

Eyes on the Curve: Visual Constraints and Steering Accuracy in a VR Driving Simulator

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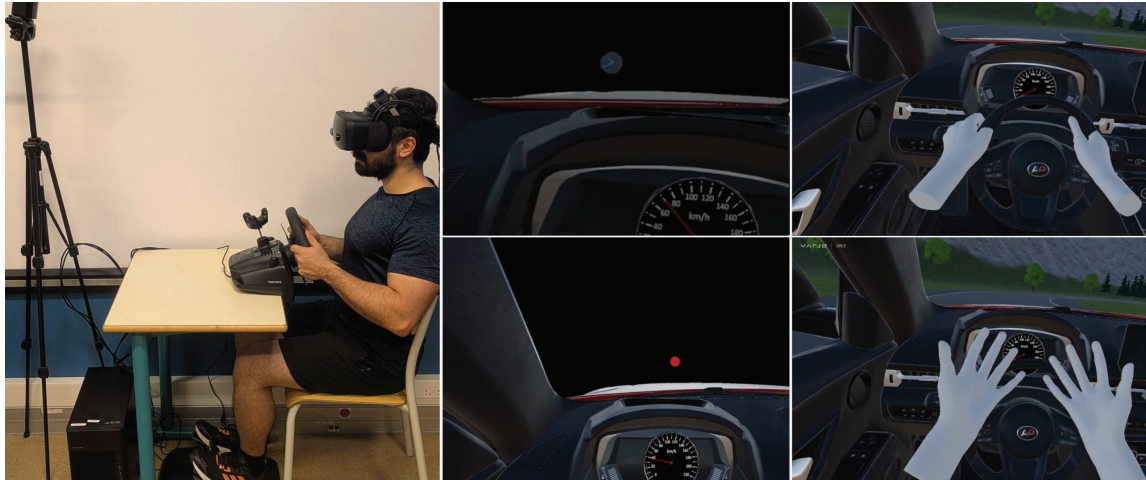


Figure 1: The experimental setup and the virtual environment under different visual conditions. Left: A participant using the VR-based driving simulator with an integrated steering wheel and pedal system. Right: In-simulation views from the driver's perspective showing (top to bottom) the circular viewing aperture in the zero offset condition, the red obstruction at the tangent point, and full visibility under normal (unrestricted) conditions. Hand models and cockpit environment provide realism and immersion during the task.

Abstract

Human vision is critical to safe driving, enabling drivers to track the curvature of the road, maintain lane position, and anticipate hazards. Although traditional driving studies have identified key gaze behaviors, the mechanisms by which visual field manipulations affect steering remain difficult to isolate in real-world settings. This study uses immersive VR to manipulate visual input and investigate its effects on steering and gaze behavior.

We introduce a depth-aligned aperture method allowing controlled manipulation of the visible field relative to road geometry. Twenty-eight participants drove through curved road segments in a VR simulator under seven conditions: normal vision, tangent point-aligned tunnel vision, misaligned offsets ($\pm 0.75^\circ$, $\pm 1.5^\circ$), and an occluded central reference. Integrated eye tracking and vehicle telemetry assessed lateral control, gaze distribution, variability, and pupil dilation as a proxy for mental workload.

The results show that restricting vision to a foveal region significantly impairs steering accuracy. Even when aligned with the tangent point, foveal information alone is insufficient to obtain accurate control, whereas misalignment induces systematic performance degradation. These findings provide causal evidence that visuomotor control in curve driving depends on the integration of multiple visual cues, including peripheral information.

More broadly, this work demonstrates how immersive VR can be used to causally investigate the visual information supporting complex visuomotor behavior.

CCS Concepts

• **Software and its engineering** → Virtual worlds training simulations; • **Human-centered computing** → User studies.

Keywords

Driving simulation, Visual attention, Steering behavior

ACM Reference Format:

Obaida Alrazouk, Hichem Arioui, and Amine Chellali. 2026. Eyes on the Curve: Visual Constraints and Steering Accuracy in a VR Driving Simulator. In *ACM Symposium on Applied Perception 2026 (SAP '26)*, August 26–27, 2026, Rennes, France. ACM, New York, NY, USA, 9 pages. <https://doi.org/10.1145/3821409.3821451>



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ACM ISBN 979-8-4007-2799-3/26/08

<https://doi.org/10.1145/3821409.3821451>

1 Introduction

Visually guided steering is a fundamental sensorimotor task in which drivers must continuously integrate visual information to control vehicle trajectory. When negotiating curves, this process requires precise coordination between gaze behavior and steering actions, allowing drivers to anticipate road geometry while maintaining stable lane position. Despite decades of research, the nature of visual information supporting this coordination remains debated.

A central theory in the literature is the *tangent point* (TP) model, which proposes that drivers use a geometrically defined point on the inner road edge to guide steering [Land and Lee 1994]. The visual angle to the TP provides information about road curvature, suggesting that steering can be anchored to a single visual cue. However, subsequent work has challenged this model, arguing that drivers instead rely on multiple sources of information, including the future path, the road edges, and the optic flow [Itkonen et al. 2015; Lappi 2014; Salvucci and Gray 2004].

