error! Reference source not found.**). Due to the high heterogeneity across studies, a sensitivity analysis using a leave-one-out approach was conducted to identify potential influential studies. The results indicated that excluding the study by Zhu et al. (2024) reduced heterogeneity to a negligible level (I2 = 0%). Additionally, omitting this study revealed a significant positive effect of directional TORs on time to first fixation on the road (n = 146, MD = 0.16, 95% CI [0.02, 0.30], Figure 5).

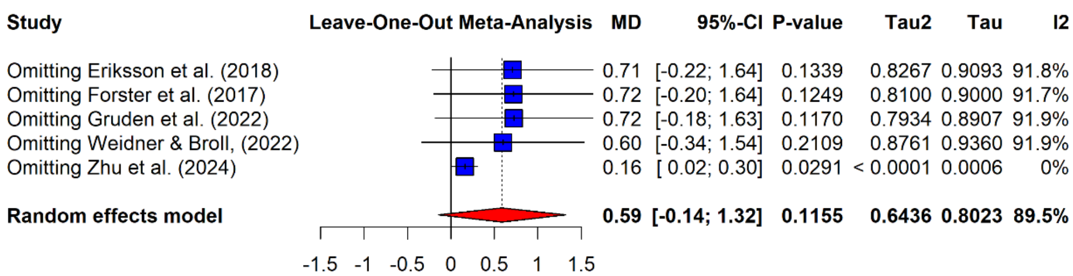

Figure 5. Leave-one-out sensitivity analysis for the meta-analysis comparing the effect of directional vs. non-directional TORs on the time to first fixation to the road.

The pooled results revealed that directional TORs significantly increased the total fixation duration on the road (k = 4, n = 150, SMD = 1.51, 95% CI [1.11; 1.90], $p < 0.001$; $I^2 = 92\%$, Table 5). Sensitivity analysis using a leave-one-out approach showed that excluding the study by Shi et al. (2024) resulted in a more pronounced effect, with longer fixation time on the road in response to directional TORs compared to non-directional ones. Omitting this study also reduced heterogeneity to a low level ($I^2 = 7\%$), identifying it as an influential study (Figure 6).

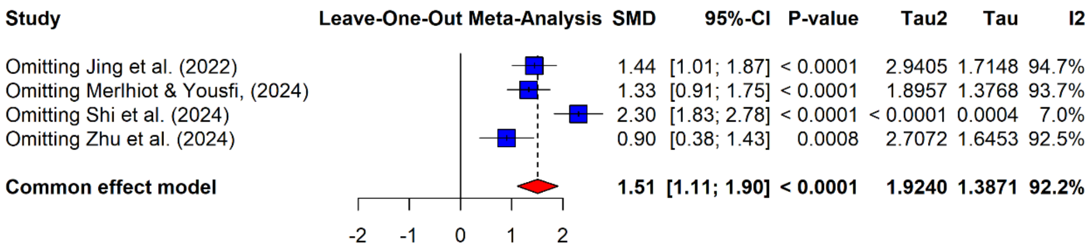

Figure 6. Leave-one-out sensitivity analysis for the meta-analysis comparing the effect of directional vs. non-directional TORs on the total fixation duration on the road.

3.3.5 The effect of directional TORs on cognitive workload

The pooled results indicated that there was a significant reduction in the pupil diameter when drivers received directional TORs, compared to non-directional ones (k = 2, n = 160, MD = -0.15, 95% CI [-0.30; -0.01], $p = 0.03$, $I^2 = 0\%$, Table 5).

4 Discussion

The objective of this systematic review and meta-analysis was to examine the effects of directional TORs on drivers' gaze behaviour while taking over from automated driving. To achieve this goal, this systematic review screened 3882 studies and selected 22 relevant research papers. The findings are further discussed in the following sub-sections.

