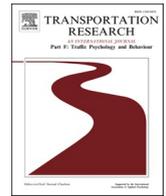




ELSEVIER

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

## Transportation Research Part F: Psychology and Behaviour

journal homepage: [www.elsevier.com/locate/trf](http://www.elsevier.com/locate/trf)

# Guiding drivers' attention to the right place at the right time during transitions from SAE level 2 driving system: Effects of warning directionality and audiovisual asynchrony

Ali Arabian<sup>\*</sup>, Courtney M. Goodridge, Rafael Cirino Gonçalves, Natasha Merat

Institute for Transport Studies, University of Leeds, UK

## ARTICLE INFO

## Keywords:

Automated vehicles  
Directional auditory warnings  
Stimulus onset asynchrony  
Gaze behaviour

## ABSTRACT

Driver visual attention is crucial for the safe transition of control from higher levels of automation to manual driving. Without efficient visual sampling of their surroundings during the transition process, drivers have an increased risk of collisions, due to reduced situation awareness, imposed by automated driving. The use of directional auditory warnings has been proposed as an effective way for guiding drivers' attention to the right place at the right time, during transitions of control that require a lane change for obstacle avoidance. Here, directional auditory warnings either direct drivers' attention towards a free lane (i.e., *towards-free-lane warnings*) or towards a hazard (i.e., *towards-hazard warnings*). Whilst studies have demonstrated that the towards-hazard warnings facilitate faster hazard detection, relative to non-directional warnings, little is known about the effects of towards-free-lane auditory warnings on gaze behaviours. Studies have also shown that temporal separation of auditory warnings and visual information can improve the effectiveness of warnings, by attenuating the visual dominance effect. However, the impact of this temporal separation on drivers' gaze behaviour during transitions from automation remains unknown. Using a driving simulator study with forty-eight participants, we investigated how directional auditory warnings and asynchronous presentation of auditory warnings and visual information affect drivers' gaze behaviour during transitions from a hands-on SAE L2 driving system. Results showed that, compared to non-directional warnings, directional auditory warnings reduced the probability of fixation to wing mirrors. Towards-hazard and towards-free-lane warnings effectively guided drivers' visual attention to the hazard location and the free lane, respectively, and also led to faster fixations on these areas. However, under towards-hazard warnings, drivers still adhered to their habit of checking the free lane wing mirror during lane changes with these warnings. Finally, longer stimulus onset asynchronies (SOA) were associated with faster fixations to the wing mirrors and quicker hazard detection, suggesting that longer SOAs attenuated visual dominance effect, leading to an increase in the effectiveness of directional auditory warnings in guiding drivers' visual attention. Findings from this study provide valuable insights for the design of in-vehicle warning systems in automated vehicles.

<sup>\*</sup> Corresponding author.

E-mail address: [tsaar@leeds.ac.uk](mailto:tsaar@leeds.ac.uk) (A. Arabian).

<https://doi.org/10.1016/j.trf.2025.103505>

Received 17 September 2025; Received in revised form 19 November 2025; Accepted 26 December 2025

Available online 29 December 2025

1369-8478/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

As the level of automation in road vehicles increases, operational control of the vehicle is the first element of driving that is removed (Mole et al., 2019). Although drivers are removed from the operational control loop during SAE Level 2 driving (see SAE, 2021), they are technically still driving and thus must actively monitor the road environment, and driving assistance systems, being ready to resume control, if required. However, both on-road and simulator studies show that when drivers are not in active physical control of the vehicle, the pattern of their eye movements changes; gaze becomes more dispersed (Louw & Merat, 2017), visual attention towards the road centre is reduced (Carsten et al., 2012; Louw et al., 2015; Pipkorn et al., 2024), and fewer glances are made to safety critical areas (Gonçalves et al., 2019). Drivers also tend to direct their gaze further ahead in the road scene (Mackenzie & Harris, 2015). Horizontal gaze dispersion is also seen to be higher during automation, when compared to manual driving (Damböck et al., 2013; Louw & Merat, 2017). Such erratic gaze patterns and inattention to the road ahead may take drivers out-of-the-loop (OOTL) (Merat et al., 2019); a condition generally associated with reduced Situation Awareness (SA) (Endsley, 1995, 2017) and poorer performance during transitions of control (Louw et al., 2017). For example, Louw et al. (2017) found that, when resuming control from a hands-off L2 driving system, drivers with erratic eye scanning patterns were more likely to crash into a lead vehicle, while those with a smoother pattern, focusing on the forward roadway, were more likely to avoid a crash (see also Goodridge et al., 2025). On-road studies with hands-on or -off L2 systems also show that drivers look away from the forward roadway and towards the dash area (typically the location of information about automation status) during transition of control, which significantly impedes their ability to react in time or safely to an impending collision (Gaspar & Carney, 2019; Pipkorn et al., 2024). Therefore, appropriate visual attention, to the right place at the right time, is crucial for facilitating fast and safe transitions to manual driving.

To facilitate safe driving, many modern vehicles are equipped with a range of advanced driver assistance systems that help drivers by warning them about impending collisions with hazards. Examples include blind spot detection (Bengler et al., 2014), lane departure (Narote et al., 2018), and forward collision warnings (Cicchino, 2017; Jamson et al., 2008). As the number of automated functionalities in vehicles increases, so may the number and type of warnings associated with these assistance systems. For hands-on SAE L2 systems, this may include driver alerts when hands are removed from the steering wheel for an unacceptable period of time (E.g. 15 s - see UNECE, 2017), or if a request to intervene (RTI) is provided when the vehicle reaches a limitation or the end of its Operational Design Domain (ODD) (SAE, 2021). However, as outlined above, such requests for resumption of manual control can lead to erratic eye movement behaviours, which can be associated with an expectation mismatch (Victor et al., 2018) and confusion by drivers, which may in turn increase the probability of collisions (Louw et al., 2017). Therefore, simply making drivers aware of hazards (without information about its location, or how to respond) is not sufficient, and may even be detrimental to safety. Rather, a warning system that guides drivers' visual attention towards the right place at the right time in an attempt to facilitate safer transitions of control may be more effective.

### 1.1. Directional auditory warnings and visual attention in driving

The use of directional auditory warnings in vehicles is one method for guiding drivers' attention to the right place at the right time, especially during transitions of vehicle control from automation. Since driving is a primarily visual task, the use of auditory warnings reduces the overload imposed on drivers' visual system (Ho & Spence, 2005; Liu, 2001; Meng & Spence, 2015; Noyes et al., 2006; Spence & Driver, 1997b). Processing of auditory information is also much faster than visual processing (Cooper, 1999; Ho & Spence, 2005; Spence et al., 2012). Auditory warnings are also more effective than e.g. tactile warnings, since they are not dampened by the thickness of clothing or vibrations from the vehicle itself (Meng & Spence, 2015). Overall, due to their demonstrated advantages, auditory warnings are increasingly recommended and applied as directional warnings in driving (Borojeni et al., 2016, 2018; Chen et al., 2022; de Winter et al., 2022; Forster et al., 2017; Gruden et al., 2022; Ho & Spence, 2005; Kim et al., 2024; Lundqvist & Eriksson, 2019; J. Ma et al., 2023; Straughn et al., 2009; Wang et al., 2003, Wang et al., 2007; Wright et al., 2017, 2018).

When it comes to assistance with safe lane changes, directional auditory warnings are generally divided into two broad categories: warnings that provide information about the location of a free lane (i.e., "towards-free-lane warnings") and warnings that provide information about the location of a potential hazard that should be avoided (i.e., "towards-hazard warnings"). Towards-free-lane warnings have also been called "ipsilateral" warnings (Arabian et al., 2024, 2025; de Winter et al., 2022; Straughn et al., 2009; Wang et al., 2003; Wang et al., 2007); with the towards-hazard warnings also term "contralateral" warnings (Arabian et al., 2024, 2025; de Winter et al., 2022; Straughn et al., 2009; Wang et al., 2003; Wang et al., 2007). Previous research has examined the impact of directional auditory warnings on manual driving (Ho & Spence, 2005; Serrano et al., 2011), and shown that directional auditory warnings can successfully capture drivers' attention to the right location (Ho & Spence, 2005) and lead to faster detection of road hazards (Serrano et al., 2011). In the context of automated driving, the use of directional auditory warnings is also becoming more widespread. A few studies have investigated the effects of directional auditory Takeover Requests (TORs) on drivers' gaze behaviour while transitioning from SAE L3 to manual driving (Ma et al., 2023; Wright et al., 2017). These studies have shown that towards-hazard directional auditory TORs result in a higher percentage of hazard detection (Wright et al., 2017), faster hazard detection (Ma et al., 2023), and higher fixation rates on hazards (Ma et al., 2023), when compared to non-directional auditory TORs. Therefore, towards-hazard TORs are better at guiding drivers' visual attention towards hazards, relative to non-directional warnings. The implication of these results is that faster and higher visual attention towards hazards can accelerate the development of drivers' SA, improving takeover performance.

However, these studies have only compared towards-hazard directional warnings with *non-directional* warnings. Relatively less work has been done on investigating the utility of directional auditory warnings that indicate the location of a free lane for drivers to

move in to, for collision avoidance. For example, [de Winter et al. \(2022\)](#) conducted a study to compare the impact of towards-free-lane, towards-hazard, and non-directional auditory warnings on drivers' gaze behaviour. Participants were presented with an animated video depicting a three-lane highway, presented on a single PC screen, without a steering wheel or pedals. In response to different auditory warnings, participants were asked to indicate the direction in which they would theoretically steer, to avoid a collision with a stationary vehicle blocking the middle lane, while another vehicle was overtaking the ego vehicle on the left or right side. This response was recorded by pressing the left or right arrow on a keyboard. No significant differences were observed between the warning types in terms of gaze behaviour. First fixations typically landed on the most salient object (i.e., the stationary vehicles). Subsequent fixations were also goal-oriented, based on the lane change scenario, where fixations landed in the rear-view mirrors to evaluate the traffic situation behind the vehicle. The eye-tracking data indicated that visual attention was primarily influenced by the driving context (i.e., drivers relied on visual scanning of the driving environment to respond to the lane change scenario), rather than using the auditory cues. In other words, visual information was dominant and more prominent than the type of auditory warnings provided. Therefore, the hypothesis that drivers would follow auditory instructions to attend to the driving environment was not supported by this study. However, this study had a number of limitations. Firstly, a simple, computer-based task, using observation of videos is not comparable to real-world driving. Secondly, participants' response was based on a button press, and not an actual steering manoeuvre within a driving context.

