

Training and Assessing Hazard Perception in High-Risk Occupations: Toward and AI-Driven Adaptive and Immersion Simulation

Sébastien Tremblay¹, Cindy Chamberland¹, Isabelle Turcotte², and François Vachon¹

¹École de psychologie, Université Laval, Québec, Canada

²Centre de recherche et d'innovation en sécurité civile (Centre RISC), Campus Notre-Dame-de-Foy, Québec, Canada

ABSTRACT

Work-related accidents in high-risk occupations remain a recurring and costly challenge. Emergency vehicle driving (EVD) is ranked among the most hazardous occupations, with a large proportion of accidents attributed to poor risk perception and inadequate situation awareness (SA). The capacity to identify hazards is a multidimensional cognitive process that may benefit from training and cannot be assumed to develop through experience alone. Yet most occupational safety programs focus on technical skills. The objective of this research is to present the conceptual framework behind a simulation-based cognitive training approach and to discuss the ongoing development and validation of a proof-of-concept: an AI-powered adaptive simulation for hazard perception (HP) training in which eye-tracking is the enabling technology for real-time performance assessment and feedback. The conceptual framework is grounded in the NSEEV model (Noticing, Saliency, Effort, Expectancy, Value) and the concept of SA. In the case of EVD, the platform presents drivers with short video clips recorded from the perspective of an emergency vehicle, with hazardous events time-stamped by experienced field instructors. Eye-tracking provides an objective measure of attentional allocation and can reveal which hazards drivers fail to detect and whether specific scan patterns are associated with anticipated hazard detection. These oculometric and behavioural data feed a Bayesian knowledge-tracing algorithm that adjusts training content. Preliminary results from early versions of the platform provide support for the feasibility of the approach and for its potential as a low-cost, portable complement to high-fidelity simulation training.

Keywords: Hazard perception, Situation awareness, Emergency vehicle driving, Eye-tracking, Adaptive training, Simulation

INTRODUCTION

Emergency vehicle driving (EVD) is consistently identified as one of the most hazardous occupations. Ambulance drivers, firefighters, and police officers face a significantly elevated risk of work-related collisions compared to the general population and other professional drivers (Delavary et al.,

2023). Emergency vehicle drivers are confronted with considerable cognitive demands: driving under time pressure, managing fatigue from extended shifts, navigating unfamiliar areas, and operating in adverse weather conditions; all of which reduce reaction time and impair visual efficiency (NIOSH, 2024). One of the most frequently cited causes of emergency vehicle incidents is sudden braking, which often results from inattentive driving associated with engagement in secondary tasks such as dispatcher communications, momentary drowsiness, or brief glances away from the road (Hsiao et al., 2018). Despite sustained efforts to improve safety, a substantial number of injuries and fatalities linked to EVD continue to be reported and the associated socioeconomic costs are considerable (Mazzolini, 2020).

A central yet underaddressed determinant of safe emergency driving is hazard perception (HP): the ability to detect, interpret, and anticipate potentially dangerous situations in a dynamic environment. HP involves a set of cognitive processes that include visual search, prediction and hazard processing (Pradhan and Crundall, 2016). Most safety errors and at-risk behaviours stem either from an inability to identify hazards or from a misperception of the associated risks (Tixier et al., 2014). HP is closely connected to situational awareness (SA), defined as the ability to perceive and comprehend a constantly evolving environment (Banbury and Tremblay, 2004; Endsley, 1995). Maintaining SA is critical for safe performance in dynamic, high-risk settings (Hasanzadeh et al., 2017), and one of the most important risk factors for EVD incidents is the drivers' capacity to perceive hazards in time (Pandit et al., 2019). Yet most occupational safety programs are focused on procedural and technical skills while neglecting the cognitive processes that underlie safe behaviour.

Research on HP training in general driving has shown that even brief, targeted interventions meaningfully improve hazard detection accuracy and reaction time, with benefits extending to experienced drivers (Horswill et al., 2013; Prabhakharan et al., 2024). A recent study by Tutenuit et al. (2026) further confirms that experienced emergency vehicle drivers employ adaptive visual search strategies that vary in proportion to driving demands, underscoring the relevance of training these skills in a targeted and context-specific manner. The emergence of digital technologies has generated growing interest in immersive simulation tools that provide ecologically valid and engaging learning experiences (Ernst et al., 2023).

