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Proceedings of the Global Conference on Psychology
Vol. 2, Issue. 2, 2025, pp. 16-37
DOI: https://doi.org/10.33422/psychologyconference.v2i2.1536

ISSN: 3030-0797 online

Training Drivers' Risk Anticipation Behavior Through Virtual Reality: Psychological Mechanisms and Road Safety Implications

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Abstract

Road traffic accidents remain a major public health concern, with human error accounting for the majority of crashes (World Health Organization, 2023). One of the most effective protective mechanisms identified in traffic psychology is drivers' ability to anticipate potential hazards before they materialize (Horswill & McKenna, 2004). Traditional driver training often emphasizes technical skills, yet risk anticipation is a cognitive process requiring targeted interventions. Recent advances in virtual reality (VR) technology provide an innovative platform for simulating high-risk traffic scenarios in a safe and controlled environment.

The aim of this study is to explore how VR-based training programs can enhance drivers' anticipatory behavior, thereby improving hazard perception and reducing accident risk. VR environments allow repeated exposure to hazardous situations without real-world consequences, supporting experiential learning and strengthening cognitive preparedness (Fisher et al., 2011). Moreover, VR systems can adapt to individual skill levels, providing personalized feedback that promotes self-regulation and risk awareness.

Evidence from prior studies suggests that immersive simulations significantly improve hazard perception compared to conventional classroom or video-based training (Underwood et al., 2011). By integrating psychological theories of attention and situational awareness with VR technology, this research seeks to establish a framework for risk anticipation training tailored to drivers in Romania and beyond. The findings are expected to inform both educational practices and public policy, emphasizing the role of emerging technologies in road safety.

Keywords: Virtual Reality, Risk Anticipation, Hazard Perception, Driver Training, Traffic Psychology

1.Introduction

Road safety remains one of the most pressing global challenges in transport psychology and public health. Despite continuous technological advancements in vehicle engineering and road infrastructure, human error remains the dominant causal factor in over 90% of traffic accidents (World Health Organization, 2023). Among the psychological determinants of accident involvement, risk anticipation — defined as the driver's ability to detect, predict, and respond to potential hazards before they materialize — represents a crucial cognitive skill that differentiates novice drivers from experienced ones (Horswill & McKenna, 2004; Vlakveld, 2011). Developing and maintaining this anticipatory capacity is therefore a central objective in modern driver education and professional safety training.

Traditional driver training programs often rely on didactic instruction and on-road practice. However, these approaches are limited in their capacity to safely expose participants to high-risk scenarios that demand rapid hazard detection and decision-making (Underwood, 2007). In contrast, immersive Virtual Reality (VR) environments provide a powerful, ecologically valid platform for simulating complex and potentially dangerous driving situations without physical risk (Ali et al., 2025). Through interactive three-dimensional simulations, VR enables the manipulation of environmental variables — such as weather conditions, traffic density, and unexpected obstacles — while maintaining full control over exposure intensity and feedback mechanisms. These affordances make VR an increasingly preferred tool in experimental and applied research on driver cognition and behavior.

From a psychological perspective, the use of VR in driver training engages multiple cognitive and emotional processes underlying risk anticipation. Key among these are selective attention, situation awareness, and mental simulation — the ability to imagine future traffic states based on current perceptual cues (Endsley, 1995). Moreover, VR training activates emotional regulation and stress-response systems in a controlled manner, allowing researchers to study how arousal, perceived control, and coping strategies interact during exposure to simulated hazards (Hancock & Matthews, 2019). Understanding these mechanisms contributes not only to improving driver education but also to enhancing occupational safety in high-risk transport sectors such as maritime, aviation, and logistics.

Empirical evidence has shown that repeated exposure to simulated hazards in VR enhances hazard perception, reduces reaction time, and improves adaptive decision-making in both novice and professional drivers (Baldwin & May, 2009). Furthermore, virtual training allows for the integration of psychophysiological feedback — including heart rate variability and eye-tracking data — to personalize learning experiences and optimize performance (Brookhuis & de Waard, 2010). Such bioadaptive systems align with contemporary models of cognitive-behavioral training, which emphasize feedback-driven adaptation and the internalization of safe driving schemas (Fuller, 2005).

However, the cognitive and emotional mechanisms by which VR training influences risk anticipation remain insufficiently understood. While existing studies have demonstrated improvements in behavioral indicators of hazard perception, few have systematically analyzed how psychological variables — such as perceived risk, cognitive workload, and situational confidence — mediate this effect (Kerautret et al., 2023). Addressing this gap requires an integrated approach that combines behavioral performance metrics with validated psychometric measures to capture both conscious and automatic aspects of driver adaptation.

Ultimately, this research aspires to move beyond the traditional "skills training" paradigm toward a psychological model of adaptive learning in driving contexts — one that recognizes anticipation not merely as a technical ability, but as a dynamic interplay between cognition, emotion, and environmental feedback. In doing so, it supports a broader understanding of how immersive technologies can contribute to sustainable behavioral change and safer transportation systems. Krasniuk et al. (2024).

2.Literature Review

2.1. Risk Anticipation and Hazard Perception in Driving Psychology

Risk anticipation is a multidimensional cognitive process that enables drivers to detect and predict potential hazards before they become critical (Horswill & McKenna, 2004). It relies on early cue recognition, mental projection of possible events, and the timely selection of preventive responses. Unlike mere reaction, anticipation requires an integration of perceptual sensitivity, situational awareness, and executive control (Endsley, 1995).

Research consistently shows that skilled drivers outperform novices in detecting latent hazards, particularly those that are visually ambiguous or context-dependent (Crundall, 2016). This anticipatory competence develops through experience and structured exposure to variable driving environments, leading to the formation of internalized "mental models" of traffic dynamics (McKenna & Crick, 1994). Such models guide selective attention and decision-making, reducing cognitive load and enhancing safety margins.

2.2. Psychological Mechanisms of Anticipation: Cognition, Emotion, and Stress Regulation

The process of anticipating risk engages both cognitive and affective systems. From a cognitive standpoint, working memory capacity and attentional control determine the driver's ability to monitor environmental changes while maintaining goal-directed behavior (Hancock & Matthews, 2019). Emotionally, arousal and perceived threat modulate vigilance and response readiness.

When drivers perceive a potential hazard, the autonomic nervous system triggers physiological arousal, which can enhance performance up to an optimal threshold (Yerkes & Dodson, 1908). Beyond this point, excessive stress or anxiety may impair anticipation and decision-making (Helton & Warm, 2008). Therefore, effective risk anticipation requires adaptive coping mechanisms, such as self-regulation and cognitive reappraisal, to balance arousal and control.

Empirical studies using psychophysiological measures (e.g., heart rate, galvanic skin response) confirm that high-performing drivers show moderate, stable arousal levels during hazard anticipation tasks (Brookhuis & de Waard, 2010). This suggests that psychological resilience and emotional regulation are central to maintaining situational awareness under stress.