### 1.2. Integrating visual and auditory information: The Colavita visual dominance effect

Attention is crossmodally coordinated, with information from one modality influencing and directing attention to another modality ([Driver & Spence, 1998a](#); [Hillyard et al., 2016](#); [McDonald et al., 2012](#)). For example, several lines of research have shown that salient peripheral sounds can attract attention and subsequently orient visual attention to that location ([Hillyard et al., 2016](#); [McDonald et al., 2012](#); [Spence & Driver, 2004](#)). Evidence that directional warnings are effective in guiding visual attention primarily comes from studies that present directional sounds *before* the appearance of a visual stimulus ([Störmer, 2019](#)). However, when auditory and visual cues are presented *simultaneously*, visual information tends to take precedence, a phenomenon known as the Colavita visual dominance effect ([Colavita, 1974](#); [Spence et al., 2012](#)). This visual dominance effect is thought to occur due to the temporal binding of auditory and visual information, also known as the unity effect ([Spence, 2007](#); [Vatakis & Spence, 2007](#); [Welch, 1999](#)). When stimuli in different sensory modalities (i.e., auditory and visual stimuli) are presented at about the same time, there is a high likelihood that participants bind and thus perceive them as a single audiovisual event. Hence, when presented concurrently, auditory signals may fail to reach awareness because the visual information takes priority, creating a unitary audiovisual event ([Baylis et al., 2002](#)). Therefore, the degree of multisensory integration is determined by the temporal separation of auditory and visual stimuli; and the Colavita effect may be attenuated when observers are able to distinguish between the two stimuli. This hypothesis was supported by [Koppen & Spence \(2007a\)](#) who found that reaction times to auditory stimuli varied according to the temporal separation between auditory and visual stimuli. We investigated the Colavita effect for a lane change after transitions of control from SAE L2, and found that drivers' time to first steer decreased significantly as the temporal separation between the auditory warning and the visual stimulus increased (Stimulus onset asynchrony = 0, 200, 400 or 600 ms), without compromising takeover quality ([Arabian et al., 2025](#)).

### 1.3. Current study

Previous research has demonstrated that directional auditory signals can guide the direction of visual attention ([Frassinetti et al., 2002](#); [McDonald et al., 2000](#)) and enhance visual processing at the cued location ([Störmer et al., 2009](#)). In the context of automated driving, studies have examined the effects of towards-hazard directional warnings on gaze behaviour, indicating that they can successfully direct drivers' visual attention to the right location, leading to higher and faster hazard detection. However, apart from the study by [de Winter et al. \(2022\)](#), very few studies have investigated the effect of *directional* auditory warnings on response, and particularly how this affects behaviour when attention is directed towards a hazard located in the drivers' adjacent lane, versus directing drivers to a free lane. As outlined above, the study conducted by [de Winter et al. \(2022\)](#) was computer-based, with response provided by a simple key press, rather than an actual driving and steering-based task, potentially limiting the generalisability of the findings. Hence, one overarching aim of the current study was to investigate the impact of different warning directionalities on drivers' gaze behaviour following resumption of control from SAE L2, using a static driving simulator. An additional aim was to investigate the impact of different SOAs between the auditory warnings and visual information in the driving scene on drivers' eye movement patterns, while resuming control from SAE L2 driving. The aim of the present study was to answer the following research questions:

- 1- Can directional auditory warnings guide drivers' visual attention to the right place (i.e., the free lane or the hazard's location) at the right time (i.e., faster fixations) following transitions of vehicle control during a lane change scenario?
- 2- Does the presence of SOAs improve response to the auditory warnings by guiding drivers' visual attention during these transitions of control?

## 2. Methods

### 2.1. Participants

Following approval from the University of Leeds Ethics Committee (Reference code: 2024-1012-1510), we recruited 48

participants (23 females, 25 males, aged 24–69 years, mean =  $41.94 \pm 13.04$  years) via the University of Leeds Driving Simulator (UoLDS) database, supplemented by a range of social media advertisements. Two participants did not report their approximate annual mileage and the length of their driving experience. The remaining 46 participants were regular drivers (Mean annual mileage =  $7673.91 \pm 3306.92$  miles, range = 5000 to 25,000 miles) and had a valid UK driving licence (Mean =  $20.22 \pm 14.48$  years, range = 2 to 50 years). Participants were compensated £15 for taking part in the study.

## 2.2. Apparatus

The experiment used the University of Leeds fixed-base driving simulator, consisting of an ultra-widescreen curved 49-in. 32:9 ( $3840 \times 1080$  pixels) LED monitor, with a FANATEC force feedback steering wheel and pedal system. The accelerator and brake pedals were placed on a stable Next Level Racing® Wheel Stand Direct Drive (Fig. 1). Participants wore a set of Beyerdynamic DT-990 Pro 250 Ohm headphones throughout the study, which were used to present the auditory warnings. Eye-tracking data was recorded on a SmartEye Pro 3-camera fixed-based eye tracking system at 60 Hz and analysed using SmartEye Pro software version 10.2.

## 2.3. Driving scenario

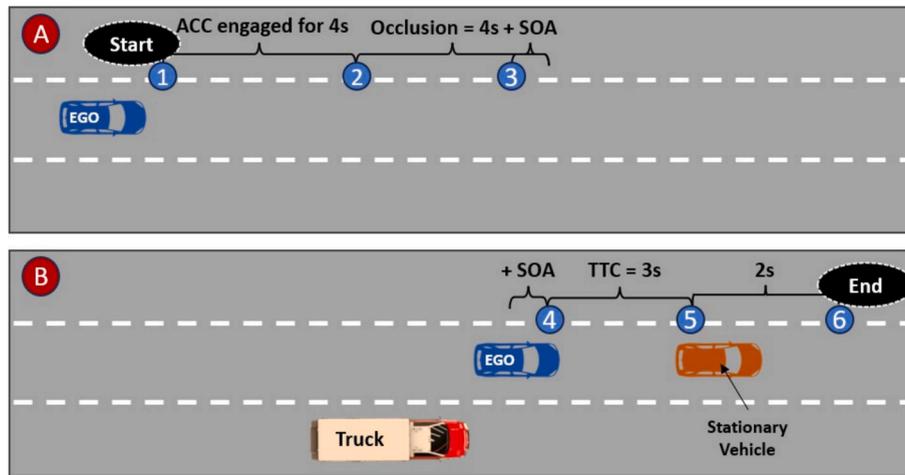
A 348-m section of a 3-lane UK motorway was used for this study. Each drive began with an SAE Level 2 hands-on driving section, which was activated when the driver pressed a button on the steering wheel. This allowed the ego vehicle to travel at a constant speed of 60mph in the centre of the middle lane. After 4 s of automated driving, all screens (the main driving scene and all mirrors) were occluded by a grey mask for 4 s + the SOA. This occlusion was implemented to control the presentation of the auditory warnings and visual elements in the driving scene. Before the occlusion ended, an auditory warning was delivered through a set of headphones, and after a short time gap (i.e., an SOA) the driving scene re-appeared. The onset of the auditory warning coincided with the onset of the SOA, although participants were not explicitly informed about the presence of an SOA. For example, in a trial with an SOA of 0 ms, the driving scene appeared simultaneously with the onset of the auditory warning; in a trial with an SOA of 600 ms, the driving scene appeared 600 ms after the onset of the auditory warning. As the occlusion ended, the L2 assistance system was also turned off, and a stationary vehicle appeared in the middle lane, blocking the ego vehicle's path. Simultaneously, a truck, travelling at 70 mph, appeared in either the left or right adjacent lane, precluding drivers from moving into that lane. Participants were required to quickly steer into the available lane (i.e., free lane) to avoid colliding with the stationary lead vehicle and the truck, within a 3-s time-to-collision (TTC) window. The trials ended after the driver made a manoeuvre or collided with the stationary lead vehicle. Participants were then prompted to press the same button on the steering wheel to initiate the next trial. A schematic overview of the driving scenarios and timing windows is provided in Fig. 2.

## 2.4. Design and procedure

This study used a 3 (warning direction: towards-free-lane, towards-hazard, and non-directional) x 4 (SOAs: 0, 200, 400, and 600 ms) x 2 (audio type: speech and beep) within-participants experimental design. Each participant took part in four main drives, presented in a counterbalanced order: one with speech towards-hazard warnings, one with beep towards-hazard warnings, one with speech towards-free-lane warnings, and one with beep towards-free-lane warnings. Non-directional speech and beep warnings were included as control conditions within their respective drives. The directional speech warnings included a human voice delivering the words “Left” and “Right,” presented via headphones to participants' left or right ear, respectively. The word “Look” was presented in



Fig. 1. Fixed-base driving simulator set up.



**Fig. 2.** Schematic representation of the Time Windows taken from Arabian et al. (2025). (A) represents the “before occlusion” and “occlusion” phase of the scenario, as follows: (1) The ego vehicle begins travelling at 60 mph in the central lane; (2) The occlusion starts, masking all visual information from all screens. The occlusion lasts for 4 s + the SOA; (3) The onset of the auditory warning. (B) represents the “after occlusion” phase (manual driving), as follows: (4) Following the auditory warning and the time elapsed during the SOA, the occlusion ends; (5) The moment of the crash with the stationary vehicle if the driver did not intervene; (6) If the driver overtook the stationary vehicle, they would continue travelling for a further 2 s before the end of the trial.

both ears for the non-directional cues. Similarly, the beep warnings included a beep sound: played in the left or right headphone for directional warnings, or in both headphones simultaneously for a non-directional warning. Audibility of the words and beeps was confirmed with each participant at the beginning of the practice drives. However, because the results for beep and speech warnings were similar and showed no significant differences, we focus only on the speech warnings in this study to highlight the effects of directionality and audiovisual asynchrony. Each main drive consisted of 24 randomised trials incorporating hazard location (left vs. right), directional/non-directional warnings, and SOAs see Table 1.