Visually guided steering has also been described within an ecological framework, where control emerges from the continuous coupling between perception and action through optic flow and environmental structure [Fajen and Warren 2000; Warren 2006]. Within this perspective, gaze is flexibly distributed across the scene, supporting both anticipatory planning and online control. A key limitation in resolving this debate lies in the difficulty of experimentally isolating specific visual cues while preserving naturalistic viewing conditions. Previous studies have relied on fixation instructions, screen-based occlusions, or simplified visual environments [Gordon 1966; Kountouriotis et al. 2012; Mars 2008]. While informative, these approaches often disrupt normal gaze behavior or fail to respect the 3D structure of the scene, making it difficult to draw causal conclusions about the role of specific visual inputs.

In this work, we address this limitation by introducing a controlled manipulation of visual information in an immersive environment. Using a VR HMD with integrated eye tracking, we restrict the visible scene to a narrow (2°) experimental aperture positioned relative to the road geometry. This allows us to selectively isolate foveal information aligned with, or offset from, the TP, while preserving stereoscopic depth and natural head movements. Unlike previous visual field restriction paradigms, this approach enables a geometrically consistent, depth-aligned manipulation of the visible scene relative to the TP, allowing direct comparison between TP-centered and multi-cue accounts of visual guidance.

This design provides a strong causal test of competing models of visuomotor control. If steering can be supported by a single visual anchor, then performance should remain stable when the aperture is aligned with the TP. Conversely, if steering depends on integrating multiple visual cues, restricting vision to a narrow foveal region should degrade performance, even under optimal alignment. Furthermore, systematic offsets between the aperture and the TP allow us to examine whether misaligned visual input leads to predictable biases in steering behavior.

To investigate these questions, participants performed curve-driving tasks under seven visual conditions, including aligned, misaligned, and fully occluded views. We measured lateral control, gaze behavior, and pupil diameter as indicators of visuomotor coordination and task demands.

This paper makes three contributions. First, we introduce a depth-aligned experimental paradigm that enables controlled isolation of foveal visual information in immersive environments. Second, we provide a causal test of the TP's role in steering control. Third, we provide evidence that maintaining access to the TP alone is insufficient to preserve normal steering performance, supporting models that emphasize the integration of multiple visual cues beyond a single visual anchor.

2 Related Work

2.1 Visual control of steering

Steering is widely understood as a visually guided control process in which drivers use scene information to regulate heading and lane position. A dominant account is the TP model, which proposes that drivers rely on a geometrically defined point on the inner road edge to infer curvature [Land and Lee 1994]. The visual angle to the TP has been shown to correlate with steering behavior, suggesting that control could be anchored to a single cue.

However, this view has been increasingly challenged. Alternative approaches emphasize that steering relies on multiple sources of visual information, including the future path, road edges, and optic flow [Itkonen et al. 2015; Lappi 2014; Salvucci and Gray 2004]. In particular, two-point control models distinguish between near-road information for lateral stabilization and far-road information for anticipatory guidance [Salvucci and Gray 2004]. More recent theoretical work further argues that visuomotor control integrates feedback and feedforward processes across multiple cues rather than relying on a single geometric reference [Lappi and Mole 2018]. Empirical studies show that gaze is not consistently fixed on the TP but distributed across the scene according to task demands [Itkonen et al. 2015; Lappi 2022]. From an ecological perspective, steering has also been described as a continuous control process based on dynamically evolving visual information, such as optic flow and target-relative motion [Fajen and Warren 2003; Wilkie et al. 2008a]. These theories reinforce the idea that steering behavior emerges from the integration of multiple perceptual cues rather than a single fixation strategy.

2.2 Gaze behavior and visuomotor coupling

The relationship between gaze and steering has been extensively studied to understand how visual attention supports motor control. Early work suggested that gaze direction directly influences steering ("look where you want to go") [Wann and Swapp 2000], with fixations providing information about the intended trajectory. Experimental manipulations have shown that constraining gaze to specific locations can bias steering behavior, indicating a tight coupling between eye movements and motor output [Mars 2008; Robertshaw and Wilkie 2008].

At the same time, naturalistic studies report flexible gaze strategies, where drivers dynamically alternate between near-road and far-road regions rather than maintaining fixation on a single point [Itkonen et al. 2015; Lappi 2014]. This flexibility supports both anticipatory planning and online control. Recent work further suggests that steering may rely on multiple prospective targets or waypoints rather than a single visual anchor [Jansen and Fajen 2024], consistent with multi-cue models of visuomotor coordination.

2.3 Visual restriction as a probe of perceptual control

A common approach to studying the role of visual information in steering is to restrict or manipulate the available visual input. Occlusion paradigms have shown that limiting access to road edges or peripheral vision degrades steering performance and alters gaze behavior [Gordon 1966; Kountouriotis et al. 2012]. Drivers typically compensate by reallocating gaze toward remaining informative regions, although performance remains impaired.