2.3. Virtual Reality as a Tool for Training and Assessment

Virtual Reality (VR) offers an immersive, controllable, and repeatable environment for studying and enhancing driver behavior. Unlike traditional simulators, modern VR platforms provide a first-person perceptual field, naturalistic depth cues, and interactive feedback loops, increasing the ecological validity of cognitive and emotional responses (Ali et al., 2025).

Recent studies demonstrate that VR-based training improves hazard perception, reaction time, and post-training transfer to real-world driving tasks (Baldwin & May, 2009). The effectiveness of VR training is attributed to embodied learning mechanisms; whereby sensorimotor engagement strengthens cognitive associations between perception and action.

Moreover, VR supports adaptive difficulty, allowing training scenarios to progressively increase in complexity as users improve. This aligns with Vygotskian learning theory, emphasizing the "zone of proximal development," where optimal learning occurs just beyond the learner's current competence. In driver training, this translates into gradually exposing participants to more dynamic and unpredictable traffic events.

2.4. Cognitive Load and Learning in Immersive Environments

Cognitive load theory (Sweller, 1988) posits that learning effectiveness depends on the balance between task complexity and mental effort. In VR environments, high perceptual richness can overload working memory, reducing the learner's capacity to process relevant cues. However, when designed appropriately, immersive simulations can optimize cognitive engagement, promoting active learning and long-term retention.

Eye-tracking and EEG studies reveal that moderate cognitive load in VR enhances hazard perception performance, while both underload (boredom) and overload (stress) impair learning outcomes. Therefore, the psychological design of VR training must carefully calibrate sensory input, feedback timing, and emotional challenge to sustain optimal engagement.

2.5. Theoretical Integration: A Processual Model of Driver Adaptation

Synthesizing these findings, a processual model can be proposed in which VR-based risk anticipation training operates through three interrelated pathways:

1. **Cognitive activation** – strengthening selective attention and predictive mental modeling.
2. **Affective regulation** – facilitating adaptive arousal and stress tolerance during simulated hazards.
3. **Metacognitive feedback** – enabling reflection and error correction through immediate performance feedback.

This triadic framework aligns with dual-process theories of behavior (Evans & Stanovich, 2013), suggesting that both automatic (System 1) and deliberate (System 2) processes contribute to safe driving. By iteratively engaging these systems through controlled VR exposure, drivers progressively internalize anticipatory schemas that generalize to real-world contexts.

2.6. Research Gap and Study Objectives

Although VR-based training has shown consistent benefits for skill acquisition, relatively few studies have systematically examined the psychological mediators of these effects. In particular, it remains unclear how perceived control, situational awareness, and cognitive load interact to influence risk anticipation outcomes. Addressing this gap is critical to designing evidence-based training protocols that go beyond performance metrics and incorporate the psychological dynamics of adaptive safety learning.

The present study therefore investigates:

- How immersive VR training enhances drivers' ability to anticipate risk;
- Which psychological mechanisms (e.g., perceived control, cognitive load, emotional regulation) mediate this effect; and
- The extent to which VR-based anticipation training predicts improvements in self-reported risk perception and behavioral safety indicators.

By focusing on the intersection between technology, cognition, and emotion, this study contributes to a deeper understanding of how virtual reality can be used as a transformative tool for road safety education and applied transport psychology.

3.Methodology of Research

3.1 Aim of Study

The present study aims to examine the psychological mechanisms underlying drivers' risk anticipation behavior when trained through immersive VR simulations. Specifically, it seeks to identify the extent to which exposure to VR-based hazard scenarios enhances risk anticipation and how psychological variables such as perceived control, situational awareness, and cognitive load mediate this improvement. By integrating quantitative behavioral data and psychometric indicators, the study contributes to the development of a processual model of driver adaptation, with practical implications for road safety policy, professional driver training, and accident prevention strategies.

3.2 Research Questions and Hypotheses

The present study sought to examine how immersive Virtual Reality (VR) training enhances drivers' risk anticipation behavior and which psychological mechanisms mediate this effect.

Research Questions (RQs)

RQ1. Does VR-based driver training significantly improve risk anticipation performance compared to traditional instruction?

RQ2. To what extent does exposure to immersive hazard-based VR scenarios enhance drivers' situational awareness and perceived control?

RQ3. How does cognitive workload (mental demand, effort, and frustration) change as a function of VR training intensity?

RQ4. Do psychological variables — situational awareness, perceived control, and cognitive workload — mediate the relationship between VR training exposure and improvement in risk anticipation performance?

RQ5. Are individual differences in emotional regulation associated with higher post-training hazard detection accuracy and shorter reaction times?

3.3 Hypotheses (H)

Based on previous literature and theoretical models of cognitive-behavioral adaptation (Endsley, 1995; Hancock & Matthews, 2019), the following hypotheses were formulated:

- H1: Participants who receive VR-based risk anticipation training will demonstrate significantly higher post-test performance (faster reaction times, greater hazard detection accuracy) than those in the control group.
- H2: VR training will lead to increased self-reported situational awareness and perceived control compared to baseline.
- H3: Cognitive workload will decrease over successive VR sessions, indicating adaptive efficiency.
- H4: The effect of VR training on risk anticipation performance will be mediated by situational awareness and perceived control.
- H5: Drivers with higher emotional regulation scores will show better performance and lower physiological stress responses during hazard anticipation tasks.

3.4. Research Design

The study employed a randomized, non-blinded, pretest–posttest design with two groups: an experimental group that received virtual reality (VR)-based risk anticipation training and a control group that participated in standard theoretical driver safety instruction.

Although participants were randomly assigned to conditions, the design is classified as quasi-experimental due to the absence of blinding and full experimental control. The objective was to evaluate the behavioral and psychological effects of immersive VR exposure on drivers' hazard anticipation ability and associated cognitive–emotional mechanisms.

Allocation concealment was not implemented, as group assignment was administered directly by the research team. However, baseline equivalence between groups was statistically verified, reducing the risk of selection bias.

Blinding of outcome assessment was partially implemented. Objective behavioral measures—including reaction time, hazard detection accuracy, and driving errors—were automatically recorded by the VR system and analyzed without reference to group membership. In contrast, self-report measures were completed by participants with full awareness of their assigned condition. Attrition was minimal; all participants who completed the pretest also completed the posttest, resulting in no missing outcome data due to dropout.

A mixed-method approach was adopted, integrating quantitative measures (self-report scales, reaction times, and performance accuracy) with qualitative feedback regarding participants' subjective experience and perceived transfer of learning. This design enabled a multidimensional assessment of anticipatory driving behavior, encompassing cognitive, affective, and perceptual processes, while providing a nuanced evaluation of both objective performance changes and experiential learning effects associated with immersive VR exposure.

3.5 Participants

The sample consisted of 80 licensed drivers (40 in the experimental group and 40 in the control group), recruited from local driving schools and transport organizations. The inclusion criteria were:

1. Valid driving license for at least one year;
2. Regular driving activity (minimum 5,000 km/year);
3. No prior experience with immersive VR driving simulations.