THEORETICAL FRAMEWORK

The framework draws on two complementary bodies of theory. First, Endsley's (1995) three-level model of SA posits that safe performance in dynamic environments depends on perceiving relevant cues (Level 1), comprehending their meaning (Level 2), and projecting their future state (Level 3). Failures at any level can lead to unsafe decisions or missed hazards. Second, the NSEEV model (Noticing, Salience, Effort, Expectancy, Value; Wickens, 2021) provides a theoretically grounded account of how visual attention is allocated across a dynamic workspace. By integrating basic visual perception with task demands and environmental characteristics, NSEEV enables the

modelling of attentional distribution and the prediction of which elements are likely to be noticed, overlooked, or prioritized.

Evidence from cognitive ergonomics and driving research shows that eye movement data can be linked to SA: fixation patterns and visual search strategies reflect how drivers perceive and process hazards, and oculometric patterns can identify at-risk individuals with reduced SA (Zhang et al., 2023). In the case of EVD, Tutenuit et al. (2026) documented that experienced paramedics adapt their visual search strategies in proportion to driving demands, showing longer fixation times, more frequent scanning, and greater variety in search patterns as driving complexity increases. As these strategies are trainable, simulation-based training with oculometric feedback is a promising avenue for improving HP in EVDs.

PLATFORM DESIGN AND PROOF OF CONCEPT

We developed an initial proof-of-concept platform. The platform is a web-based application accessible on standard devices, designed to be low-cost and portable, addressing a key limitation of high-fidelity driving simulators whose cost and infrastructure requirements restrict their accessibility (Prohn and Herbig, 2020).

Stimuli

Short video clips were recorded by expert fire truck drivers in real operational conditions, providing ecologically valid content rooted in the actual perceptual environment of emergency driving (see Figure 1). Hazardous events were identified and time-stamped by experienced field instructors, with each hazard specified by its spatial location and the earliest moment at which it could be perceived. This annotation method allows the system to distinguish correct and timely detections from late detections, misses, and false alarms, and enables the precise computation of anticipation time.



Figure 1: Example frame from the EVD footage used as stimulus material. Videos are recorded from the driver's perspective in real operational conditions.

Task and Procedure

Participants watch video clips on a tablet and are instructed to detect and spatially localize hazardous events as quickly and accurately as possible by tapping the screen at the location of the perceived hazard. The task captures detection accuracy, reaction time, and anticipation (i.e., the time between the earliest possible detection and the participant's response). After each clip, outcome feedback indicates the number of correct detections, false alarms, and average reaction time. Cognitive feedback specifies the nature of errors, including whether the driver missed a hazard entirely, detected it late, failed to anticipate it from early precursor cues, or misallocated attention (as detected through the analysis of eye movement) in the moments preceding it (Figure 2).