4.1 The effect of directional TORs on gaze behaviour to hazard

The meta-analysis review results indicated that in comparison to non-directional TORs, directional TORs indicating hazard's location led to faster hazard detection by reducing the time to first fixation on the hazard (MD = - 0.41 second, $p = 0.01$), also increased the probability of fixation to the hazard by 14 percentage points (MD = 14%, $p = 0.01$). Findings therefore support the hypotheses that directional TORs are effective in guiding drivers' visual attention to the right place (i.e., hazard's location) at the right time (i.e., faster fixation) (Arabian et al., 2026). The sensitivity analysis indicated that the study by Arabian et al. (2026) had an influential effect on both the overall effect size and the observed heterogeneity in the time to first fixation to hazards. One possible explanation for this discrepancy relates to differences in the level of vehicle automation. Four of the five included studies examining directional versus non-directional TORs were conducted in SAE Level 3 automated vehicles, in which drivers were engaged with an NDRT. In contrast, the study by Arabian et al. (2026) implemented Level 2 automation, where drivers were required to continuously monitor the driving environment and remain ready to resume control. Notably, this study reported the smallest effect size (MD = −0.05 s, see supplementary appendix B). This difference may be attributed to the reduced attentional demands in Level 3 automation. When allowed to disengage from monitoring the driving environment, drivers typically redirect their gaze towards NDRTs, making directional cues more beneficial for guiding attention back to hazards. Consequently, studies conducted under Level 3 automation demonstrated stronger effects of directionality on accelerating hazard detection. Conversely, when drivers remain visually engaged with the driving scene—as in Level 2 automation—the advantage of directional over non-directional warnings is present but diminished.

Unlike the hypothesis mentioned in Table 2, towards-hazard TORs did not reduce fixation duration on hazard. The included studies reported both positive and negative effects, contributing to the high heterogeneity observed across studies. Subgroup analysis showed that hazard visibility may explain this inconsistency, acting as a moderating factor in the relationship between TOR directionality and the total fixation duration on hazards.

Specifically, when hazards were overt and clearly visible within the driver's forward field of view, such as overt motorbikes, trucks, and cars (A. Huang et al., 2024) or overt traffic accidents and motorbikes ahead (Ma et al., 2023), directional TORs were associated with increased fixation duration. In such scenarios, directional TORs may reinforce attention towards an already visible hazard, encouraging prolonged visual engagement. In contrast, when hazards were covert and difficult to spot, such as a covert pedestrian (Huang et al., 2024) or a covert trailing vehicle in the adjacent lane (Yu et al., 2025), directional TORs were associated with reduced fixation duration. In these cases, directional TORs may help drivers better understand the situation and quickly establish situational awareness, without necessarily increasing fixation duration on the hazard.

4.2 The effect of directional TORs on gaze behaviour to the TOR display

The findings of our meta-analyses showed that directional TORs significantly increased the number of fixations and total fixation duration on the TOR display. This finding is consistent with a previous scoping review that found providing additional information along with a visual display was associated with an increased frequency and duration of fixations on the display (Kanaan et al., 2024). This result suggests that a TOR with additional information (i.e., directionality feature) may require drivers to spend more time processing it, thereby occupying more of their visual attention (Goncalves et al., 2022). Therefore, if the display is presented in the instrument cluster or centre console, it may lead to an increase in eyes off the road. It has been shown that a HUD display encourages drivers to glance at the road earlier after TORs by reducing glances to the instrument cluster, which can reduce eyes off the road time (Xu et al., 2023). In this regard, Jing et al., (2022) used AR-HUD interfaces to indicate the hazard location. The authors found that in comparison to the non-AR-HUD interface presented in the instrument cluster, the directional AR-HUD interfaces effectively decreased eyes off the road time, where the non-directional TOR was presented in both conditions.

4.3 The effect of directional TORs on mirror-checking behaviour

Mirror-checking behaviour is the most important predictor of drivers' lane-change decisions in both manual (Salvucci et al., 2001; Doshi and Trivedi, 2009) and automated (Goncalves et al., 2020; Goncalves et al., 2022) driving scenarios. Studies hypothesised that providing directional TOR might decrease the frequency and duration of fixations on side mirrors during a lane change scenario (Borojeni et al., 2018). This is because directional TORs could inform drivers about the hazard location or indicate the free lane direction, helping them make correct decisions without needing to check side mirrors frequently. However, the meta-analysis findings of this review indicated that directional TOR signals had no impact on the number and duration of fixations to mirors. This aligns with the findings of (Goncalves et al., 2022), who reported that drivers are not generally used to initiating a lane change without first checking the mirrors, regardless of the HMI condition. Additionally, variability in both the location and the amount of information presented in the directional TOR displays across studies may further account for the observed differences in effectiveness. Shi et al. (2024) and Borojeni et al. (2018) presented directional LEDs on the vehicle frame or dashboard, which were associated with a decrease in the number and duration of fixations on mirrors, whereas Rodrigues, (2024) employed an AR-HUD with bounding boxes around mirrors in different colours to indicate the location and distance of adjacent vehicles (i.e., green - manoeuvre is safe, nearest vehicle is far away; red - manoeuvre is not safe, executing it would cause a collision with the other vehicle), resulting in increased number and duration of fixations on mirrors. Therefore, when directional TORs presented in the mirrors with additional informations, they may increase the number and duration of fixations to mirrors. Taken together, these results suggest that the influence of directional TORs on mirror-checking behaviour may be moderated by the location of the display and the amount of information it conveys.