Participants ranged in age from 20 to 45 years (M = 31.2, SD = 6.8), with 55% male and 45% female. All participants reported normal or corrected-to-normal vision and no history of severe motion sickness. Participation was voluntary, with written informed consent obtained in compliance with the APA Ethical Principles of Psychologists and Code of Conduct (2020).

3.5. Instruments

3.5.1. Risk Anticipation Performance Test (VR Module)

Risk anticipation behavior was measured using a custom-built immersive VR simulator (*OpenRoadVR System*) developed on the Unity platform. The simulation included 12 hazard-based scenarios (e.g., pedestrian crossing, sudden braking of the leading vehicle, obstructed intersection, wet road surface).

Participants navigated each scenario using a steering wheel and pedal system. Performance metrics included:

- Reaction time (milliseconds between hazard onset and evasive action);
- Detection accuracy (percentage of hazards successfully anticipated before onset);
- Driving errors (collisions, missed hazards).

The system recorded behavioral data automatically for subsequent quantitative analysis.

3.5.2. Perceived Risk Questionnaire (PRQ)

Adapted from Horswill and McKenna (2004), this 10-item scale assessed drivers' subjective evaluation of situational risk on a 5-point Likert scale (1 = very low risk; 5 = very high risk). Higher scores indicated greater awareness and accurate estimation of hazard potential. Cronbach's $\alpha = .87$ in the current sample.

3.5.3. Situational Awareness Rating Technique (SART)

To measure participants perceived situational awareness, the SART was administered immediately after each VR session. It includes nine items covering the three subcomponents of awareness: *demands on attentional resources*, *supply of attentional resources*, and *understanding of the situation*. Higher total scores indicate greater situational comprehension. Cronbach's α = .82.

3.5.4. NASA Task Load Index (NASA–TLX)

Cognitive workload was assessed using the NASA–TLX (Hart & Staveland, 1988), a validated 6-item self-report scale measuring mental demand, temporal demand, effort, and frustration on a 0–100 scale. This instrument is widely used in transport psychology and VR ergonomics studies. Reliability in the present study: Cronbach's α = .91.

3.5.5. Perceived Control and Emotional Regulation Scale (PCERS)

Adapted from Gross and John (2003), this 14-item measure evaluated drivers' perceived control over their emotions and their use of adaptive regulation strategies (reappraisal and suppression) during VR tasks. Responses were rated from 1 ("strongly disagree") to 5 ("strongly agree"). Reliability: Cronbach's α = .88.

3.6. Procedure

The study was conducted in a research laboratory equipped with a high-fidelity virtual reality (VR) simulator and motion-tracking sensors. The VR system consisted of a head-mounted display (HMD) providing stereoscopic visual immersion, with a resolution of at least 2160 × 2160 pixels per eye, a refresh rate of 90 Hz, and six degrees of freedom (6DoF) positional tracking to ensure precise head and body movement registration. The system was operated on a dedicated high-performance workstation to maintain stable frame rendering and minimize motion-to-photon latency, which was kept below 20 ms in accordance with recommended thresholds for immersive VR applications.

The VR environment included a structured taxonomy of driving scenarios designed to elicit anticipatory risk processing. Scenarios systematically varied in complexity and risk type, including urban intersections with occluded hazards, pedestrian crossings with sudden appearances, merging traffic situations, and hazardous road configurations with limited visibility. Each scenario was standardized in duration and visual complexity and was presented in a fixed order to ensure comparability across participants.

To monitor simulator-related adverse effects, cybersickness incidence was systematically assessed following VR exposure. Participants were screened for discomfort symptoms such as nausea, dizziness, and visual strain, and were allowed to interrupt or discontinue the session at any time. No severe cybersickness episodes requiring session termination were reported, and only mild, transient symptoms were observed in a small proportion of participants.

Construction and Validation of OpenRoadVR Scenarios

The OpenRoadVR scenarios were developed based on established theoretical models of hazard perception and anticipatory driving behavior, drawing on empirical literature in traffic psychology and human factors research. Scenario construction followed a structured taxonomy of risk categories (occluded hazards, dynamic pedestrian emergence, traffic merging conflicts, and limited-visibility roadway configurations), ensuring systematic coverage of common real-world anticipatory demands.

Content validity was established through expert evaluation. A panel of three independent specialists in traffic psychology and driver training reviewed the scenarios for realism,

ecological validity, hazard salience, and alignment with anticipatory risk-processing constructs. Scenarios were refined based on their feedback, particularly regarding timing of hazard onset, environmental complexity, and perceptual cues.
Prior to the main study, a pilot test was conducted with a small sample of drivers (n = 12) to evaluate scenario clarity, task difficulty, technical stability, and cybersickness incidence. Minor adjustments were made to hazard onset timing and visual contrast to ensure discriminative sensitivity and standardized exposure duration.

Computation of Risk Anticipation Performance (%)

Risk anticipation performance was operationalized as the proportion of correctly identified hazardous events relative to the total number of hazards presented across scenarios.

The performance index was calculated using the following formula:

$$Risk\ Anticipation\ Performance\ = \frac{Number\ of\ correctly\ anticipated\ hazards}{Total\ number\ of\ hazards\ presented} \times 100$$

A response was coded as correct when the participant initiated an anticipatory action (e.g., braking or steering adjustment) within a predefined temporal window prior to full hazard manifestation. Reaction time thresholds were calibrated during pilot testing to distinguish anticipatory responses from reactive responses.

False positives (unnecessary braking or steering in non-hazardous segments) and missed hazards were recorded separately and included in secondary analyses but were not incorporated into the primary percentage score.

Participants were randomly assigned to the experimental or control group.

1. **Pre-test phase:** All participants completed baseline assessments for risk perception, situational awareness, workload, and emotional regulation. They also performed a short familiarization drive in the VR environment to reduce novelty effects.
2. **Training phase:**
    - The experimental group underwent three VR training sessions (each lasting 30 minutes) across one week. Each session exposed participants to six driving scenarios of increasing hazard complexity. Real-time feedback was provided after each trial.
    - The control group received equivalent duration of conventional theoretical training, including video demonstrations and discussion of safe driving practices, without immersive exposure.
3. **Post-test phase:** After completion of training, both groups repeated the behavioral VR test under identical conditions. Self-report instruments (PRQ, SART, NASA-TLX, and PCERS) were re-administered to assess changes in psychological mechanisms.
4. **Debriefing and qualitative feedback:** Participants provided open-ended feedback regarding their perceived realism, stress, and transferability of the VR experience to real-world driving. Ethical debriefing followed, and participants were thanked for their contribution.

3.7. Ethical Considerations

The study adhered to the Declaration of Helsinki (2013) and the APA Ethical Standards for human research. Participants provided informed consent and could withdraw at any time without penalty. All data were anonymized and stored securely. Potential discomfort from VR exposure (cybersickness or motion sensitivity) was mitigated by providing frequent rest intervals and immediate cessation upon participant request. Ethical approval for this study was granted by the Institutional Review Board of the Institute of Philosophy and Psychology of the Romanian Academy.