Upon arrival, participants were asked to read the information sheet, sign an informed written consent form, and complete a pre-experiment questionnaire to report their demographic information (gender, age, and driving experience). The experimenter also gave a verbal explanation of the experimental procedure, the objectives of the study, and an explanation of the choice of auditory warnings used for each drive. To help drivers become familiar with the equipment, driving scenario, auditory warnings, and the driving simulator dynamics, they were asked to take part in a practice drive before each main drive. The practice drives resembled the main drives and included 12 trials; however, they did not include an audiovisual asynchrony (i.e. SOA = 0). After each practice drive, participants took part in the corresponding main drive, which lasted about 7 min. There was a break of 5 min after each main drive. The entire experiment took approximately 60 mins, and participants were compensated £15.

2.5. Measurements

The time window between points 4 and 5 (i.e., TTC = 3 s) in Fig. 2 was utilised for analysing the eye-tracking data. We defined nine areas of interest (AOIs) in the 3-D world model to examine how drivers allocate their visual attention during a lane-change transition scenario in response to different warning directionalities. These AOIs included the forward roadway (FR), dashboard (D), right lane

**Table 1**  
The experimental design.

| Experimental drives            | Towards-free-lane drive (24 trials) |                               |   |  | Towards-hazard drive (24 trials) |                               |   |  |
|--------------------------------|-------------------------------------|-------------------------------|---|--|----------------------------------|-------------------------------|---|--|
| <b>Audio message</b>           | “Left” from left headphones         | “Right” from right headphones | “Look” from both headphones (Truck in right lane) | “Look” from both headphones (Truck in left lane) | “Left” from left headphones      | “Right” from right headphones | “Look” from both headphones (Truck in right lane) | “Look” from both headphones (Truck in left lane) |
| <b>Correct driver response</b> | Steer left (8 trials)               | Steer right (8 trials)        | Steer left (4 trials)                             | Steer right (4 trials)                           | Steer right (8 trials)           | Steer left (8 trials)         | Steer left (4 trials)                             | Steer right (4 trials)                           |
| <b>SOAs</b>                    | 2                                   | 2                             | 1   | 1  | 2                                | 2                             | 1   | 1  |
| <b>200 (6 trials)</b>          | 2                                   | 2                             | 1   | 1  | 2                                | 2                             | 1   | 1  |
| <b>0 (6 trials)</b>            | 2                                   | 2                             | 1   | 1  | 2                                | 2                             | 1   | 1  |
| <b>400 (6 trials)</b>          | 2                                   | 2                             | 1   | 1  | 2                                | 2                             | 1   | 1  |
| <b>600 (6 trials)</b>          | 2                                   | 2                             | 1   | 1  | 2                                | 2                             | 1   | 1  |

(RL), left lane (LL), rear-view mirror (RVM), right-wing mirror (RWM), left-wing mirror (LWM), Sky, and Unknown (i.e., outside the defined AOIs), as shown in Fig. 3.

Four dependent variables were analysed to determine how directional auditory warnings and the presence of SOAs affect drivers' gaze behaviour during transitions of control in a lane-change scenario. Gaze behaviour towards the wing mirrors is the most important predictor of drivers' lane-change decisions in both manual (Doshi & Trivedi, 2009; Salvucci et al., 2001) and automated (Goncalves et al., 2020; Goncalves et al., 2022) driving scenarios. To assess whether directional auditory warnings guide drivers' visual attention to the right place (i.e., the free lane or the hazard lane) in a lane-change scenario, we calculated the probability of fixations to the hazard lane wing mirror (HLWM) and the free lane wing mirror (FLWM). To calculate these metrics, we redefined some of the AOIs. In trials where the truck was located in the left lane, the left-wing mirror was defined as the (HLWM); the right-wing mirror was defined as the (FLWM). Conversely, when the truck was in the right lane, the right-wing mirror was defined as the HLWM; the left-wing mirror as the FLWM. We then created a binary variable indicating whether participants fixated to the HLWM and the FLWM or failed to do so, within each trial. Finally, we calculated the probability of fixation to the HLWM and FLWM during lane-change manoeuvres. The probability of fixation to the HLWM was defined as the percentage of trials in which drivers fixated on the HLWM. Similarly, the probability of fixation to the FLWM was defined as the percentage of trials in which drivers fixated on the FLWM. To identify fixations, we used the velocity-threshold fixation identification method, which detects fixations based on the gaze velocity (Salvucci & Goldberg, 2000). According to this method, when gaze velocity falls below a predefined threshold (i.e., < 100 deg./s), a fixation is detected. In this study, we set the velocity threshold at 75 (deg/s), thus any gaze velocity below this value was defined as a fixation.

To examine whether using different directional warnings and the presence of SOAs resulted in faster fixations to the right place (the free lane or the hazard), we calculated the time to first fixation (TTFF) on the FLWM and the hazard. The TTFF on the FLWM was defined as the elapsed time between the end of the occlusion and the first fixation towards the FLWM. The TTFF on the hazard was defined as the elapsed time between the end of the occlusion and the first fixation towards the HLWM within the first second following the end of the occlusion period. During this period, the hazard (a truck) was visible in the HLWM before appearing on the main screen. These changes in visibility were driven by the truck's motion as it overtook the ego vehicle at a speed of 70 mph. This one-second period was critical for early hazard detection, indicating whether directional warnings and the presence of SOA effectively result in faster hazard detection. Trials with a TTFF of 0 s, indicating that drivers were already fixating on the HLWM or the FLWM before the end of occlusion, were excluded from the TTFF analyses. Prior to exclusion these trials, we examined whether these early fixations were systematically related to warning directionality or the presence of SOAs; however, no significant effects were found. These instances were therefore considered to result from random variation.

Finally, to understand the impact of directional auditory warnings and the presence of SOA on drivers' gaze distribution across the AOIs, we plotted the distribution of gaze for each AOI as a stacked histogram (inspired by the work of Goncalves et al. (2022) & Pipkorn et al. (2024)).

## 2.6. Data analysis

Each of the two drives consisted of 24 randomised trials incorporating hazard location (left vs. right), directional versus non-directional warnings, and SOAs. Of the 2304 trials completed (48 participants  $\times$  2 drives  $\times$  24 trials), eye-tracking data were available for 2296 trials, with eight omitted due to technical issues. Given the repeated measures design and hierarchical data structure, where multiple observations were collected from each participant within each condition, we utilised a multilevel modelling approach. Due to the non-normal distribution of the eye-tracking data, Generalized Linear Mixed Models (GLMMs) were employed for the analysis.

The log-odds (probability of fixation to the HLWM, and the FLWM) and the population mean (TTFF on the FLWM, and the hazard) were modelled via a linear combination of an intercept ( $\beta_0$ ), the auditory warning type ( $W, \beta_W$ ), the SOA ( $SOA, \beta_{SOA}$ ), and an interaction between these variables ( $WSOA, \beta_{W,SOA}$ ). The auditory warning type was parametrised as  $W \in \{ND, TFL, TH\}$  whereby non-directional

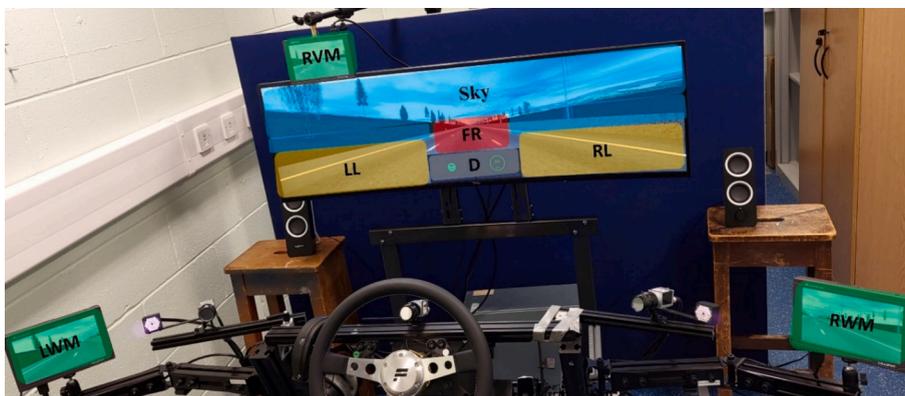


Fig. 3. AOIs overlaid onto the simulator set up.

warnings (ND) were the reference and were contrasted against towards-free-lane (TFL) and towards-hazard (TH) warnings. SOA was treated as a continuous variable and standardised in order to maintain model convergence.

A binomial distribution with a logit link function was used to model the probability of fixation to the HLWM, and the FLWM data. The model equation was as follows:

$$Y_{ij} \sim \text{Bernoulli}(P_{ij})$$

$$\ln\left(\frac{P}{1-P}\right) = (\beta_0 + \beta_{0j}) + (\beta_{W_{TFL}} W_{TFL_i}) + (\beta_{W_{TH}} W_{TH_i}) + (\beta_{SOA} SOA_i) + (\beta_{W_{TFL} \cdot SOA} W_{TFL_i} SOA_i) + (\beta_{W_{TH} \cdot SOA} W_{TH_i} SOA_i)$$

$$\beta_{0j} = N(0, \sigma_{\beta_{0j}})$$

Where  $Y$  denotes the outcome metric,  $i$  specified the condition of each variable,  $j$  specified the participant.