More recent studies using gaze-contingent displays, simulated visual field loss, and functional field-of-view paradigms have demonstrated that restricting central or peripheral vision disrupts stable vehicle control, alters gaze behavior, and increases task demands [Biebl et al. 2022; Biswas and Admoni 2023; Gaspar et al. 2016; Glen et al. 2016; Vater et al. 2022]. In particular, Biebl et al. [Biebl et al. 2022] highlighted both the opportunities and limitations of gaze-contingent displays for studying driving behavior under restricted visual conditions, showing that such manipulations can substantially affect steering performance and visual strategies. Recent reviews further emphasize that peripheral vision plays a critical role in real-world visuomotor tasks by supporting spatial awareness, optic-flow processing, and movement guidance beyond the current point of fixation [Vater et al. 2022]. In addition, impairments in visual field availability, such as unilateral cortical blindness, lead to systematic steering biases and altered gaze strategies, reinforcing the importance of distributed visual information in steering control [Giguere et al. 2026]. This suggests that steering performance depends not only on foveal targets but also on the availability of peripheral and contextual information supporting optic-flow and road-geometry processing [Giguere et al. 2024].

Together, these studies highlight the importance of visual information for steering control, but several limitations remain. First, while multi-cue theories of steering are well established, most experimental paradigms do not allow precise isolation of individual visual contributions without disrupting natural behavior. Second, many existing methods rely on 2D or screen-based manipulations that alter the spatial structure of the scene, potentially biasing visuomotor strategies. While previous studies have established the importance of peripheral vision and visual field restrictions for driving performance, they do not directly manipulate the spatial relationship between the remaining visual information and steering-relevant scene geometry. As a result, the specific role of foveal information relative to scene geometry remains insufficiently understood. In this work, we address this gap by introducing a depth-aligned manipulation of visual input in immersive VR, enabling controlled isolation of foveal cues while preserving naturalistic visuomotor coupling during steering.

3 User study

3.1 Study Rationale and Objectives

Safe curve navigation relies on visually guided control, where drivers extract information from road geometry to regulate steering. While prior work has debated whether control depends on a single cue, such as the TP, or on integrating multiple visual sources, isolating the contribution of these cues remains challenging.

In this study, we use immersive VR with eye tracking to manipulate the spatial availability of visual information in a controlled manner. By restricting the visible scene to a depth-aligned aperture positioned relative to the TP, we directly investigate how the location and availability of visual cues affect steering behavior, gaze allocation, and mental effort.

To approximate foveal vision, the visible scene was restricted to a 2° circular aperture, thereby suppressing peripheral information, such as optic flow and contextual cues. Seven visual conditions were tested: five horizontal offsets relative to the TP (-1.5° , -0.75° , 0° , $+0.75^\circ$, $+1.5^\circ$), one opaque TP-centered condition removing scene information, and a normal-vision baseline. These manipulations allow us to dissociate the effects of gaze anchoring, spatial alignment, and visual context on steering control.

Road curvature (shallow vs. sharp) and direction (left vs. right) were varied to assess how visual constraints interact with task demands. Together, these conditions enable us to evaluate the relative contribution of foveal TP-based information and broader visual cues in visuomotor coordination.

In addition, we assess subjective simulator discomfort to evaluate the tolerability of immersive VR for perceptual driving studies.

The study addresses the following research questions:

- (1) How do visual offset conditions affect lane-keeping and steering behavior?
- (2) How do they influence gaze patterns and pupil-based indicators of mental effort?
- (3) How does simulator-induced discomfort vary across individuals?

Based on competing accounts of visual guidance in steering, we formulate the following hypotheses for our study:

- **H1.** Restricting visual input to a narrow foveal region centered on the TP will degrade lane-keeping performance compared to normal vision, reflecting the loss of peripheral and contextual information.
- **H2.** Misalignment between the foveal aperture and the TP will induce systematic steering errors, with larger offsets leading to greater deviations from the lane center.
- **H3.** Visual restriction will reduce gaze variability, reflecting constrained visual exploration, and increase pupil diameter as an index of elevated perceptual and cognitive demands.

3.2 Participants

Twenty-eight licensed drivers participated in the study (4 female, 24 male; mean age = 36.07 ± 12.79 years, range = 22–60). They were recruited among students, university staff, and external participants. Driving experience ranged from 1 to 42 years (15.93 ± 13.64 years). In terms of driving frequency, 16 participants reported driving every day, 6 drove once a week, 5 drove once a month, and 1 participant drove every other day. The study was approved by the local ethics committee, and all participants provided informed consent.

3.3 Apparatus

Participants used a Varjo VR-3 HMD to experience the virtual driving environment (Figure 1). The HMD provides a wide field of view (a horizontal FoV of approximately 115 degrees and a vertical FoV

of 96 degrees). Operating at a 90 Hz refresh rate, the HMD minimizes motion blur and latency, which are essential for naturalistic visuomotor tasks. It includes integrated eye-tracking at 200 Hz with sub-degree precision and automatic interpupillary distance adjustment (59–71 mm), enabling both accurate gaze measurement.

Driving input was performed using a G923 force-feedback steering wheel and pedal set (Logitech). A Vive Tracker was mounted on the steering wheel to track its position and orientation, allowing real-time co-localization with the virtual steering wheel. Steering rotation was mapped one-to-one between the physical and virtual wheel, ensuring consistent visuomotor correspondence (Figure 1).

The virtual environment was developed using Unity 2019, with RoadArchitect for Unity¹, enabling the creation of customized driving scenarios and integration with hardware components. The simulation included 28 curved road segments.