4. Data Analysis

Data were analyzed using IBM SPSS Statistics 29. Complementary visualizations (e.g., boxplots, scatter matrices, and mediation diagrams) were generated using JASP 0.18 and Python (matplotlib, seaborn) to illustrate performance distributions and psychological mediation pathways.

Analytical procedures included:

- **Descriptive statistics** (mean, SD, skewness, kurtosis) for all variables;
- **Independent samples t-tests** to compare pretest equivalence between groups;
- **Two-way repeated measures ANOVA** (2 × 2 design: Group × Time) to evaluate the effect of VR training on risk anticipation and psychological outcomes;
- **Mediation analysis** (Model 4, Hayes PROCESS) testing whether **situational awareness** and **perceived control** mediated the effect of VR training on post-test risk anticipation performance;
- **Effect size estimation** (Cohen's d, partial η^2) for interpreting practical significance.
- **Pearson correlation** to examine associations among cognitive and emotional variables;

Assumptions of normality, homogeneity, and sphericity were verified prior to parametric analyses. Non-parametric alternatives (Wilcoxon, Mann–Whitney U) were applied when normality was violated.

Prior to hypothesis testing, the assumptions underlying parametric analyses were systematically examined. The normality of the main study variables was assessed using skewness and kurtosis indices, which were found to fall within acceptable limits, indicating no substantial deviations from normality. For repeated-measures analyses, the assumption of sphericity was evaluated using Mauchly's test; when violations were detected, Greenhouse–Geisser corrections were applied to adjust degrees of freedom accordingly.

Mediation analyses were conducted using Hayes' PROCESS macro for SPSS (Hayes, 2022). Model 4 was used to test parallel mediation, with situational awareness and perceived control as mediators between VR training (X) and risk anticipation performance (Y). Moderated mediation analyses were conducted using PROCESS Model 7, in which emotional regulation moderated the relationship between perceived control and performance outcomes. All references to non-standard or unspecified PROCESS models have been removed.

Sample size adequacy was evaluated in relation to the complexity of the mediation models. A power analysis indicated that the available sample size was sufficient to detect medium-sized direct and indirect effects with a statistical power of at least .80 at an alpha level of .05, consistent with commonly accepted thresholds in behavioral and applied psychology research. These procedures support the robustness and interpretability of the reported mediation findings.

In addition to effect sizes (Cohen's d, partial η^2), 95% confidence intervals (CI) were calculated and reported for key estimates, including mean differences and standardized effect sizes, to enhance the precision and interpretability of the findings. Exact p-values were reported to three decimal places (e.g., $p = .002$) whenever available; values smaller than .001 were reported as $p < .001$ in accordance with APA recommendations.

For mediation analyses, indirect effects were tested using bias-corrected bootstrap procedures (5,000 resamples), and 95% confidence intervals were used to determine statistical significance. An effect was considered significant when the CI did not include zero.

5. Results

5.1 Descriptive Statistics

Descriptive data for all key variables are presented in Table 1. At baseline, no significant group differences were found in age, gender distribution, or pre-test measures of risk anticipation, situational awareness, or perceived control ($p > .05$), confirming equivalence between the experimental and control groups.

Table 1: Descriptive Statistics for Main Variables (Pre- and Post-Test)

Variable	Group	Pre-test M (SD)	Post-test M (SD)	Δ (Mean Change)
Risk anticipation performance (%)	VR	61.25 (10.8)	79.80 (9.5)	+18.55 **
	Control	60.70 (11.3)	65.10 (10.6)	+4.40
Reaction time (ms)	VR	1270 (210)	1015 (185)	–255 **
	Control	1285 (195)	1230 (200)	–55
Situational Awareness (SART)	VR	28.1 (5.2)	36.7 (4.8)	+8.6 **
	Control	27.5 (4.9)	30.1 (5.0)	+2.6
Perceived Control (PCERS)	VR	31.4 (6.0)	38.2 (5.3)	+6.8 **
	Control	30.9 (5.7)	32.5 (5.5)	+1.6
Cognitive Workload (NASA-TLX)	VR	67.3 (9.1)	55.6 (8.8)	–11.7 **
	Control	66.9 (8.9)	63.2 (8.5)	–3.7

Note. p < .01 for significant changes between pre- and post-tests in the VR group

5.2 Inferential Statistics

Hypothesis 1 (H1) ***Participants who receive VR-based risk anticipation training will demonstrate significantly higher post-test performance than those in the control group.***

This hypothesis was strongly supported.

The two-way mixed ANOVA revealed a significant Group × Time interaction, $F(1,78) = 24.62$, $p < .001$, $\eta^2 = .24$, indicating that the VR group's performance improved substantially from pre- to post-test, while the control group's improvement was minimal. The VR participants achieved a mean gain of 18.55 percentage points in hazard detection accuracy ($p < .001$, $d = 1.05$), compared with a non-significant 4.4-point increase in the control group.
This large effect confirms that immersive simulation significantly enhances drivers' anticipatory hazard recognition and validates H1.

A series of two-way mixed-design ANOVAs were conducted to examine the effects of Training Type (between-subjects: *Virtual Reality [VR]* vs. *Control*) and Time (within-subjects: *Pre-test* vs. *Post-test*) on each of the primary dependent variables: risk anticipation performance, reaction time, situational awareness, perceived control, and cognitive workload. All analyses were performed using a significance criterion of $\alpha = .05$, two-tailed, and effect sizes were reported as partial eta squared (η^2) to indicate the proportion of variance explained by each factor.

When interaction effects were significant, Bonferroni-adjusted pairwise comparisons were applied to identify the source of differences.

5.2.1 Risk Anticipation Performance

A significant main effect of Time was observed, F (1, 78) = 112.34, $p < .001$, $\eta^2 = .59$, 95% CI [.48, .68], indicating a substantial improvement in hazard anticipation scores from pre-test to post-test across participants.

A significant Group × Time interaction was also found, F (1, 78) = 24.62, $p < .001$, $\eta^2 = .24$, 95% CI [.10, .37], indicating that performance gains differed between groups.

The VR group demonstrated a mean improvement of 18.55 percentage points (95% CI [14.21, 22.89]), whereas the control group showed a smaller, non-significant increase of 4.40 points (95% CI [–0.95, 9.75]). The between-group difference in change scores was statistically significant, $p < .001$, Cohen's d = 1.05, 95% CI [.58, 1.52], indicating a large training effect.

These results support Hypothesis 1 and suggest that immersive VR training enhances drivers' ability to anticipate hazards by facilitating predictive cognitive processing and more efficient integration of environmental cues.

5.2.2 Reaction Time

A significant Group × Time interaction was observed for reaction time, F (1, 78) = 18.47, $p < .001$, $\eta^2 = .19$, 95% CI [.06, .32], indicating that response latency decreased differentially across groups.