TTF on the FLWM, and the hazard (i.e., truck) was positively skewed and thus modelled using a Gamma distribution with a log link function. The model equation for the TTF on the hazard metric was as follows:

$$Y_{ij} \sim \text{Gamma}(\mu_{ij}, \sigma_{ij})$$

$$\log(\mu_{ij}) = \eta_{ij}$$

$$\eta_{ij} = (\beta_0 + \beta_{0j}) + (\beta_{W_{TFL}} W_{TFL_i}) + (\beta_{W_{TH}} W_{TH_i}) + (\beta_{SOA} SOA_i) + (\beta_{W_{TFL} \cdot SOA} W_{TFL_i} SOA_i) + (\beta_{W_{TH} \cdot SOA} W_{TH_i} SOA_i)$$

$$\beta_{0j} = N(0, \sigma_{\beta_{0j}})$$

Where  $Y$  denotes the outcome metric,  $i$  specified the condition of each variable,  $j$  specified the participant.

All models were fitted using the lme4 R package (Bates et al., 2015). To check multicollinearity of the fixed effects (i.e., the auditory warning type, the SOA, and the interaction between these variables), we calculated variance inflation factors (VIFs) using the R package Performance (Lüdtke et al., 2021). All fixed effects included in the GLMMs had a VIF < 5, indicating that there was no significant collinearity among them in the models (Akinwande et al., 2015). To assess which random effects should be included in the models, we started with a maximal model and compared against nested models. To maintain adequate model convergence, only random intercepts were kept for the final models. Data and analysis code are available in the following link ([https://github.com/ali-arabian/warning\\_directionality\\_soa\\_gaze.git](https://github.com/ali-arabian/warning_directionality_soa_gaze.git)).

### 3. Results

#### 3.1. Probability of fixation to the HLWM

Data from Table 2 shows a main effect of warning type on the probability of fixation to the HLWM. Post-hoc analyses revealed that non-directional warnings ( $M = 0.245$ ,  $SE = 0.054$ ) resulted in a significantly higher likelihood of fixations to the HLWM ( $p < 0.001$ ), when compared to the towards-free-lane ( $M = 0.044$ ,  $SE = 0.013$ ) and the towards-hazard ( $M = 0.113$ ,  $SE = 0.030$ ) warnings. The pairwise comparison between the two directional warnings also showed that the towards-hazard warnings were associated with a significantly higher probability of fixation to the HLWM, than the towards-free-lane warnings ( $p = 0.002$ ). However, the main effect of SOA and the interaction between SOA and warning types were not statistically significant (Fig. 4). Overall, drivers were more likely to fixate the HLWM following non-directional auditory cues. Additionally, among the two directional warnings, the towards-hazard warnings led to a significantly higher probability of fixation on the HLWM.

#### 3.2. Probability of fixation to the FLWM

Data from Table 3 shows a main effect of warning type on the probability of fixation to the FLWM. Post-hoc analyses revealed that

**Table 2**  
ANOVA table and model diagnostics for the probability of fixation to the HLWM GLMM.

| Predictors         | $\chi^2$ | DF | p-value |
|--------------------|----------|----|---------|
| Intercept          | 14.598   | 1  | < 0.001 |
| Warning type       | 141.108  | 2  | < 0.001 |
| SOA                | 0.001    | 1  | 0.977   |
| Warning type * SOA | 4.063    | 2  | 0.131   |
| AIC                | 1794.1   |    |         |
| BIC                | 1834.3   |    |         |
| Log-likelihood     | -890.0   |    |         |

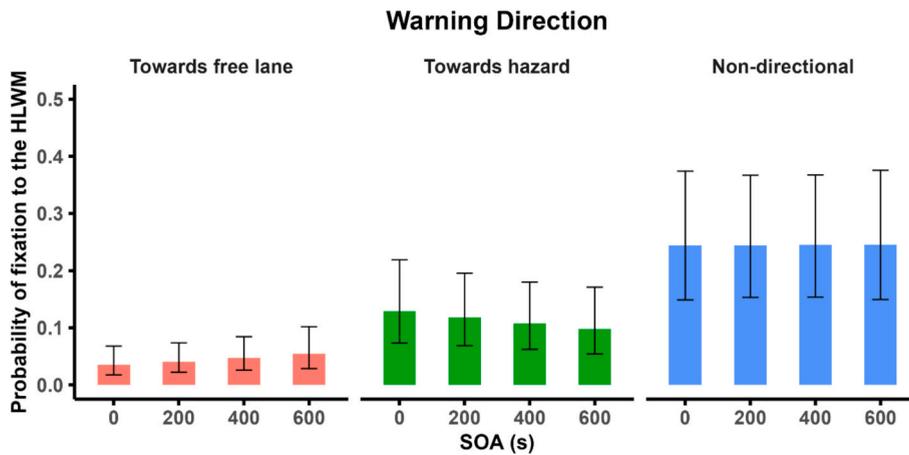


Fig. 4. The mean and 95 % CI of the probability of fixation to the HLWM, i.e., comparing SOAs within a warning direction.

Table 3  
ANOVA table and model diagnostics for the probability of fixation to the FLWM GLMM.

| Predictors         | $\chi^2$ | DF | p-value |
|--------------------|----------|----|---------|
| Intercept          | 8.969    | 1  | 0.003   |
| Warning type       | 58.445   | 2  | < 0.001 |
| SOA                | 0.017    | 1  | 0.896   |
| Warning type * SOA | 1.770    | 2  | 0.413   |
| AIC                | 1856.6   |    |         |
| BIC                | 1896.8   |    |         |
| Log-likelihood     | -921.3   |    |         |

non-directional warnings ( $M = 0.227$ ,  $SE = 0.072$ ) were associated with a significantly higher likelihood of fixations to the FLWM compared to the towards-free-lane ( $M = 0.147$ ,  $SE = 0.052$ ,  $p = 0.018$ ) and the towards-hazard ( $M = 0.085$ ,  $SE = 0.032$ ,  $p = 0.003$ ) warnings. The pairwise comparison between the two directional warnings showed that the towards-free-lane warnings led to a significantly higher probability of fixations to the FLWM, compared to the towards-hazard warnings ( $p = 0.029$ ). However, the main effect of SOA and the interaction between SOA and warning types were not statistically significant (Fig. 5). Once again, drivers were more likely to fixate the FLWM following non-directional auditory cues. In addition, towards-free-lane warnings resulted in a higher likelihood of fixation to the FLWM compared to towards-hazard warnings.

### 3.3. TTF on the FLWM

Data from Table 4 shows a main effect of warning type. Post-hoc analyses revealed that the towards-free-lane warnings ( $M = 0.604$ ,

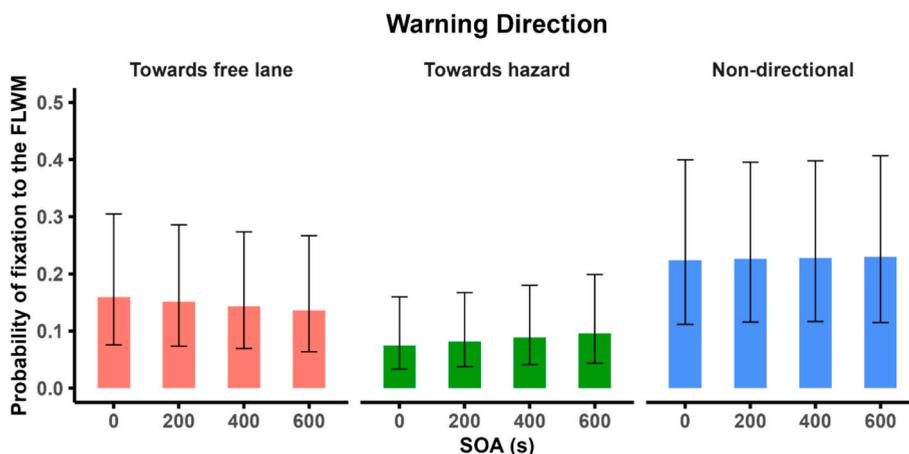


Fig. 5. The mean and 95 % CI of the probability of fixation to the FLWM, i.e., comparing SOAs within a warning direction.

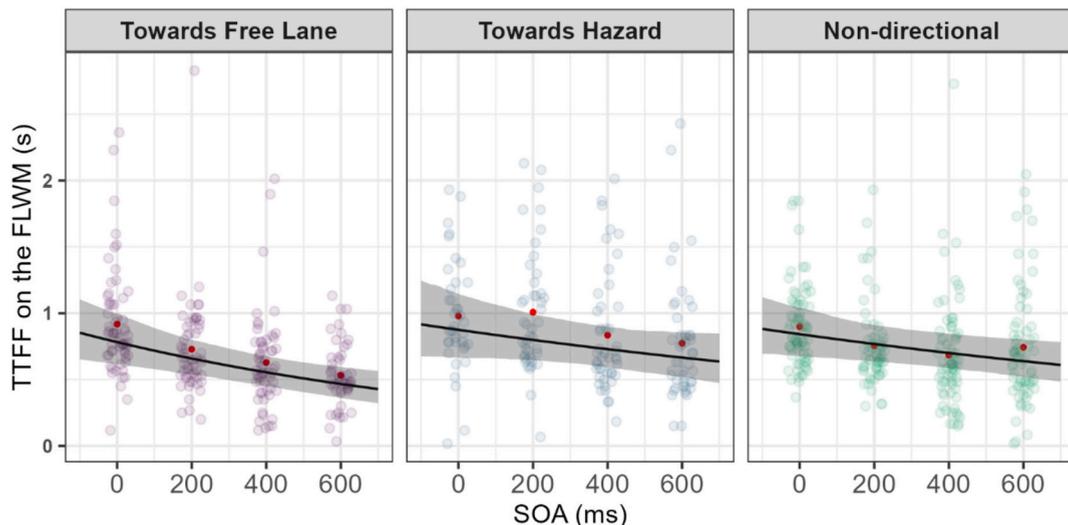
**Table 4**  
ANOVA table and model diagnostics for TTFF on the FLWM GLMM.

| Predictors         | $\chi^2$ | DF | p-value |
|--------------------|----------|----|---------|
| Intercept          | 19.260   | 1  | < 0.001 |
| Warning type       | 35.100   | 2  | < 0.001 |
| SOA                | 18.985   | 1  | < 0.001 |
| Warning type * SOA | 7.603    | 2  | 0.022   |
| AIC                | 333.9    |    |         |
| BIC                | 370.0    |    |         |
| Log-likelihood     | -158.9   |    |         |

SE = 0.045) resulted in a significantly faster time to first fixation on the FLWM compared to the towards-hazard ( $M = 0.763$ , SE = 0.058,  $p < 0.001$ ) and non-directional ( $M = 0.733$ , SE = 0.052,  $p < 0.001$ ) warnings. The pairwise comparison between the towards-hazard and non-directional warnings was not significant ( $P = 0.636$ ). The results showed a significant negative effect of SOA on the TTFF on the FLWM. Additionally, the GLMM showed a significant interaction effect between warning type and SOA ( $p = 0.022$ ), which implies that the effect of SOA on reaction time was dependent on warning type. For every 1 unit increase in standardised SOA, towards-free-lane, non-directional, and towards-hazard warnings led to a 18.21 % ( $p < 0.001$ ), 10.19 % ( $p < 0.001$ ), and 10.10 % ( $p = 0.001$ ) reduction in time to first fixation on the FLWM, respectively (Fig. 6). The slope for the towards-free-lane warnings was significantly steeper than that for the non-directional warnings ( $p = 0.032$ ). Overall, drivers were faster to fixate the FLWM for the towards-free-lane auditory cues. Furthermore, as the SOA increased, the time to first fixation on the FLWM decreased, especially for the towards-free-lane warnings.