3.4 Experimental conditions and design

In all aperture conditions (Figure 2), visual information was restricted to a 2°-diameter circular window positioned relative to the road's TP. At each frame, the horizontal angular position of the TP, denoted $\theta_{TP}(t)$, was used to define the aperture center as:

$$\theta_{ap}(t) = \theta_{TP}(t) + \Delta,$$

where $\Delta \in \{-1.5^\circ, -0.75^\circ, 0^\circ, +0.75^\circ, +1.5^\circ\}$ represents a fixed horizontal offset. Positive offsets ($\Delta > 0$) correspond to positions toward the inside of the curve (mirrored for left/right turns), while negative offsets correspond to the outside.

The aperture was stabilized relative to the TP and updated at each frame. Importantly, it was *gaze-independent*, ensuring that the manipulation affected the spatial availability of visual information rather than eye movements.

In addition to the offset conditions, a “red point” condition presented a 2° opaque disc centered on the TP, removing all scene information while preserving a fixation anchor. A normal vision condition without occlusion served as a baseline.

The study followed a within-subjects design with three factors: visual condition (7 levels: five offsets, red point, normal vision), curvature (2 levels: sharp/shallow), and direction (2 levels: left/right). Each participant completed 28 trials, corresponding to all combinations of these factors. Trial order was counterbalanced using a Latin square to mitigate order effects.

Participants were instructed to drive naturally using the steering wheel and pedals. No explicit speed constraint was imposed in order to preserve natural visuomotor behavior, consistent with prior work on visually guided steering [Fajen and Warren 2003; Land and Lee 1994; Wilkie et al. 2008b]. Each trial ended automatically at the end of the curve segment.

3.5 Experimental procedure

Participants first provided informed consent and completed demographic, motion sickness susceptibility (VIMSSQ), and baseline VR sickness (VRSQ) questionnaires. They then received task instructions, were equipped with the HMD, underwent eye-tracking calibration, and performed a short familiarization drive.

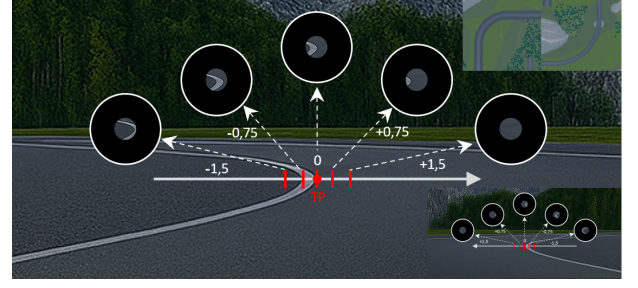


Figure 2: Visualization of TP and horizontal offsets on a left-hand curve, with 0° aligned to the TP and positive offsets directed inside the curve. Insets show top views of both curves (top right) and a mirrored right-hand curve offset axis (bottom right).

Participants subsequently completed the main experiment consisting of the 28 trials. After the experiment, they completed the VRSQ again to assess simulator-induced discomfort. The entire session lasted approximately 30 minutes.

3.6 Data Collection and Analysis

Objective data on eye movements, steering inputs, and vehicle dynamics were recorded throughout the experiment. In addition, subjective measures of simulator sickness were collected using standardized questionnaires.

3.6.1 Subjective Measures. Motion sickness susceptibility was assessed prior to the experiment using the **Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ)** [Keshavarz and Hecht 2011]. Simulator-induced symptoms were measured using the **Virtual Reality Sickness Questionnaire (VRSQ)** [Kim et al. 2018], administered before and after the experiment. Changes in VRSQ scores were used to quantify VR-induced discomfort.

3.6.2 Objective Measures.

Driving performance. Lane-keeping behavior was quantified using the mean lateral distance from the lane center, a standard measure of tracking accuracy in curve driving, and its standard deviation, reflecting the stability of lateral control over time. Steering behavior was assessed using the standard deviation of the steering angle, capturing variability in control inputs and the extent of ongoing steering corrections required to maintain the trajectory. The mean steering angle was not analyzed, as it is primarily determined by road geometry rather than by visuomotor control processes.

Eye behavior. Visual guidance was characterized using two complementary metrics grounded in established models of gaze-based steering control [Land and Lee 1994; Lappi and Mole 2018; Salvucci and Gray 2004]. First, the root-mean-square error (RMSE) between gaze direction and the TP quantified the alignment of gaze with a task-relevant reference for curve negotiation. Second, the standard deviation of gaze angle captured the spatial dispersion of gaze, reflecting the extent of visual exploration beyond the TP.

Mental effort. Cognitive demand was estimated using pupil diameter, a widely used physiological proxy for mental workload [Beatty

¹<https://github.com/MicroGSD/RoadArchitect>

1982; Palinko and Kun 2012; Radhakrishnan et al. 2023]. Mean pupil diameter reflected overall workload, while its standard deviation captured temporal fluctuations in cognitive effort. Because pupil size is strongly influenced by luminance, comparisons involving the normal vision condition were excluded from workload-related interpretation.

3.6.3 Statistical Analysis. Statistical analyses were conducted using repeated-measures ANOVA with factors offset condition, curvature, and direction. Normality and sphericity assumptions were assessed using Shapiro–Wilk and Mauchly’s tests, respectively. Greenhouse–Geisser corrections were applied when necessary, and post hoc comparisons were adjusted using Bonferroni corrections. A significance level of $\alpha = 0.05$ was adopted.