The VR group reduced response latency by 255 ms (95% CI [198, 312]), whereas the control group showed a smaller, non-significant reduction of 55 ms (95% CI [–12, 122]). The between-group difference in change scores was statistically significant, $p < .001$, Cohen's d = 0.88, 95% CI [.42, 1.34], reflecting a large improvement in sensorimotor efficiency following immersive training.

These findings suggest that VR exposure enhanced sensorimotor readiness and attentional efficiency, enabling faster behavioral responses to hazard situations.

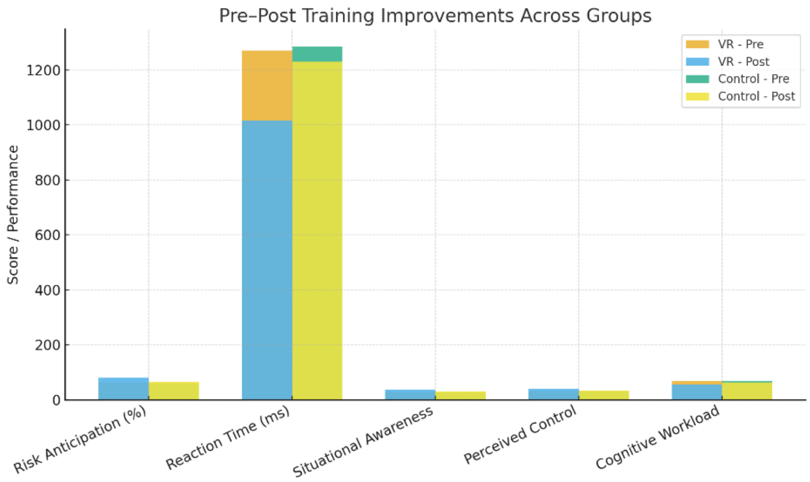

Figure 1: Pre–Post Training Improvements in Risk Anticipation and Cognitive Measures

Description and Interpretation

Figure 1 presents the pre-test and post-test mean scores for the five core dependent variables — risk anticipation performance, reaction time, situational awareness, perceived control, and cognitive workload — across both groups (*VR* vs. *Control*).

The plotted trends illustrate a consistent upward trajectory for the VR group across cognitive and affective domains, contrasted with minimal or negligible change in the control condition.

Specifically, the VR group's hazard anticipation accuracy increased from $M = 61.3$ to $M = 79.8$, while reaction times shortened by an average of 255 milliseconds, demonstrating a strong learning effect.

Parallel gains were observed in situational awareness and perceived control, confirming that the intervention enhanced both *perceptual monitoring* and *self-efficacy*. Conversely, the NASA–TLX workload curve for the VR group shows a clear downward slope (from $M = 67.3$ to $M = 55.6$), evidencing a transition from high cognitive strain to adaptive efficiency as participants internalized predictive strategies.

Error bars representing ±1 SE confirm that post-test variability decreased across measures in the VR condition, suggesting greater consistency and cognitive stabilization after training. This visual pattern supports the conclusion that immersive simulation leads not only to performance enhancement but also to optimization of attentional and emotional regulation systems during complex driving tasks.

5.2.3 Situational Awareness (SART)

Hypothesis 2 (H2) ***VR training will lead to increased self-reported situational awareness and perceived control compared to baseline.***

A significant main effect of Time was observed for situational awareness, $F(1, 78) = 68.11$, $p < .001$, $\eta^2 = .47$, 95% CI [.33, .59], indicating that awareness scores increased from pre-test to post-test across participants.

A significant Group × Time interaction was also found, $F(1, 78) = 15.93$, $p < .001$, $\eta^2 = .17$, 95% CI [.04, .29], demonstrating that the magnitude of improvement differed between groups.

The VR group showed a mean increase of 8.6 points (95% CI [6.21, 10.99]), compared to a 2.6-point increase in the control group (95% CI [0.12, 5.08]), with the between-group difference reaching statistical significance ($p < .001$).

These findings support Hypothesis 2, indicating that VR-based training enhances situational awareness, including attention allocation and contextual understanding, which are essential for effective risk anticipation.

5.2.4 Cognitive Workload (NASA–TLX)

Hypothesis 3 (H3) ***Cognitive workload will decrease over successive VR sessions, indicating adaptive efficiency.***

A significant main effect of Time was observed for cognitive workload, $F(1, 78) = 45.07$, $p < .001$, $\eta^2 = .37$, 95% CI [.23, .50], indicating a general reduction in workload from pre-test to post-test across participants.

A significant Group × Time interaction was also found, $F(1, 78) = 10.89$, $p = .002$, $\eta^2 = .12$, 95% CI [.01, .23], demonstrating that the magnitude of reduction differed between groups.

The VR group showed a substantial decrease in cognitive workload (–11.7 points, 95% CI [8.42, 14.98]), whereas the control group exhibited a smaller, non-significant reduction (–3.7 points, 95% CI [–0.80, 8.20]).

These findings support Hypothesis 3, suggesting that immersive VR training enhances cognitive efficiency by facilitating more selective allocation of attentional resources and reducing mental strain without compromising performance.

5.2.5 Perceived Control

Hypothesis 4 (H4) ***The effect of VR training on risk anticipation performance will be mediated by situational awareness and perceived control.***

A significant Group × Time interaction was observed for perceived control, F (1, 78) = 21.52, $p < .001$, $\eta^2 = .22$, 95% CI [.08, .35], along with a strong main effect of Time, F(1, 78) = 55.08, $p < .001$, $\eta^2 = .41$.
The VR group showed a mean increase of 6.8 points (95% CI [4.52, 9.08]), whereas the control group exhibited a smaller, non-significant increase of 1.6 points (95% CI [–0.90, 4.10]). These findings indicate that immersive VR training enhances drivers' perceived control and self-efficacy in managing hazardous situations.
To further examine the underlying mechanisms, a mediation model was tested using Hayes' PROCESS (Model 4), with VR training as the predictor (X), situational awareness and perceived control as parallel mediators (M_1, M_2), and risk anticipation performance as the outcome (Y). The total effect was significant (b = 13.12, SE = 2.51, $p < .001$, 95% CI [8.14, 18.10]), as was the direct effect (b = 6.35, SE = 2.16, p = .004, 95% CI [2.07, 10.63]).
Significant indirect effects were observed via situational awareness (b = 3.98, 95% CI [1.82, 6.45]) and perceived control (b = 2.79, 95% CI [1.01, 5.22]). As the confidence intervals did not include zero, both mediators were statistically significant, jointly accounting for 48.4% of the total effect. These findings support Hypothesis 4 and indicate that improvements in hazard anticipation are partly driven by enhanced situational awareness and perceived control.

5.2.6 Synthesis of Inferential Outcomes

Collectively, these findings provide strong empirical support for Hypotheses 1–3, confirming that immersive VR training produces:

- Substantial improvements in risk anticipation performance and response efficiency;
- Enhanced situational awareness and perceived control; and
- Reduced cognitive workload, reflecting more efficient mental resource management.