The findings also showed no significant difference in the time to first fixation to mirrors between directional and non-directional TORs. However, the effect varied depending on the modality of the directional signal. While auditory directional warnings were associated with faster fixations to mirrors compared to non-directional auditory warnings (Arabian et al., 2026), the use of a directional AR-HUD carpet rendered onto the road led to significantly longer time to first fixation to mirrors (Lorenz et al., 2014). Since driving is a primarily visual task, the use of auditory warnings reduces the overload imposed on drivers' visual system (Spence and Driver, 1997; Liu, 2001; Ho and Spence, 2005; Noyes et al., 2006; Meng and Spence, 2015). As a results, directional auditory TORs, being eyes-free, facilitate faster attention shifts to mirrors. In contrast, directional AR-HUD carpet captures drivers' visual attention immidiately after the TOR, thereby delaying the time to first fixation on mirrors. Overall, these findings highlight that the modality of directional TORs plays a critical role in shaping drivers' visual attention, with directional auditory signals facilitating quicker mirror engagement and directional visual AR-HUD potentially delaying it.

4.4 The effect of directional TORs on gaze behaviour to the road environment

The findings of the meta-analysis showed that directional TORs did not have a significant effect on the time to first fixation to the road. In other words, the inclusion of directionality feature did not influence how quickly drivers redirected their attention to the road. However, a high level of heterogeneity was observed across studies, indicating variability in findings that warranted further investigation. Sensitivity analysis revealed that the study by Zhu et al. (2024) had a considerable influence on the observed heterogeneity. When this study was excluded, heterogeneity was reduced to a negligible level (I2 = 0%). A plausible explanation for the divergent findings relates to differences in post-TOR task demands. In four of the five included studies, drivers were required to actively resume vehicle control following the TOR, typically to avoid a potential hazard. In contrast, in Zhu et al. (2024), drivers were not required to take control of the vehicle, as the system automatically decelerated and managed the situation until the end of the scenario. As a result, drivers may have experienced lower urgency and engagement, which could have altered their visual behaviour typically observed in real-world driving. This difference in task requirements may explain why the inclusion of this study significantly increased heterogeneity. Excluding this study from the meta-analysis also revealed a significant positive effect of directional TORs on time to first fixation to the road, indicating that drivers required more time to redirect their gaze to the roadway compared with non-directional TORs. This finding may be explained by the inclusion of directional information, particularly when conveyed through visual displays located on the dashboard (e.g., Weidner and Broll, 2022; Gruden et al., 2022). Such displays may initially capture drivers' attention, leading them to longer fixate on the directional TORs comparted to non-directional ones before shifting their gaze back to the road.

The meta-analysis demonstrated that directional TORs significantly increased total fixation duration on the road compared with non-directional TORs. However, considerable heterogeneity across studies suggests that this effect is not consistent and may vary across included studies. Sensitivity analysis further indicated that the study by Shi et al. (2024) had an influential effect on the overall results, as its exclusion both strengthened the positive effect and considerably reduced heterogeneity. In the studies by Merlhiot & Yousfi, (2024), C. Jing et al. (2022), and Zhu et al., (2024), directional TORs were presented as AR-HUD highlighting the hazard location in the road environment, whereas Shi et al. (2024) used a visual directional TOR display presented in the instrument panel. In Shi et al.'s (2024) study, drivers spent more time fixating on the instrument panel following a directional TOR, which decreased their total fixation duration on the road. These findings suggest that the impact of directional TORs on road fixation duration depends on their location, with directional AR-HUD cues supporting increased road fixation duration and in-vehicle displays presented in the dashboard decreasing it.

4.5 The effect of directional TORs on cognitive workload

Pupil diameter is a well-established physiological indicator of cognitive workload (Heikoop et al., 2018) and has been widely used to measure drivers' workload during the takeover process (Weidner and Broll, 2022; Ma et al., 2023; Radhakrishnan et al., 2023; Yu et al., 2025). Pupil dilation typically occurs when drivers are under high cognitive load, whereas pupil constriction is associated with lower cognitive load (Tsai et al., 2007; Radhakrishnan et al., 2023). Additionally, excessive memory overload has also been found to be associated with pupil constriction (Kosachenko et al., 2023). Our meta-analysis results showed that directional TORs significantly decrease pupil diameter compared to non-directional TORs. This reduction may be attributed to the assistance information provided by directional TORs, which helped drivers recognise and process road information, reduced time pressure during the takeover process, and optimised decision-making processes, thereby reducing cognitive workload.