4 Results

4.1 Subjective Evaluation

The results provide an overview of participants’ baseline susceptibility and the evolution of simulator-related symptoms during the experiment.

4.1.1 Visually Induced Motion Sickness Susceptibility. As shown in Figure 3, VIMSSQ scores were predominantly low, indicating generally low susceptibility to visually induced motion sickness across participants. Responses were recorded to a 0–3 scale, summed (0–33), and expressed as percentages. The distribution was right-skewed, with most participants scoring near zero, while a small subset exhibited higher susceptibility levels exceeding 40%.

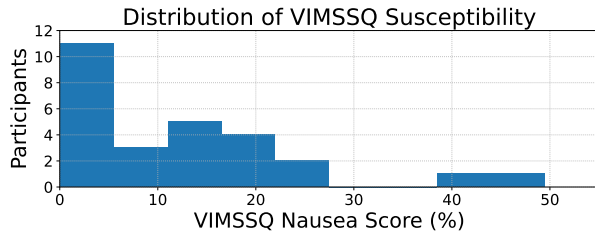


Figure 3: Histogram of VIMSSQ nausea susceptibility

4.1.2 Virtual Reality Sickness Questionnaire. As illustrated in Figure 4, VRSQ scores increased from baseline to post-test. Paired-sample t -tests revealed significant increases in *Oculomotor* ($t(27) = 2.21, p = .035$), *Disorientation* ($t(27) = 3.32, p = .003$), and *Total* scores ($t(27) = 4.11, p < .001$), indicating a measurable increase in simulator-related symptoms following the VR driving task.

4.1.3 Trait–state relationship. As shown in Figure 5, a Spearman test revealed a significant positive correlation between VIMSSQ scores and the increase in VRSQ total score ($\rho = .48, p = .009$). Participants with higher baseline susceptibility tended to exhibit larger increases in simulator sickness symptoms.

4.2 Driving Performance Metrics

Driving performance metrics capture complementary aspects of vehicle control, including lane-keeping accuracy, stability, and steering variability. Results are reported with respect to the experimental

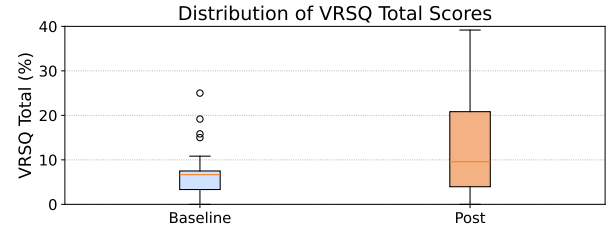


Figure 4: Box-and-whisker plot of VRSQ total scores

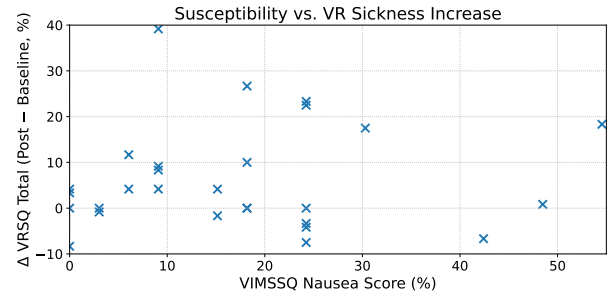


Figure 5: Relationship between VIMSSQ susceptibility and change in VRSQ total score

factors of visual offset, road curvature, and direction. Figures highlight the most relevant effects for each metric.

4.2.1 Mean Lateral Distance. As shown in Figure 6a, lane-keeping performance varied across visual conditions, with the normal vision condition yielding the lowest lateral deviation.

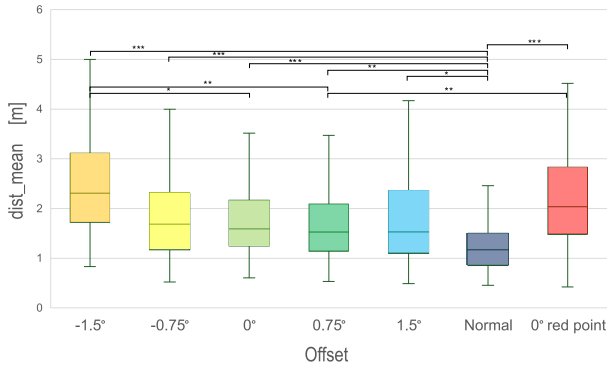
A significant main effect of the offset condition was observed ($F_{(6,162)} = 13.85, p < .001, \eta^2 = .339$), whereas neither direction nor curvature showed significant effects. A significant Offset $\times$ Direction interaction was found ($F_{(6,162)} = 2.87, p = .011, \eta^2 = .096$), with no other interactions reaching significance.

Pairwise comparisons indicated that the normal condition (1.27m) significantly outperformed misaligned conditions such as -1.5° (2.68m) and the 0° red condition (2.28m). The aligned 0° aperture condition (1.82m) also showed higher deviation than normal vision. Larger errors were generally observed for negative offsets.