### 3.4. TTFF on the hazard

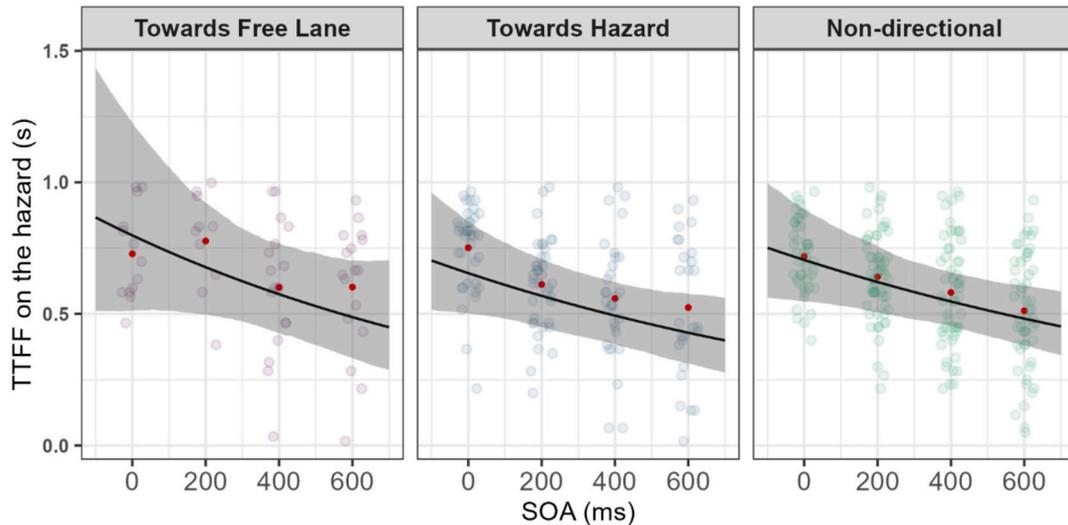
The GLMM showed a significant effect of warning type on drivers' first fixation on the hazard (Table 5). Post-hoc analysis showed that the towards-hazard warnings ( $M = 0.530$ , SE = 0.035) resulted in a significantly faster first fixation on the hazard, compared to the towards-free-lane ( $M = 0.624$ , SE = 0.047,  $p = 0.02$ ) and non-directional ( $M = 0.583$ , SE = 0.035,  $p = 0.05$ ) warnings. The model further revealed a significant negative association between SOA and the time to first fixation on the hazard ( $p < 0.001$ ). For every 1 unit increase in standardised SOA, non-directional, towards-hazard, and towards-free-lane warnings led to a 13.76 % ( $p < 0.001$ ), 15.23 % ( $p < 0.001$ ), and 17.46 % ( $p < 0.001$ ) reduction in time to first fixation on the hazard, respectively (Fig. 7). However, the model showed no significant interaction effect between SOA and warning types. Overall, these results suggest two key behaviours. Firstly, that drivers were faster to fixate the hazard for the towards-hazard auditory cues; secondly, that as the SOA increased, the time to first fixation on the hazard decreased.



**Fig. 6.** Time to first fixation on the FLWM plotted against SOAs for the three warning directions. The black line represents the predicted mean from the model, and the grey ribbon represents 95 % confidence interval bounds for the model estimate. The sample means of TTFF on the FLWM for each level of SOA is plotted to aid the interpretation of the model fit (red solid circles). The model estimate and 95 % confidence interval bounds capture the mean response well. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 5**  
ANOVA table and model diagnostics for time to first fixation on the hazard GLMM.

| Predictors         | $\chi^2$ | DF | p-value |
|--------------------|----------|----|---------|
| Intercept          | 80.936   | 1  | < 0.001 |
| Warning type       | 9.888    | 2  | 0.007   |
| SOA                | 36.792   | 1  | < 0.001 |
| Warning type * SOA | 0.770    | 2  | 0.681   |
| AIC                | -111.4   |    |         |
| BIC                | -79.5    |    |         |
| Log-likelihood     | 63.7     |    |         |



**Fig. 7.** Time to first fixation on the hazard plotted against SOAs for the three warning directions. The black line represents the predicted mean from the model, and the grey ribbon represents 95 % confidence interval bounds for the model estimate. The sample means of time to first fixation on the hazard for each level of SOA is plotted to aid the interpretation of the model fit (red solid circles). The model estimate and 95 % confidence interval bounds capture the mean response well. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

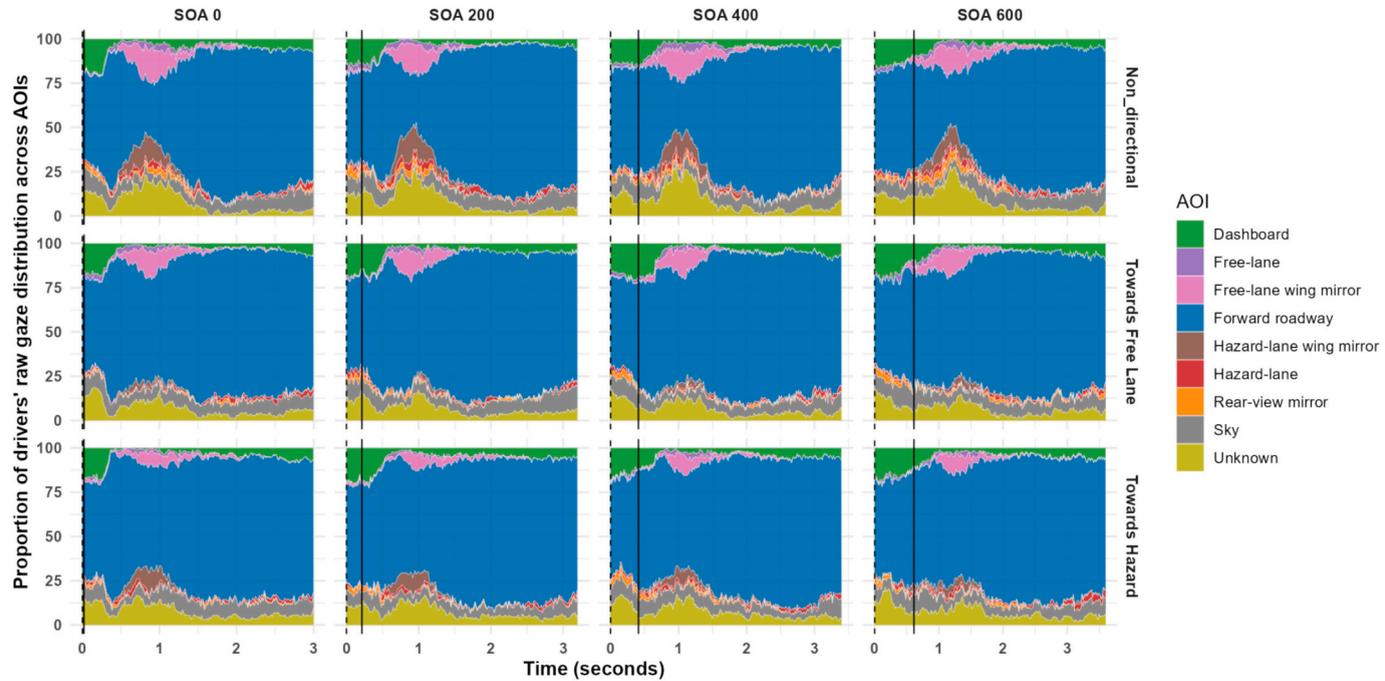
### 3.5. Gaze distribution across AOIs

**Fig. 8** shows the percentage of drivers' raw gaze distribution to the different AOIs from the onset of auditory warnings until the TTC of 3 s – for each warning type and SOA condition. The dashed vertical lines represent the onset of auditory warnings, and the solid lines represent the presentation of the visual information. Regarding the effect of warning directionality on drivers' gaze distribution across the AOIs, compared to directional warnings, non-directional warnings resulted in a higher percentage of gaze towards both the HLWM and the FLWM, when the occlusion was lifted. This is clearly shown by the peak of gaze distribution directed towards the HLWM and the FLWM after the solid line (i.e., end of occlusion). Furthermore, in response to the towards-hazard warnings, drivers checked both the HLWM and the FLWM, while in response to the towards-free-lane warnings, drivers mostly just checked the FLWM.

In terms of the impact of SOA on drivers' gaze distribution across AOIs, **Fig. 8** shows a distinct peak in the proportion of gaze directed to the forward roadway (FR) for the no SOA condition, after the occlusion is lifted. This suggests that, in the absence of an SOA, drivers tend to first reorient their attention to the FR before checking the wing mirrors. However, as SOA increases, this post-occlusion peak in FR glances diminishes, with drivers directing their attention to the wing mirrors immediately after the occlusion is lifted.