4.6 Limitations and future directions

There are several limitations that should be considered when interpreting the findings of this review study. First, the quantitative syntheses for the number of fixations to mirrors, number of fixations to TOR display, probability of fixation to hazard, time to first fixation to mirrors, total fixation duration on hazard, total fixation duration on mirrors, total fixation duration on the road, and pupil diameter are based on less than five studies. A study has shown that the results of such meta-analyses with a limited number of small studies may be inconclusive and should be considered with considerable caution (Egger et al., 1997). Therefore, future research is needed to address the impact of directional TORs on gaze measures to provide conclusive results. As such, we suggest that future meta-analyses should be conducted with more studies.

Second, previous studies have shown that experienced drivers have different gaze patterns compared to novice drivers (Wright et al., 2016), and gaze patterns vary between younger and older drivers (Kunishige et al., 2019). In addition, takeover time budget has been known an an influential factor on gaze behaviour during transitions from vehicle automation (Deniel and Navarro, 2023). As these variables varied across the included studies, they may have contributed to differences in gaze outcomes and suggest that the influence of directional TORs on gaze measures may depend on age, driving experience, and time budget. Although these variables could be examined as covariates in their meta-regressions, these were not feasible due to the limited number of included studies. According to the Cochrane Handbook (section 10.11.5.1) (Chandler et al., 2019), typically at least ten studies per covariate are required to ensure reliable and meaningful meta-regression results, which was not met in this review. Therefore, future research with a larger body of studies is needed to enable robust meta-regression analyses and to better understand the moderating effects of these factors.

Third, mean pupil diametre was used to measure cognitive workload in response to directional vs non-directional TORs. Recent evidence suggests that the phasic fluctuations in pupil diameter, rather than mean levels, may provide a more precise index of cognitive resource mobilisation during task engagement (Goodridge et al., 2026). Future research should also complement mean pupil measures with phasic indices to better capture dynamic fluctuations in cognitive engagement.

Finally, all included studies in this review were conducted using driving simulators. Although simulator-based research is widely used in automated driving studies and allows for precise control of experimental conditions without exposing participants to real-world risks, it has limitations in terms of generalisability. Driver behaviour observed in simulated environments may not fully reflect behaviour in real traffic conditions (De Winter et al., 2012; Morando et al., 2019), particularly with respect to risk-taking behaviour. Consequently, the extent to which the observed gaze patterns generalise to real-world automated driving contexts remains uncertain. Future research employing controlled on-road experiments would be valuable to determine whether the attentional benefits associated with directional TORs observed in this review extend to real-world driving contexts.

5 Conclusion

The present study systematically reviewed the literature and synthesised the results of existing research on the impact of directional TORs on drivers' gaze behaviour while taking over automated driving, using quantitative and qualitative analyses. Our findings revealed that directional TORs enhance drivers' visual attention and reduce cognitive workload during takeover situations. Specifically, directional TORs indicating hazard's location improved hazard detection by shortening the time to first fixation and increasing the likelihood of fixating on hazards, although their effect on fixation duration varied depending on hazard visibility. Directional TORs significantly increased both the number and duration of fixations on the TOR display. Although, they led to faster hazard detection, when presented in the instrument cluster, this may raise concerns about increased eyes-off-road time and time to first fixation on the road. Regarding the mirror-checking behaviour, the modality and location of display emerged as key factors moderating gaze behaviour: auditory directional TORs facilitated quicker mirror engagement, while visual directional AR-HUD carpets delayed it. Taken together, these findings suggest that the benefits of directional TORs depend strongly on how and where they are presented. While they effectively guide attention to hazards and reduce cognitive demands, their influence on mirror-checking and road fixations varies with display modality and location.

Author contributions

CRediT: **Ali Arabian**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing; **Courtney M. Goodridge**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project Administration, Supervision, Validation, Writing – original draft, Writing – review & editing; **Yee Thung Lee**: Conceptualization, Data Curation, Investigation, Methodology; **Rafael C. Gonçalves**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – review & editing; **Rory Coyne**: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – review & editing; **Natasha Merat**: Conceptualization, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

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Data availability statement

All data and analysis code related to this systematic review and meta-analysis are available at the following URL: https://github.com/ali-arabian/Directional_TOR_Gaze_Behaviour_Meta_Analysis.git.

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