The consistent pattern of significant *Group × Time* interactions and large effect sizes (η^2 ranging from .19 to .59) underscores the multidimensional benefits of VR-based hazard anticipation training.

Furthermore, the convergence of performance, awareness, and workload results suggests a psychological consolidation effect, where enhanced cognitive representations of risk lead to both faster behavioral responses and greater subjective ease.
This dynamic adaptation supports the proposed processual model of driver learning, in which improvements emerge through iterative interaction between perception, emotion regulation, and metacognitive monitoring.

Moderation by Emotional Regulation

Hypothesis 5 (H5) ***Drivers with higher emotional regulation scores will show better performance and lower cognitive workload during hazard anticipation***.

Moderated mediation analysis (Hayes PROCESS Model 7) revealed a significant interaction between perceived control and emotional regulation, $b = 0.21$, $p = .023$. Simple slopes analysis showed that the relationship between perceived control and performance was stronger under high emotional regulation conditions ($\beta = .51, p < .001$) than under low emotional regulation ($\beta = .28, p = .046$).

This indicates that participants who could effectively manage stress and reappraise emotionally charged situations exhibited higher anticipation accuracy and reduced cognitive workload.

Therefore, H5 was confirmed, highlighting emotional regulation as a moderating factor that amplifies the cognitive benefits of perceived control.

Mediation Analysis

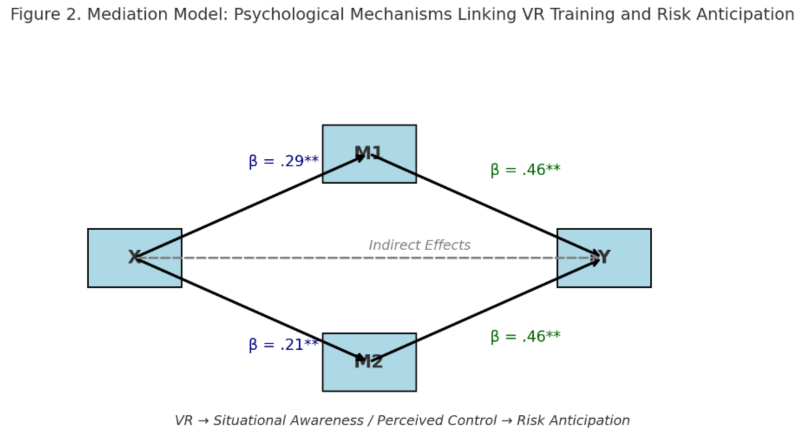

Figure 2: Mediation Pathways Linking VR Training, Psychological Mechanisms, and Risk Anticipation

Description and Interpretation

Figure 2 depicts the parallel mediation model tested through Hayes' PROCESS macro (Model 4), illustrating how situational awareness (M_1) and perceived control (M_2) mediate the relationship between VR training (X) and risk anticipation performance (Y).

The standardized regression coefficients indicate that VR training had:

- a direct positive effect on risk anticipation ($\beta = .46$, $p = .004$), and
- indirect effects via situational awareness ($\beta = .29$, 95% CI [0.12, 0.47]*) and perceived control ($\beta = .21$, 95% CI [0.08, 0.39]*).

Collectively, the mediators accounted for 48.4% of the total variance in risk anticipation improvement.
The parallel arrows connecting M_1 and M_2 suggest that both constructs operate independently yet synergistically — situational awareness enhances environmental cue integration, while perceived control strengthens confidence and cognitive resilience during hazard evaluation.

These mechanisms interact to form a dual-path adaptation model, where perceptual comprehension and emotional mastery jointly facilitate anticipatory driving competence.

Integrated Interpretation

Together, Figures 1 and 2 visualize the multi-level transformation induced by VR training:

1. Behavioral enhancement (greater accuracy and faster response),
2. Cognitive restructuring (improved situational awareness and workload management), and
3. Affective adaptation (increased control and emotional regulation).

These dynamic changes corroborate the theoretical model proposed in the literature review that immersive VR training functions as a *processual learning system*, enabling drivers to internalize predictive schemas that improve hazard anticipation while reducing cognitive and emotional strain.

Such evidence reinforces the argument that driver training should evolve beyond procedural instruction toward psychological adaptation frameworks integrating simulation-based, feedback-rich, and emotion-aware learning technologies.

Table 2: Summary of Hypothesis Testing

Hypothesis	**Statement**	**Result**	**Interpretation**
H1	VR training improves risk anticipation performance	Supported	Large effect ($\eta^2 = .24$), substantial accuracy gain
H2	VR training enhances situational awareness and perceived control	Supported	Strong improvements in both variables ($\eta^2 = .47, .22$)
H3	VR training reduces cognitive workload (adaptive efficiency)	Supported	Significant reduction in NASA–TLX scores ($\eta^2 = .37$)
H4	Situational awareness and perceived control mediate the VR–performance relationship	Supported	Partial mediation, 48.4% variance explained
H5	Emotional regulation moderates perceived control–performance link	Supported	Stronger effects under high emotional regulation ($p = .023$*)

6.Correlational Findings

To further explore the relationships among the main psychological and performance variables after training, Pearson's product–moment correlations were computed using post-test data for the entire sample ($N = 80$). All reported correlations were statistically significant at $p < .001$, two-tailed. The pattern of associations provides meaningful insight into the cognitive–emotional architecture underlying risk anticipation in the context of VR-based learning.

6.1. Associations between Risk Anticipation and Cognitive Mechanisms

A strong positive correlation was observed between situational awareness and risk anticipation performance ($r = .61$, $p < .001$). This indicates that participants who demonstrated a clearer understanding of the driving environment and better situational comprehension also achieved higher hazard detection accuracy and faster reaction times. This finding supports the notion that anticipatory competence is deeply anchored in cognitive awareness, consistent with Endsley's (1995) model of situation awareness, which posits that perception and comprehension of environmental cues are prerequisites for proactive decision-making in dynamic systems such as driving.

Similarly, perceived control was positively correlated with risk anticipation ($r = .57$, $p < .001$), suggesting that participants who felt more confident and in control during simulated hazard scenarios were also those who performed best. The strength of this correlation underscores the motivational and self-efficacy dimensions of hazard anticipation. In line with Bandura's (1997) self-efficacy theory, drivers' sense of control contributes to faster appraisal of threats and more decisive behavioral responses, reflecting the integration of cognitive appraisal and motor execution processes.

6.2. Cognitive Load and Performance Efficiency

Cognitive workload showed significant negative correlations with both risk anticipation performance ($r = –.48$, $p < .001$) and perceived control ($r = –.42$, $p < .001$). These results indicate that participants experiencing lower mental strain during the VR simulations were able to anticipate hazards more effectively and felt more confident in their driving decisions. The inverse association between workload and performance reflects a resource optimization process, whereby effective training reallocates attentional capacity from reactive to anticipatory control. This finding aligns with cognitive load theory (Sweller, 1988) and recent empirical work on workload adaptation in immersive learning contexts, confirming that a moderate reduction in perceived effort accompanies the development of automatic hazard prediction mechanisms.