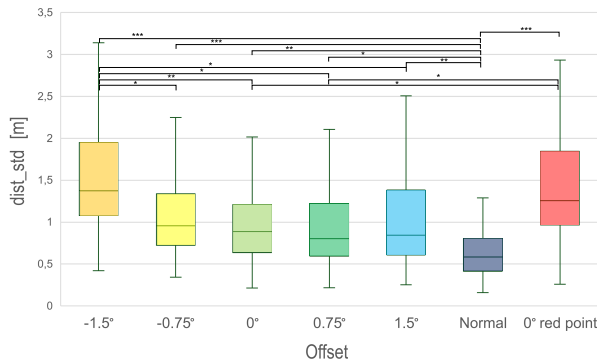
4.2.2 Standard Deviation of Lateral Distance. As shown in Figure 6b, lateral variability followed a similar pattern, with the normal condition yielding the most stable performance.

A significant main effect of the offset condition was observed ($F_{(6,162)} = 15.42, p < .001, \eta^2 = .364$), with no significant effects of direction, curvature, or interactions. The normal condition showed the lowest variability (0.675m), whereas the -1.5° condition yielded the highest (1.75m). All offset conditions significantly exceeded the normal baseline.

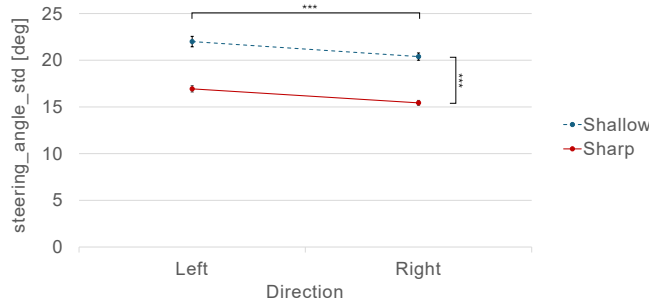
4.2.3 Standard Deviation of Steering Angle. As shown in Figure 6c, steering variability was primarily driven by road geometry. No main effect of offset was found ($F_{(6,162)} = 0.83, p = .545$), whereas significant effects of direction ($F_{(1,27)} = 20.37, p < .001, \eta^2 = .430$)



(a) Mean lateral distance (m) across all visual conditions.



(b) Standard deviation of lateral distance (m).



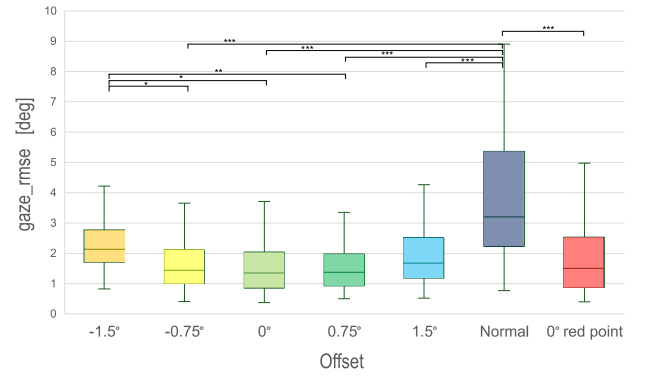
(c) Standard deviation of steering angle (deg).

Figure 6: Performance metrics across visual offset conditions. (*: $p < 0.05$, **: $p < 0.005$, ***: $p \leq 0.001$)

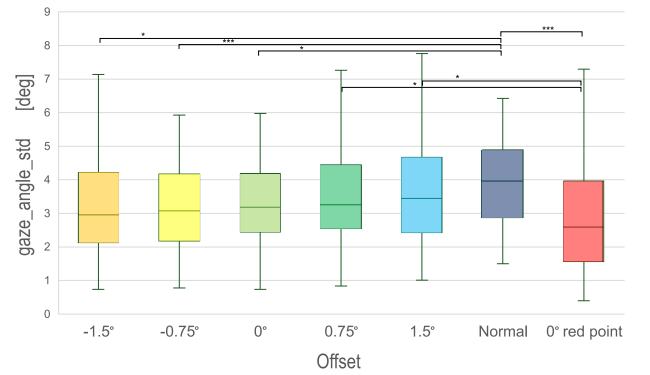
and curvature ($F_{(1,27)} = 134.56, p < .001, \eta^2 = .833$) were observed. No interactions reached significance.

4.3 Eye Behavior Metrics

4.3.1 Root-Mean-Squared Gaze Error. Gaze RMSE was significantly affected by offset ($F_{(6,162)} = 20.68, p < .001, \eta^2 = .434$), with additional effects of direction and curvature, and an Offset $\times$ Curvature interaction ($F_{(6,162)} = 2.34, p = .034$). The normal condition yielded



(a) Gaze RMSE from the tangent point (deg).



(b) Standard deviation of gaze angle (deg).

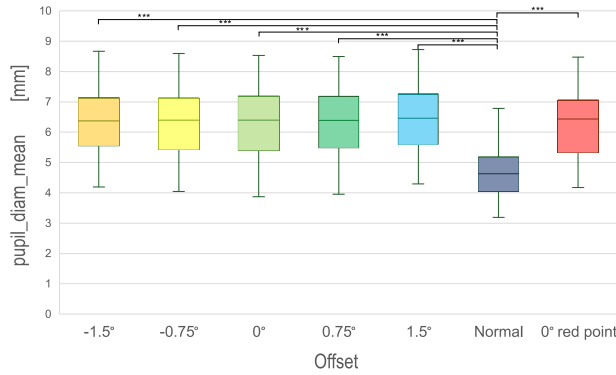
Figure 7: Eye behavior metrics across visual offset conditions. (*: $p < 0.05$, **: $p < 0.005$, ***: $p \leq 0.001$)

the highest RMSE (4.62°), whereas constrained conditions showed lower values (Figure 7a), likely due to restricted gaze dispersion within the aperture rather than improved accuracy.