## 4. Discussion

Using data collected from a driving simulator experiment, the present study aimed to answer two research questions: (1) whether directional auditory warnings can guide drivers' visual attention to the right place (i.e., the free lane or the hazard's location) at the right time (i.e., faster fixations) following transitions of vehicle control from hands-on SAE L2 driving during a lane change scenario, and (2) whether the presence of audiovisual asynchrony (using a range of SOAs) enhances this effect. Visual attention to different areas of the driving scene and the mirrors was assessed by investigating fixation patterns to the free lane and hazard lane wing mirrors, before the lane change, which was instigated by the warnings, in order to avoid colliding with a lead vehicle and a truck travelling in the adjacent lane (hazard). The results confirmed both research questions: directional auditory warnings successfully oriented gaze to



**Fig. 8.** Drivers' gaze distribution across the nine AOIs. The X-axis shows time in seconds from the onset of auditory warnings to the TTC of 3 s. The dashed line represents the onset of auditory warnings, and the solid line indicates the end of occlusion. The time between dashed and solid lines represents SOAs. The Y-axis shows the percentage of drivers gazing towards each AOIs for each time step in the interval from the onset of auditory warnings to the TTC of 3 s.

the relevant mirror, and increasing SOA facilitated faster gaze redirection. The results associated with each research question will now be discussed in detail in the following paragraphs.

#### 4.1. Impact of directional auditory warnings on driver visual attention

Results showed a significant difference in mirror-checking behaviour, in response to the different types of warning. When responding to the non-directional warnings, drivers were more likely to fixate the two wing mirrors, while these were rarely checked after presentation of the directional warnings. One possible explanation for this difference stems from the informative content of the warnings. Non-directional warnings, which lacked information about the free lane or the hazard, compelled drivers to rely on environmental information by checking the wing mirrors to inform their decision-making. In contrast, directional warnings were informative and covertly directed drivers' attention without consequential shifts in the overt receptors (i.e., the eyes). Previous research supports the link between audiovisual signals and covert spatial orientation showing that directional auditory cues can attract covert attention towards the location of stimuli in other modalities (Driver & Spence, 1998a, 1998b; Spence et al., 1998; Spence & Driver, 1997a). The observed gaze behaviour may also be explained by the relationship between the transparency of warning systems and user trust. Previous studies have repeatedly shown that increased transparency in HMIs enhances individuals' trust to these interfaces (Colley et al., 2021; Du et al., 2019; Häußschmid et al., 2017; Koo et al., 2015; Ma et al., 2021). Due to the informative nature of directional warnings, drivers may have trusted them more, resulting in lane-changes without additional shifts in eye movements. From a safety perspective, these gaze patterns highlight how the type of auditory cue influences drivers' information-seeking behaviour. Under non-directional warnings, drivers appear to engage in compensatory scanning, checking both mirrors to gather environmental information, which leads to more erratic gaze patterns; a condition generally associated with poorer performance during transitions of control (Goodridge et al., 2026; Louw et al., 2017), especially in short time-to-collision situations. This gaze finding aligns with drivers' response data, where faster steering reactions were observed for directional warnings compared with non-directional ones (Arabian et al., 2025). Such improvements for directional warnings likely occurred because drivers could initiate steering without additional eye movements or mirror checks, enabling quicker, and smoother responses. In contrast, higher probability of fixations towards mirrors after non-directional warnings may have delayed steering reactions.

Towards-hazard warnings led to a higher likelihood of fixations to the hazard, while the towards-free-lane warnings resulted in a higher probability of fixations to the FLWM. Therefore, drivers used the auditory instructions to guide their gaze towards the right location in the driving environment, supporting the notion that directional warnings can successfully guide drivers' visual attention to the right place. However, these findings are in contrast with the results reported by de Winter et al. (2022), who found that drivers' visual attention was primarily influenced by the traffic situation (e.g., other road users) rather than by the auditory warnings. One possible explanation for this discrepancy stems from methodological differences between the two studies. de Winter et al. (2022) utilised computer-based videos presented on a 24-in. monitor for their lane change scenarios, which reduces the generalisability of these metrics to more realistic driving conditions.

In addition to guiding drivers' visual attention to the right place, the directional warnings presented in this also prompted a faster redirection of drivers' visual attention. This is supported by results which showed that drivers' time to first fixation (TTF) to the free lane wing mirror was faster after the towards-free-lane warnings, and faster towards the hazard after the towards-hazard warnings, supporting results from previous studies (Huang et al., 2024; Ma et al., 2023). When comparing the towards-hazard versus towards-free-lane warnings, a nuanced difference was observed in gaze patterns. When responding to the towards-hazard warnings, drivers checked both wing mirrors, whereas the towards-free-lane warning mostly resulted in checks of the FLWM. In other words, despite the benefit of the towards-hazard over the towards-free-lane warnings, in terms of aiding faster hazard detection, drivers still checked the free lane wing mirror, prior to a lane change (Fig. 8), which is a common driving habit. This behavioural gaze pattern may explain why the interaction effect between warning type and SOA was significant for the TTF on the FLWM but not for the hazard. In response to towards-hazard warnings, some drivers appeared to check the FLWM before fixating on the HLWM, while for towards-free-lane warnings, drivers primarily fixated on the FLWM. Therefore, as SOA increased, TTF decreased for both mirrors, but the effect was stronger for towards-free-lane warnings. These results may also explain faster steering responses with the towards-free-lane warnings, compared to the towards-hazard warnings observed in drivers' operation data (Arabian et al., 2025). In response to towards-free-lane warnings drivers could initiate steering without first detecting the hazard, leading to faster steering response compared to the towards-hazard warnings. In this sense, the two directional warnings serve slightly different safety goals: towards-hazard warnings enhance situation awareness of the hazard, whereas towards-free-lane warnings facilitate faster avoidance manoeuvres. Our findings therefore suggest that towards-free-lane warnings may be more beneficial when time-critical steering actions are required.

#### 4.2. Impact of SOAs on guiding driver attention

Finally, the results showed that the presence and duration of an SOA influenced gaze behaviour. Overall, as the SOA increased, there was a reduction in time to first fixation to the hazards and the wing mirrors, which corresponded well with the instructions given by the auditory message. In the absence of an SOA (i.e., SOA = 0), drivers initially fixated on the forward roadway, immediately after the end of an occlusion, followed by a shift of attention towards the wing mirrors, which delayed fixations to the mirrors. However, as the SOA increased, the proportion of gaze distributions directed towards the forward roadway decrease, in favour of checks towards the wing mirrors, resulting in faster fixations towards the mirrors. These findings are supported by the attenuation of visual dominance effect, which suggest that when auditory signals and visual information are presented simultaneously, individuals prioritise the visual component, at the detriment of the auditory signals (Arabian et al., 2025; Colavita, 1974; Colavita et al., 1976; Koppen & Spence,

2007; Sinnott et al., 2007).

## 5. Limitations and future research

Our study investigated the impact of directional auditory warnings on drivers' gaze behaviour, while also highlighting the effect of audiovisual asynchrony during transitions from L2 driving in a lane change scenario. The occlusion of visual information between the visual and auditory stimulus could be considered a simulation of non-driving related task (NDRT) engagement, or at the very least, an off-road glance at a critical moment before a transition of control. However, off-road glances (towards NDRTs or otherwise) often do not solely rely upon visual faculties (Strayer et al., 2011). Rather, cognitive resources may also be used and thus the impact of elevated mental workload may want to be investigated within the context of asynchronous auditory warnings. Several studies have shown that engaging in NDRTs, that take drivers' mind off the road and loads their working memory resources can significantly increase drivers' workload levels, compared to just monitoring the drive during L2, or manual driving (Goodridge et al., 2024, 2026; Radhakrishnan et al., 2022; Wu et al., 2019). When drivers have high workload due to engaging with an NDRT (e.g., n-back task, see Goodridge et al., 2026) their gaze can also continue to be concentrated on the road centre during the manual driving period after a TOR (Goodridge et al., 2026; Li et al., 2020), a phenomenon known as visual tunnelling (Reimer, 2009). This effect may reduce gaze dispersion across the horizontal axis, resulting in less gaze concentration towards the rear-view and wing mirrors under high mental workload conditions (Goodridge et al., 2026). Therefore, future studies should investigate how directional auditory warnings, presented at different SOAs, might affect drivers' gaze patterns during lane-change takeover scenarios, when they experienced high mental workload due to engagement in an NDRT during automated driving.

Another limitation is related to the delivery of auditory warnings through headphones. Although the use of headphones ensured precise control over spatial presentation (i.e., delivering auditory warnings from left, right, or both channels), this method may not fully represent how drivers would perceive warnings in a real vehicle environment. In practice, drivers are unlikely to wear headphones for safety reasons; instead, in-vehicle warning systems typically use integrated loudspeakers. Future studies should therefore examine how the directionality and timing of auditory warnings perform when delivered via in-vehicle loudspeakers (left, right, or both), rather than headphone channels.

## 6. Conclusions

This research provides valuable insights about the impact of warning directionality and asynchronous presentation of auditory and visual components of audiovisual directional warnings on drivers' gaze behaviour during transitions in a lane-change scenario. Due to the informative nature of directional warnings, drivers' behaviours implied a higher level of trust and they made lane changes without additional shifts in their eye movements, compared to non-directional warnings. Additionally, both directional warnings were found to be effective in guiding drivers' attention to the right place (i.e., the free lane or the hazard's location) at the right time (i.e., faster fixations). Despite the benefit of the towards-hazard over the towards-free-lane warnings in faster hazard detection, drivers still checked the free lane wing mirror during lane changes. The findings also highlighted the potential benefits of temporally separating auditory and visual components of audiovisual directional warnings in automated vehicles, where longer SOAs were associated with faster fixations at the wing mirrors and quicker hazard detection.

## CRediT authorship contribution statement

**Ali Arabian:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Courtney M. Goodridge:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **Rafael Cirino Gonçalves:** Methodology, Formal analysis, Conceptualization. **Natasha Merat:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

## 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.

## Acknowledgements

The authors would like to thank Michael Daly and Albert Solernou for their help with developing the driving simulator scenarios. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101006664.