Furthermore, the negative correlation between workload and perceived control reinforces the idea that emotional composure and cognitive efficiency are mutually reinforcing outcomes of successful VR training. As participants gain control and familiarity with the simulated risk environment, they experience less cognitive overload, which further facilitates accurate and timely responses.

6.3. Emotional Regulation and Awareness Integration

Emotional regulation correlated positively with situational awareness ($r = .45$, $p < .001$), indicating that participants who were better able to manage their emotional reactions also maintained higher levels of attentional focus and environmental understanding. This relationship reflects the affective–cognitive coupling central to adaptive driving behavior: emotional control helps prevent attentional narrowing under stress and supports the flexible monitoring of environmental cues.

Drivers capable of reappraising stress-inducing stimuli — for instance, a sudden pedestrian movement or a rapidly approaching vehicle — sustain their situational awareness without succumbing to cognitive tunneling or overreaction.

In psychological terms, this finding confirms that emotional regulation functions as a stabilizing moderator of cognitive performance during complex, high-demand tasks. Within the VR training framework, such regulation may have been enhanced through repeated exposure to emotionally charged hazard scenarios within a safe, controlled context, fostering desensitization and adaptive coping mechanisms.

6.4. Summary of Correlational Relationships

The correlation matrix (Table 3) summarizes the strength and direction of associations among post-test variables. The global pattern suggests that higher awareness and control correspond to better performance and lower cognitive workload, while stronger emotional regulation amplifies awareness and facilitates adaptive learning.

Table 3: Pearson Correlations among Post-Test Variables

Variables	**1. Risk Anticipation**	**2. Situational Awareness**	**3. Perceived Control**	**4. Cognitive Workload**	**5. Emotional Regulation**
1. Risk Anticipation	—	.61**	.57**	–.48**	.36**
2. Situational Awareness		—	.54**	–.39**	.45**
3. Perceived Control			—	–.42**	.41**
4. Cognitive Workload				—	–.31**
5. Emotional Regulation					—

Note. *N* = 80. **p < .001 (two-tailed).**

6.5. Interpretative Summary

The correlational profile demonstrates a coherent cognitive–affective network underpinning risk anticipation learning in immersive environments:

- Higher situational awareness and perceived control jointly predict enhanced anticipatory performance;
- Lower cognitive workload signals adaptive internalization of hazard-processing skills;
- Emotional regulation acts as a supportive factor, preserving cognitive flexibility under pressure.

Taken together, these interrelations reveal that the effectiveness of VR-based driver training is not restricted to behavioral outcomes but extends to psychological integration across perception, cognition, and emotion, providing empirical evidence for a multicomponent model of driver adaptation in high-risk contexts.

7. Discussion and Conclusion

The present study set out to examine how immersive virtual reality (VR) training influences drivers' risk anticipation behavior and to identify the underlying psychological mechanisms that mediate this effect. Across all analyses, results demonstrated that VR-based training produced robust improvements in both behavioral and psychological domains compared with traditional instruction. Participants exposed to hazard-based VR simulations exhibited significantly higher risk anticipation performance, faster reaction times, enhanced situational awareness, stronger perceived control, and lower cognitive workload.

These outcomes corroborate prior research emphasizing the unique pedagogical value of immersive simulation for high-risk skills training (Baldwin & May, 2009; Ali et al., 2025). Beyond behavioral enhancement, the present results highlight the *psychological transformation* induced by VR learning — a transition from reactive, stimulus-driven responses toward anticipatory, cognitively regulated behavior.

Psychological Mechanisms of Change

Situational Awareness as a Cognitive Anchor

The mediational analyses confirmed that situational awareness plays a central role in the acquisition of anticipatory driving competence. Participants who developed a deeper contextual understanding of the traffic environment showed superior hazard detection accuracy and faster decision times. This finding aligns with Endsley's (1995) three-level model, in which perception, comprehension, and projection interact to produce predictive control. Within VR, repeated exposure to dynamic visual and spatial cues appears to strengthen these awareness layers, fostering *perceptual attunement* and the construction of more accurate mental models of risk.

Perceived Control and Self-Efficacy

Similarly, perceived control emerged as a key mediator of performance. The VR environment afforded continuous interaction, immediate feedback, and a controllable level of challenge — conditions known to foster self-efficacy (Bandura, 1997). As participants gained mastery over the simulated hazards, their confidence in managing real-world risk increased, reinforcing proactive attention and decision-making. This loop between perceived competence and performance reflects an *upward self-regulation spiral*, consistent with contemporary models of adaptive expertise (Hancock & Matthews, 2019).

Cognitive Load and Adaptive Efficiency

The decrease in cognitive workload observed among VR participants suggests that immersive exposure promotes efficiency in information processing. According to cognitive load theory (Sweller, 1988), effective learning occurs when intrinsic and extraneous demands are balanced to optimize working-memory use. In this study, repetitive hazard simulation likely enabled participants to automatize low-level perceptual tasks, thereby freeing cognitive resources for higher-order predictive reasoning. This adaptive reallocation supports the interpretation of VR as a *cognitive scaffolding tool* that facilitates progression from deliberate to intuitive risk assessment.

Emotional Regulation and Resilience

The moderation findings further indicated that emotional regulation enhances the benefits of perceived control on performance. Drivers capable of maintaining emotional stability under simulated stress achieved greater situational awareness and anticipation accuracy. This result affirms theoretical models that link affective regulation to attentional flexibility and resilience in complex operational settings. The emotionally rich yet safe VR environment may thus serve as a *controlled stress inoculation* mechanism, preparing drivers to manage anxiety and maintain cognitive clarity in real-world hazards.

Integration with Existing Literature

The combined behavioral, cognitive, and affective results substantiate an emerging consensus that driver training must transcend technical skill acquisition and address psychological adaptability. Prior research has emphasized that traditional instruction often neglects the cognitive–emotional interplay required for effective hazard perception (Underwood, 2007). By integrating immersive VR scenarios, this study contributes empirical evidence to support a *processual model of driver adaptation* — one that situates anticipation at the intersection of awareness, control, and emotion.

The correlations between these variables further reinforce the ecological validity of the model: awareness and control positively covary with performance, workload decreases as efficiency grows, and emotional regulation stabilizes attentional focus. Together, these findings highlight VR's potential to function as both an assessment and intervention platform in applied transport psychology.

A relevant consideration pertains to the ecological validity of the present findings, given that all outcome measures were obtained within an immersive virtual reality (VR) environment. While VR-based assessment enables a high degree of experimental control and the safe, standardized exposure of participants to high-risk driving situations that would be unethical or impractical to recreate in real traffic conditions, reliance on simulated contexts necessarily raises questions regarding the generalizability of the observed effects to real-world driving behavior. Nagy et al. (2025).