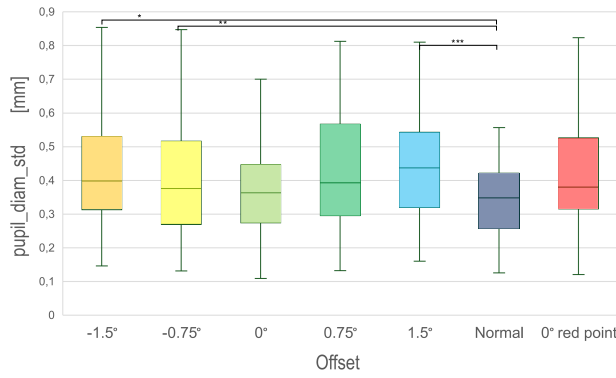
4.3.2 Standard Deviation of Gaze Angle. Gaze variability showed significant effects of offset ($F_{(6,162)} = 9.31, p < .001$) and curvature ($F_{(1,27)} = 10.76, p = .003$), with a significant three-way interaction. Variability was highest in the normal condition (3.98°) and reduced under constrained conditions (Figure 7b), indicating more localized gaze behavior.

4.4 Mental Effort Metrics

4.4.1 Mean Pupil Diameter. Mean pupil diameter showed significant effects of offset ($F_{(6,162)} = 103.80, p < .001, \eta^2 = .794$) and direction ($F_{(1,27)} = 127.41, p < .001, \eta^2 = .825$), with larger values in constrained conditions (6.3–6.5mm) than in normal vision (4.75mm) (Figure 8a). However, as pupil size is strongly affected by luminance, this difference cannot be attributed solely to cognitive workload, and the normal condition was excluded from workload comparisons. No differences were observed across equal-luminance offsets. Pupil diameter was higher for left than right bends.



(a) Mean pupil diameter (mm).



(b) Standard deviation of pupil diameter (mm).

Figure 8: Mental effort metrics across visual offset conditions.
 (*: $p < 0.05$, **: $p < 0.005$, ***: $p \leq 0.001$)

4.4.2 Standard Deviation of Pupil Diameter. The pupil variability showed significant main effects of offset ($F_{(6,162)} = 3.28, p = .005, \eta^2 = .108$), direction ($F_{(1,27)} = 13.68, p = .001, \eta^2 = .336$), and curvature ($F_{(1,27)} = 14.51, p = .001, \eta^2 = .350$), with a Direction $\times$ Curvature interaction ($F_{(1,27)} = 30.79, p < .001, \eta^2 = .533$). Variability increased under constrained conditions (Figure 8b), although interpretation remains limited by luminance effects.

Overall, the results show that restricting visual input to a narrow foveal region impairs lane-keeping performance, even when aligned with the TP, while leaving steering variability largely determined by road geometry. These effects are accompanied by systematic changes in gaze behavior and pupil responses.

5 Discussion

This study investigated how restricting visual input to a foveal region affects visuomotor control during curve driving. By systematically manipulating the spatial alignment between a gaze-contingent aperture and the TP, we provide a controlled test of competing models of visual guidance in steering.

Overall, the results provide support for the proposed hypotheses, as discussed below.

5.1 Effect of Offset vs Normal and Zero-Offset Conditions

The superior performance observed under normal vision highlights that visuomotor control in curve driving critically depends on the availability of distributed visual information rather than on a single focal cue. Even when foveal information was optimally aligned with the TP (zero-offset condition), performance remained significantly degraded compared to the full-vision condition.

This finding provides direct experimental evidence against strong interpretations of the TP model, suggesting that foveal access to this cue alone is insufficient to sustain accurate steering. Instead, the results support multi-cue accounts in which peripheral vision and optic flow contribute essential information for continuous trajectory regulation. Importantly, this result extends prior observational studies by directly manipulating the available visual information. By restricting the field of view, we demonstrate that limiting visual information fundamentally alters control strategies, rather than merely modifying gaze behavior.

These findings support H1, confirming that restricting visual input to a narrow foveal region degrades lane-keeping performance. The results indicate that peripheral and contextual information are essential for accurate visuomotor control.

5.2 Red Circle Condition and Gaze Avoidance

The red-opaque condition provides a particularly strong test of the “look where you want to go” principle. Despite offering a stable fixation anchor at the TP, performance deteriorated substantially, and participants actively avoided sustained fixation on the target.

This finding suggests that gaze direction alone does not provide sufficient information for steering control in the absence of supporting visual context. Instead, drivers appear to rely on richer perceptual cues, such as motion information, road edges, and spatial layout, which are absent in this condition.

The observed gaze avoidance further indicates that drivers prioritize visually informative regions over geometrically relevant but perceptually impoverished cues. This behavior aligns with prior work showing that gaze is guided by the informativeness of visual regions rather than by fixed task-defined anchors [Itkonen et al. 2015; Lappi et al. 2013]. This behavior is consistent with H3, suggesting that visual restriction constrains gaze strategies and reduces effective visual exploration, even when a geometrically relevant fixation target is available.