## Data availability

I have shared the link to my data/code in the paper.

## References

- Akinwande, M. O., Dikko, H. G., & Samson, A. (2015). Variance inflation factor: As a condition for the inclusion of suppressor variable(s) in regression analysis. *Open Journal of Statistics*, *05*(7), 7. <https://doi.org/10.4236/ojs.2015.57075>
- Arabian, A., Goodridge, C., & Merat, N. (2025). Asynchrony of directional auditory warnings and visual information in hands-on SAE level 2 automated vehicles: Analysis of Driver responses. *PLoS One*, *20*(11), e0336941.
- Arabian, A., Goodridge, C., Lee, Y. T., Gonçalves, R., Coyne, R., & Merat, N. Effects of directional takeover request interfaces on drivers' gaze behaviour during transitions from automation: A systematic review and meta-analysis. [https://doi.org/10.31234/osf.io/x3c4p\\_v1](https://doi.org/10.31234/osf.io/x3c4p_v1).
- Arabian, A., Goodridge, C. M., & Merat, N. (2024). Asynchrony of directional auditory warnings and visual information in driving: Analysis of eye movement patterns and Driver responses. *THE 9TH INTERNATIONAL CONFERENCE ON DRIVER DISTRACTION AND INATTENTION. THE 9TH INTERNATIONAL CONFERENCE ON DRIVER DISTRACTION AND INATTENTION*.
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*, 1–48. <https://doi.org/10.18637/jss.v067.i01>
- Baylis, G. C., Simon, S. L., Baylis, L. L., & Rorden, C. (2002). Visual extinction with double simultaneous stimulation: What is simultaneous? *Neuropsychologia*, *40*(7), 1027–1034. [https://doi.org/10.1016/S0028-3932\(01\)00144-0](https://doi.org/10.1016/S0028-3932(01)00144-0)
- Bengler, K., Dietmayer, K., Farber, B., Maurer, M., Stiller, C., & Winner, H. (2014). Three decades of Driver assistance systems: Review and future perspectives. In *IEEE Intelligent Transportation Systems Magazine*, *6*(4), 6–22. *IEEE Intelligent Transportation Systems: Magazine*. <https://doi.org/10.1109/IMITS.2014.2336271>.
- Borojeni, S. S., Chuang, L., Heuten, W., & Boll, S. (2016). Assisting drivers with ambient take-over requests in highly automated driving. 237–244.
- Borojeni, S. S., Weber, L., Heuten, W., & Boll, S. (2018). From reading to driving: Priming mobile users for take-over situations in highly automated driving. 1–12.
- Carsten, O., Lai, F. C., Barnard, Y., Jamson, A. H., & Merat, N. (2012). Control task substitution in semiautomated driving: Does it matter what aspects are automated? *Human Factors*, *54*(5), 747–761.
- Chen, J., Šabić, E., Mishler, S., Parker, C., & Yamaguchi, M. (2022). Effectiveness of lateral auditory collision warnings: Should warnings be toward danger or toward safety? *Human Factors*, *64*(2), 418–435.
- Cicchino, J. B. (2017). Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates. *Accident Analysis & Prevention*, *99*, 142–152.
- Colavita, F. B. (1974). Human sensory dominance. *Perception & Psychophysics*, *16*(2), 409–412.
- Colavita, F. B., Tomko, R., & Weisberg, D. (1976). Visual prepotency and eye orientation. *Bulletin of the Psychonomic Society*, *8*(1), 25–26. <https://doi.org/10.3758/BF03337062>
- Colley, M., Eder, B., Rixen, J. O., & Rukzio, E. (2021). Effects of semantic segmentation visualization on trust, situation awareness, and cognitive load in highly automated vehicles. *Proceedings of the 2021 CHI Conference on human factors in computing systems*, 1–11. <https://doi.org/10.1145/3411764.3445351>
- Cooper, R. (1999). Visual dominance and the control of action. In *Proceedings of the Twentieth Annual Conference of the Cognitive Science Society*. Routledge.
- Damböck, D., Weißgerber, T., Kienle, M., & Bengler, K. (2013). Requirements for cooperative vehicle guidance (pp. 1656–1661).
- Doshi, A., & Trivedi, M. M. (2009). On the roles of eye gaze and head dynamics in predicting driver's intent to change lanes. *IEEE Transactions on Intelligent Transportation Systems*, *10*(3), 453–462.
- Driver, J., & Spence, C. (1998a). Attention and the crossmodal construction of space. *Trends in Cognitive Sciences*, *2*(7), 254–262.
- Driver, J., & Spence, C. (1998b). Cross-modal links in spatial attention. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *353*(1373), 1319–1331. <https://doi.org/10.1098/rstb.1998.0286>
- Du, N., Haspiel, J., Zhang, Q., Tilbury, D., Pradhan, A. K., Yang, X. J., & Robert, L. P. (2019). Look who's talking now: Implications of AV'S explanations on driver's trust, AV preference, anxiety and mental workload. *Transportation Research Part C: Emerging Technologies*, *104*, 428–442. <https://doi.org/10.1016/j.trc.2019.05.025>
- Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors*, *37*(1), 32–64.
- Endsley, M. R. (2017). From here to autonomy: Lessons learned from human–automation research. *Human Factors*, *59*(1), 5–27.
- Forster, Y., Naujoks, F., Neukum, A., & Huestegge, L. (2017). Driver compliance to take-over requests with different auditory outputs in conditional automation. *Accident Analysis & Prevention*, *109*, 18–28.
- Frassinetti, F., Bolognini, N., & Ládavas, E. (2002). Enhancement of visual perception by crossmodal visuo-auditory interaction. *Experimental Brain Research*, *147*(3), 332–343. <https://doi.org/10.1007/s00221-002-1262-y>
- Gaspar, J., & Carney, C. (2019). The effect of partial automation on Driver attention: A naturalistic driving study. *Human Factors*, *61*(8), 1261–1276. <https://doi.org/10.1177/0018720819836310>
- Gonçalves, R., Louw, T., Madigan, R., & Merat, N. (2019). Using Markov chains to understand the sequence of drivers' gaze transitions during lane-changes in automated driving. *Driving assessment Conference*, *10*(2019), article 2019. [Doi:10.17077/drivingassessment.1698](https://doi.org/10.17077/drivingassessment.1698).
- Gonçalves, R. C., Louw, T. L., Madigan, R., Quaresma, M., Romano, R., & Merat, N. (2022). The effect of information from dash-based human-machine interfaces on drivers' gaze patterns and lane-change manoeuvres after conditionally automated driving. *Accident Analysis & Prevention*, *174*, Article 106726.
- Goncalves, R. C., Louw, T. L., Quaresma, M., Madigan, R., & Merat, N. (2020). The effect of motor control requirements on drivers' eye-gaze pattern during automated driving. *Accident Analysis & Prevention*, *148*, Article 105788. <https://doi.org/10.1016/j.aap.2020.105788>
- Goodridge, C., Gonçalves, R., Arabian, A., Horrobin, A., Solemou, A., Lee, Y. T., ... Merat, N. (2026). The impact of N-back-induced cognitive load and time budget on takeover performance. *Accident Analysis & Prevention*, *225*, 108327.
- Goodridge, C. M., Gonçalves, R. C., Arabian, A., Horrobin, A., Solemou, A., Lee, Y. T., ... Merat, N. (2024). Gaze entropy metrics for mental workload estimation are heterogeneous during hands-off level 2 automation. *Accident Analysis & Prevention*, *202*, 107560.
- Goodridge, C. M., Gonçalves, R. C., Reher, A., Kuo, J., Lenné, M. G., & Merat, N. (2025). Assessing data imbalance correction methods and gaze entropy for collision prediction. *PLoS one*, *20*(11), Article e0336777.
- Gruđen, T., Tomazić, S., Sodnik, J., & Jakus, G. (2022). A user study of directional tactile and auditory user interfaces for take-over requests in conditionally automated vehicles. *Accident Analysis & Prevention*, *174*, Article 106766.
- Häuslschmid, R., von Bülow, M., Pflöging, B., & Butz, A. (2017). SupportingTrust in autonomous driving. In *Proceedings of the 22nd International Conference on intelligent user interfaces* (pp. 319–329). <https://doi.org/10.1145/3025171.3025198>
- Hillyard, S. A., Störmer, V. S., Feng, W., Martinez, A., & McDonald, J. J. (2016). Cross-modal orienting of visual attention. *Neuropsychologia*, *83*, 170–178. <https://doi.org/10.1016/j.neuropsychologia.2015.06.003>
- Ho, C., & Spence, C. (2005). Assessing the effectiveness of various auditory cues in capturing a driver's visual attention. *Journal of Experimental Psychology: Applied*, *11*(3), 157.
- Huang, W.-C., Fan, L.-H., Han, Z.-J., & Niu, Y.-F. (2024). Enhancing safety in conditionally automated driving: Can more takeover request visual information make a difference in hazard scenarios with varied hazard visibility? *Accident Analysis & Prevention*, *205*, Article 107687. <https://doi.org/10.1016/j.aap.2024.107687>
- Jamson, A. H., Lai, F. C. H., & Carsten, O. M. J. (2008). Potential benefits of an adaptive forward collision warning system. *Transportation Research Part C: Emerging Technologies*, *16*(4), 471–484. <https://doi.org/10.1016/j.trc.2007.09.003>
- Kim, S., van Egmond, R., & Happee, R. (2024). How manoeuvre information via auditory (spatial and beep) and visual UI can enhance trust and acceptance in automated driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, *100*, 22–36.
- Koo, J., Kwac, J., Ju, W., Steiner, M., Leifer, L., & Nass, C. (2015). Why did my car just do that? Explaining semi-autonomous driving actions to improve driver understanding, trust, and performance. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *9*(4), 269–275. <https://doi.org/10.1007/s12008-014-0227-2>
- Koppen, C., & Spence, C. (2007). Audiovisual asynchrony modulates the Colavita visual dominance effect. *Brain Research*, *1186*, 224–232.