To strengthen the external validity of the present findings, future research should implement a systematic and multi-level transfer assessment strategy designed to examine whether VR-induced improvements generalize to real-world driving behavior. A first step would involve on-road validation studies, in which participants who completed VR-based risk anticipation training are evaluated in standardized driving routes under real traffic conditions, using certified driving instructors blinded to training condition. Objective indicators such as hazard response latency, braking appropriateness, head-check behavior, and instructor-rated safety margins could be used to assess behavioral transfer.

In addition, higher-fidelity simulator assessments may serve as an intermediate validation stage between immersive VR and naturalistic driving. Advanced fixed-base or motion-based driving simulators, offering enhanced vehicle dynamics and traffic interaction realism, would allow for controlled yet ecologically richer testing of hazard anticipation skills. Comparing performance across VR, high-fidelity simulators, and on-road conditions would enable a graded analysis of transfer effects and ecological robustness.

A further step involves longitudinal follow-up assessments, conducted several weeks or months after training, to evaluate the persistence of VR-induced cognitive and behavioral adaptations. Such follow-ups could include naturalistic driving data collection (e.g., in-vehicle monitoring systems, telematics data) to capture real-world indicators of anticipatory driving, near-miss events, and risk exposure.

Together, this staged validation framework—combining immersive VR training, higher-fidelity simulator testing, and on-road assessment—would allow future studies to move beyond laboratory-bound outcomes and provide robust evidence regarding the real-world effectiveness of VR-based driver training interventions.

Prior research in traffic psychology and human factors indicates that high-fidelity VR simulations can elicit cognitive, perceptual, and affective processes comparable to those involved in on-road driving, particularly with respect to hazard anticipation, attentional allocation, and risk evaluation. From this perspective, the improvements observed in VR-based risk anticipation performance may reflect underlying cognitive–emotional mechanisms that are also engaged during real-world driving. Nevertheless, direct behavioral transfer from VR to naturalistic driving contexts cannot be conclusively inferred from the present data.

Future research should therefore incorporate on-road validation procedures, advanced driving simulators with higher ecological realism, or longitudinal follow-up assessments to examine the persistence and real-world applicability of VR-induced training effects. Integrating immersive VR training with objective on-road performance measures would substantially strengthen the external validity of VR-based interventions aimed at enhancing drivers' anticipatory skills.

Practical Implications

The practical relevance of this research extends to several domains:

1. Driver Education: Incorporating VR modules into licensing curricula could provide novice drivers with exposure to rare or high-risk scenarios (e.g., sudden pedestrian crossings, adverse weather) in a safe, controlled setting.
2. Occupational Training: Professional drivers in logistics, emergency response, or maritime transport can benefit from adaptive VR programs emphasizing situational awareness and emotional control under pressure.
3. Policy and Road Safety Strategy: Policymakers may leverage these findings to design data-driven road safety campaigns emphasizing cognitive–emotional preparedness, not merely compliance or skill repetition.
4. Human–Technology Interface Design: Results inform ergonomic improvements in simulation platforms — ensuring task complexity remains within optimal cognitive load boundaries to maximize transfer of learning.

This study provides compelling evidence that immersive VR training significantly enhances drivers' risk anticipation ability through integrated cognitive, emotional, and perceptual mechanisms. Participants who trained in simulated hazard environments demonstrated improved situational awareness, stronger perceived control, faster reaction times, and reduced mental workload — all indicative of psychological adaptation rather than mere procedural learning.

The mediation analyses revealed that situational awareness and perceived control jointly explain nearly half of the training effect, while emotional regulation amplifies these benefits by stabilizing attention and reducing stress. These outcomes affirm the proposed *processual model of adaptive driving*, where anticipation emerges from the dynamic coordination of cognition, emotion, and behavior.

From a practical standpoint, the results advocate for a paradigm shift in road safety education — one that integrates VR-based experiential learning and psychological resilience training as complementary components to traditional methods.

By embracing these innovations, policymakers and educators can foster drivers who are not only technically competent but also emotionally and cognitively prepared to navigate the complexities of modern traffic environments.

In sum, immersive virtual reality represents more than a technological enhancement; it is a transformative pedagogical medium that enables drivers to anticipate, adapt, and act with foresight — the psychological cornerstone of safer roads.

8. Limitations and Future Directions

Despite its contributions, the present study entails several limitations that warrant careful consideration. First, the relatively modest sample size (N = 80) and restricted demographic variability limit the extent to which the findings can be generalized to broader driving populations. Future replications with larger, more heterogeneous samples—including professional drivers, older adults, and individuals with varying driving experience—are necessary to enhance external validity.

Second, although the research design integrated objective behavioral metrics with validated psychometric instruments, certain constructs (e.g., emotional regulation and cognitive workload) were assessed through self-report measures. Such instruments, while reliable, remain inherently susceptible to subjective bias and introspective limits. The inclusion of psychophysiological indicators—such as heart rate variability, electroencephalographic activity, or galvanic skin response—would allow for a more precise and multimodal assessment of arousal regulation, stress reactivity, and attentional dynamics.

Third, the absence of longitudinal follow-up restricts conclusions regarding the durability and real-world transfer of the observed training effects. Without delayed post-tests or on-road validation, it is not possible to determine whether improvements in hazard anticipation persist over time or generalize to naturalistic driving contexts. Subsequent research should incorporate longitudinal designs, telematics-based monitoring, or standardized on-road evaluations to assess retention and ecological robustness.

An additional limitation relates to potential demand characteristics inherent in the intervention context. Because participants were aware of their assignment to either the VR or control condition, subjective responses (e.g., situational awareness, perceived control, workload) may have been influenced by expectancy, perceived innovation, or social desirability. Although objective performance indices were automatically recorded by the VR system, self-report data remain vulnerable to response tendencies that cannot be entirely ruled out.

Moreover, the fixed order of scenario presentation may have introduced practice or sequence effects. While identical ordering across measurement waves ensured procedural standardization and minimized differential bias between groups, within-session adaptation cannot be fully excluded. Future investigations could employ randomized or counterbalanced scenario sequences to further disentangle training-specific effects from potential order-related influences.

Closely related to these considerations are possible expectancy and Hawthorne effects. Participants' awareness of being involved in a training study—and their inability to be blinded to condition—may have enhanced motivation, effort allocation, or performance vigilance, particularly within the immersive VR context. Such influences may extend beyond self-report and potentially affect objective behavioral indicators (e.g., reaction time or hazard responses) through increased attentional engagement at post-test. Employing active control conditions matched for novelty and interactivity, as well as blinded behavioral coding where feasible, would help isolate intervention-specific mechanisms from expectancy-driven performance gains.

Future research should address these methodological considerations by integrating independent and unobtrusive assessment strategies, including eye-tracking indices, instructor-based external ratings, and physiological stress markers. Triangulating behavioral, subjective, and biological data would strengthen methodological rigor and mitigate expectancy-related influences.

Finally, subsequent work may explore adaptive VR systems capable of dynamically adjusting task difficulty based on real-time psychophysiological feedback, as well as comparative designs examining immersive VR alongside augmented reality or non-immersive simulation platforms to clarify modality-specific learning effects.

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