5.3 Negative Offsets

The degradation observed under negative offset conditions highlights a functional dissociation between anticipatory and online control processes in steering. While shifting the aperture toward the future path may provide predictive information about upcoming curvature, it removes access to near-field cues necessary for fine-grained lateral adjustments.

This supports two-point and multi-cue models of steering, in which far-road information contributes to planning, but near-road information is essential for continuous error correction [Salvucci and Gray 2004]. Our findings extend this framework by showing that isolating predictive information alone is insufficient for stable control. Such multi-scale integration of visual information has been

emphasized in dynamical models of steering, where different spatial cues contribute to both anticipatory planning and online control [Fajen et al. 2003].

Overall, these results suggest that effective steering emerges from the integration of complementary visual cues operating at different spatial scales, rather than from reliance on a single visually salient point. These results support H2, showing that spatial misalignment between available visual information and task-relevant geometry leads to systematic steering errors. The magnitude of performance degradation further suggests that precise spatial alignment is critical for effective visuomotor coordination.

5.4 Pupil Diameter as an Index of Mental Load

The increase in pupil diameter observed under visually constrained conditions suggests elevated perceptual and cognitive demands when visual information is restricted. Interpretations of pupil diameter should nevertheless be made cautiously due to luminance-related effects, as discussed in the limitations section.

These results are consistent with the view that uncertainty in visual input increases cognitive load, requiring greater attentional resources to maintain stable control. In the context of steering, this likely reflects increased effort in integrating incomplete or spatially constrained cues to estimate trajectory and position. The absence of significant differences between offset conditions further suggests that the presence of visual constraint itself, rather than its precise spatial configuration, is sufficient to increase workload. This finding further supports H3, indicating that restricting visual input increases perceptual and cognitive demands, as reflected in pupil dilation.

5.5 Direction, Curvature, and Steering Angle

The limited influence of visual offset on steering variability, contrasted with the strong effects of curvature and direction, suggests that drivers preserved a global steering strategy adapted to road geometry even under degraded visual conditions.

This dissociation indicates that while visual constraints impair positional accuracy, they do not fundamentally disrupt the ability to generate appropriate steering magnitudes. Instead, visual information appears to play a more critical role in fine-tuning trajectory control than in determining overall steering behavior. Such findings are consistent with hierarchical models of visuomotor control, where global trajectory planning and local error correction rely on partially dissociable processes.

5.6 Design Implications and Applications

Beyond theoretical implications, these findings inform the design of visual interfaces in driving and immersive environments. The results highlight that effective visual guidance cannot rely on isolated focal cues but must preserve access to distributed visual information supporting perceptual-motor coordination. In particular, visual overlays or assistance systems that occlude or spatially misalign critical regions of the visual field may inadvertently disrupt natural control strategies. Conversely, designs that maintain peripheral awareness and respect the spatial structure of visual information are more likely to align with human perceptual capabilities.

More broadly, these findings align with ecological approaches to perception, which emphasize that behavior is guided by information distributed in the environment rather than by isolated visual features [Warren 2021].

5.7 Limitations and Future Work

The participant sample was relatively small, predominantly male, and characterized by substantial variability in driving experience. Although the within-subject design reduces inter-individual variability, future studies should examine how demographic factors and driving expertise influence visual guidance strategies.

In addition, the narrow (2°) aperture was intentionally designed to isolate foveal information and does not reflect natural driving conditions. While this manipulation provides strong experimental control, it also removes parafoveal information known to contribute to curvature perception and optic-flow processing. Future work should investigate a broader range of aperture sizes and levels of visual restriction.

Finally, pupil-diameter results should be interpreted cautiously because of luminance-related effects. More generally, extending the paradigm to more complex driving environments would help assess the generalizability of the present findings.

6 Conclusion

This paper investigated how restricting visual input to a narrow foveal region affects visuomotor control during curve driving. By systematically manipulating the spatial alignment between restricted visual information and the tangent point in an immersive driving simulator, we provided a controlled test of competing theories of visual guidance.

Our results demonstrate that foveal information centered on the tangent point is insufficient to obtain accurate steering. Even under optimal alignment, performance remained significantly degraded compared to the full-vision condition, highlighting the critical role of peripheral vision and distributed visual cues. These findings challenge strong interpretations of the tangent point model and instead support multi-cue accounts in which visuomotor control emerges from the integration of information across the visual field.

Finally, the observed behavioral adaptations and increased pupil responses indicate that restricting visual input imposes additional perceptual and cognitive demands. This suggests that drivers rely not only on geometrically relevant features, but also on the richness and structure of visual information to maintain stable control.

More broadly, this work illustrates how controlled visual manipulations in immersive environments can be used to isolate and test fundamental mechanisms of perception and action. By providing causal evidence on the role of foveal and peripheral vision in steering, our study contributes to a deeper understanding of visuomotor coordination in dynamic tasks.

Acknowledgments

The authors wish to thank all volunteers who participated in the study. This work has partially been supported by a grant from the French National Research Agency (ANR-22-CE22-0012).

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