- Li, X., Schroeter, R., Rakotonirainy, A., Kuo, J., & Lenné, M. G. (2020). Effects of different non-driving-related-task display modes on drivers' eye-movement patterns during take-over in an automated vehicle. *Transportation Research Part F: Traffic Psychology and Behaviour*, 70, 135–148.
- Liu, Y.-C. (2001). Comparative study of the effects of auditory, visual and multimodality displays on drivers' performance in advanced traveller information systems. *Ergonomics*, 44(4), 425–442. <https://doi.org/10.1080/00140130010011369>
- Louw, T., Kountouriotis, G., Carsten, O., & Merat, N. (2015). *Driver inattention during vehicle automation: How does Driver engagement affect resumption of control? [proceedings paper]. 4th International Driver distraction and inattention Conference. 4th International Conference on Driver distraction and inattention (DDI2015), Sydney: Proceedings; ARRB group.* <https://trid.trb.org/view/1402294>.
- Louw, T., Madigan, R., Carsten, O., & Merat, N. (2017). Were they in the loop during automated driving? Links between visual attention and crash potential. *Injury Prevention*, 23(4), 281–286.
- Louw, T., & Merat, N. (2017). Are you in the loop? Using gaze dispersion to understand driver visual attention during vehicle automation. *Transportation Research Part C: Emerging Technologies*, 76, 35–50.
- Lüdecke, D., Ben-Shachar, M. S., Patil, I., Waggoner, P., & Makowski, D. (2021). Performance: An R package for assessment, comparison and testing of statistical models. *Journal of Open Source Software*, 6(60), 3139. <https://doi.org/10.21105/joss.03139>
- Lundqvist, L.-M., & Eriksson, L. (2019). Age, cognitive load, and multimodal effects on driver response to directional warning. *Applied Ergonomics*, 76, 147–154. <https://doi.org/10.1016/j.apergo.2019.01.002>
- Ma, J., Guo, Y., Xu, W., & Li, J. (2023). Effect of directional auditory takeover request on takeover behavior and eye movement in conditionally automated driving. *World Electric Vehicle Journal*, 14(3), 70.
- Ma, R. H. Y., Morris, A., Herriotts, P., & Birrell, S. (2021). Investigating what level of visual information inspires trust in a user of a highly automated vehicle. *Applied Ergonomics*, 90, Article 103272. <https://doi.org/10.1016/j.apergo.2020.103272>
- Mackenzie, A. K., & Harris, J. M. (2015). Eye movements and hazard perception in active and passive driving. *Visual Cognition*, 23(6), 736–757.
- McDonald, J. J., Green, J. J., Störmer, V. S., & Hillyard, S. A. (2012). *Cross-modal spatial cueing of attention influences visual perception (The Neural Bases of Multisensory Processes)*.
- McDonald, J. J., Teder-Sälejärvi, W. A., & Hillyard, S. A. (2000). Involuntary orienting to sound improves visual perception. *Nature*, 407(6806), 906–908. <https://doi.org/10.1038/35038085>
- Meng, F., & Spence, C. (2015). Tactile warning signals for in-vehicle systems. *Accident Analysis & Prevention*, 75, 333–346. <https://doi.org/10.1016/j.aap.2014.12.013>
- Merat, N., Seppelt, B., Louw, T., Engström, J., Lee, J. D., Johansson, E., ... Itoh, M. (2019). The “out-of-the-loop” concept in automated driving: Proposed definition, measures and implications. *Cognition, Technology & Work*, 21, 87–98.
- Mole, C. D., Lappi, O., Giles, O., Markkula, G., Mars, F., & Wilkie, R. M. (2019). Getting Back into the loop: The perceptual-motor determinants of successful transitions out of automated driving. *Human Factors*, 61(7), 1037–1065. <https://doi.org/10.1177/0018720819829594>
- Narote, S. P., Bhujbal, P. N., Narote, A. S., & Dhane, D. M. (2018). A review of recent advances in lane detection and departure warning system. *Pattern Recognition*, 73, 216–234. <https://doi.org/10.1016/j.patcog.2017.08.014>
- Noyes, J. M., Hellier, E., & Edworthy, J. (2006). Speech warnings: A review. *Theoretical Issues in Ergonomics Science*, 7(6), 551–571. <https://doi.org/10.1080/14639220600731123>
- Pipkorn, L., Dozza, M., & Tivesten, E. (2024). Driver visual attention before and after take-over requests during automated driving on public roads. *Human Factors*, 66(2), 336–347.
- Radhakrishnan, V., Merat, N., Louw, T., Gonçalves, R. C., Torrao, G., Lyu, W., ... Lenné, M. G. (2022). Physiological indicators of driver workload during car-following scenarios and takeovers in highly automated driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, 87, 149–163.
- Reimer, B. (2009). Impact of cognitive task complexity on drivers' visual Tunneling. *Transportation Research Record*, 2138(1), 13–19. <https://doi.org/10.3141/2138-03>
- SAE. (2021). Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles. *SAE International*, 4970(724), 1–5.
- Salvucci, D. D., & Goldberg, J. H. (2000). *Identifying fixations and saccades in eye-tracking protocols*. 71–78.
- Salvucci, D. D., Liu, A., & Boer, E. R. (2001). Control and monitoring during lane changes. *Vision in Vehicles*, 9.
- Serrano, J., Di Stasi, L. L., Megias, A., & Catena, A. (2011). Effect of directional speech warnings on road hazard detection. *Traffic Injury Prevention*, 12(6), 630–635.
- Sinnett, S., Spence, C., & Soto-Faraco, S. (2007). Visual dominance and attention: The Colavita effect revisited. *Perception & Psychophysics*, 69(5), 673–686. <https://doi.org/10.3758/BF03193770>
- Spence, C. (2007). Audiovisual multisensory integration. *Acoustical Science and Technology*, 28(2), 61–70. <https://doi.org/10.1250/ast.28.61>
- Spence, C., & Driver, J. (1997a). Audiovisual links in exogenous covert spatial orienting. *Perception & Psychophysics*, 59(1), 1–22. <https://doi.org/10.3758/BF03206843>
- Spence, C., & Driver, J. (1997b). Cross-modal links in attention between audition, vision, and touch: Implications for interface design. *International Journal of Cognitive Ergonomics*, 1(4), 351–373.
- Spence, C., & Driver, J. (2004). *Crossmodal space and crossmodal attention*. Oxford University Press.
- Spence, C., Nicholls, M. E. R., Gillespie, N., & Driver, J. (1998). Cross-modal links in exogenous covert spatial orienting between touch, audition, and vision. *Perception & Psychophysics*, 60(4), 544–557. <https://doi.org/10.3758/BF03206045>
- Spence, C., Parise, C., & Chen, Y.-C. (2012). *The Colavita visual dominance effect (The Neural Bases of Multisensory Processes)*.
- Störmer, V. S. (2019). Orienting spatial attention to sounds enhances visual processing. *Current Opinion in Psychology*, 29, 193–198.
- Störmer, V. S., McDonald, J. J., & Hillyard, S. A. (2009). Cross-modal cueing of attention alters appearance and early cortical processing of visual stimuli. *Proceedings of the National Academy of Sciences*, 106(52), 22456–22461. <https://doi.org/10.1073/pnas.0907573106>
- Straughn, S. M., Gray, R., & Tan, H. Z. (2009). To go or not to go: Stimulus-response compatibility for tactile and auditory pedestrian collision warnings. *IEEE Transactions on Haptics*, 2(2), 111–117.
- Strayer, D. L., Watson, J. M., & Drews, F. A. (2011). Cognitive distraction while multitasking in the automobile. In , Vol. 54. *The psychology of learning and motivation: Advances in research and theory* (pp. 29–58). Elsevier Academic Press.
- UNECE. (2017). *Addendum 78: UN Regulation No. 79. UNECE.* <https://unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2018/R079r4e.pdf>.
- Vatakis, A., & Spence, C. (2007). Crossmodal binding: Evaluating the “unity assumption” using audiovisual speech stimuli. *Perception & Psychophysics*, 69(5), 744–756. <https://doi.org/10.3758/BF03193776>
- Victor, T. W., Tivesten, E., Gustavsson, P., Johansson, J., Sangberg, F., & Ljung Aust, M. (2018). Automation expectation mismatch: Incorrect prediction despite eyes on threat and hands on wheel. *Human Factors*, 60(8), 1095–1116. <https://doi.org/10.1177/0018720818788164>
- Wang, D.-Y. D., Pick, R. F., Proctor, R. W., & Ye, Y. (2007). *Effect of a side collision-avoidance signal on simulated driving with a navigation system*, 4.
- Wang, D.-Y. D., Proctor, R. W., & Pick, D. F. (2003). *Stimulus-Response Compatibility Effects for Warning Signals and Steering Responses*, 2.
- Welch, R. B. (1999). Meaning, attention, and the “unity assumption” in the intersensory bias of spatial and temporal perceptions. In , Vol. 129. *Advances in psychology* (pp. 371–387). Elsevier.
- de Winter, J., Hu, J., & Petermeijer, B. (2022). Ipsilateral and contralateral warnings: Effects on decision-making and eye movements in near-collision scenarios. *Journal on Multimodal User Interfaces*, 16(3), 303–317.
- Wright, T. J., Agrawal, R., Samuel, S., Wang, Y., Zilberstein, S., & Fisher, D. L. (2017). Effects of alert cue specificity on situation awareness in transfer of control in level 3 automation. *Transportation Research Record*, 2663(1), 27–33.
- Wright, T. J., Agrawal, R., Samuel, S., Wang, Y., Zilberstein, S., & Fisher, D. L. (2018). Effective cues for accelerating young drivers' time to transfer control following a period of conditional automation. *Accident Analysis & Prevention*, 116, 14–20.
- Wu, C., Wu, H., Lyu, N., & Zheng, M. (2019). Take-over performance and safety analysis under different scenarios and secondary tasks in conditionally automated driving. *IEEE Access*, 7, 136924–136933. <https://doi.org/10.1109/ACCESS.2019.2914864>