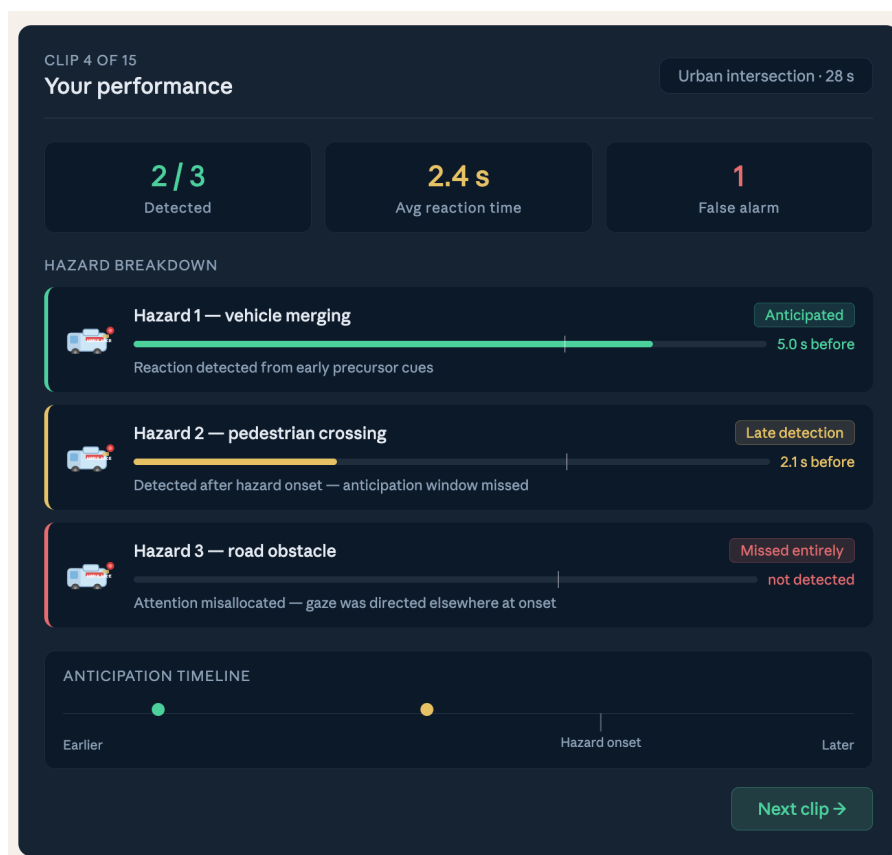


Figure 2: Example of the user-centred feedback screen, showing the spatial location of a correctly detected hazard and an incorrect response on a driving scene frame.

Eye-Tracking Integration

The platform integrates eye-tracking as the enabling technology for performance assessment and feedback. Fixation patterns and visual search strategies reveal which hazards drivers fail to detect or perceive as less

threatening than they are, whether specific scan patterns are associated with anticipated and correct hazard detection, and whether detection failures reflect inattentional blindness (where a hazard is fixated but remains unnoticed). These oculometric and behavioural signals feed a Bayesian knowledge-tracing algorithm that continuously updates a learner profile and adjusts training content in real time to maintain optimal cognitive engagement and learning.

PRELIMINARY RESULTS

Although the full adaptive system is still under development, our program of research has provided support for the technical and psychometric feasibility of the platform across four lines of evidence. First, initial testing of the platform established that the video-based target detection paradigm is functional and yields sensitive performance data. In the context of team sport target (but not hazards) detection, Croteau et al. (2025) demonstrated that the platform reliably captures detection responses across a large set of video clips, with reaction times showing variability across participants. Such a sensitivity to individual differences in detection speed and accuracy is a prerequisite for any adaptive training system.

Second, the feasibility of identifying individual visual scanning strategies from eye-tracking data collected during dynamic detection tasks has been established by Hodgetts et al. (2018), who showed that oculometric profiles reliably differentiate operators by scanning behaviour and link those profiles to detection performance (see also Chen et al., 2024).

Third, the technical integration of eye-tracking into a real-time gaze-aware feedback system has been validated in a high-fidelity surveillance simulation (with heavy reliance on target detection) by Marois et al. (2026). These authors successfully embedded eye-tracking within an augmented reality platform to deliver live gaze-based feedback to operators, demonstrating that oculometric data can be captured, processed, and fed back to users in real time within a dynamic task environment.

Fourth, the EVD-specific content pipeline has been successfully implemented: real emergency vehicle footage has been uploaded to the platform, hazard targets configured in collaboration with field instructors, and the annotated content converted into a time-sensitive anticipation task. The full workflow from expert knowledge to user-facing training interface is operational. These four lines of evidence provide a promising proof of concept on which the full adaptive system will be built.

DISCUSSION AND FUTURE DIRECTIONS

The proposed framework addresses a gap in occupational safety training by targeting the cognitive and perceptual processes that underlie HP, rather than procedural knowledge alone. By combining real operational footage, user-centred feedback, eye-tracking, and adaptive AI, it aims to provide evidence-based training that is accessible to frontline emergency workers. Also, demonstrating both educational value and user acceptability is essential for

organizational adoption. Future evaluation of the platform will therefore include measures of learner reactions, behavioural transfer to real driving, and user acceptance.

Ongoing work is extending the platform in several directions. Longitudinal data collected across expert and non-expert populations will characterize how HP and SA develop with adaptive practice, and whether oculometric profiles can reliably identify at-risk drivers. The full adaptive version, incorporating Bayesian knowledge tracing and real-time eye-tracking feedback, is currently under development and will be validated in a controlled experiment with emergency vehicle drivers. A parallel stream of work is adapting the framework for construction site safety, with scenarios developed in collaboration with industry experts, broadening the reach beyond the EVD domain. Future iterations will incorporate portable eye-tracking hardware compatible with tablet-based delivery.

CONCLUSION

This paper presented the conceptual framework and preliminary results related to the development of a simulation-based cognitive training approach for hazard perception. Based on the NSEEV model and the concept of SA, and enabled by eye-tracking and adaptive AI, the platform offers a scalable, low-cost alternative to high-fidelity simulation for training non-technical cognitive safety skills. Preliminary findings provide support for the validity and sensitivity of the approach. Our training system is anticipated to improve hazard detection performance, reduce unsafe attention patterns, and foster metacognition.

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