Double Master's Degree in Cognitive Neuroscience and Clinical Neuropsychology (UNIPD) and Neurociencia Cognitiva y del Comporamiento (UGR)

Master Thesis

The Effects of Active Luminous Road Markings Solutions on Simulated Driving Performance: an Experimental Study

Main Author

Gaia Giarrizzo

Thesis Advisors:

Leandro Luigi Di Stasi

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ABSTRACT

Driving at night or in hazardous weather could be risky if artificial lighting is inadequate or insufficient, especially when engaging curves. Innovative solutions, like Active Luminous Road Markings (ALRMs), might assist drivers and improve road safety. However, international road regulations lack consistent guidelines for ALRMs' lighting colors and designs. We assessed different ALRMs solutions on 27 young adult drivers negotiating curves in simulated scenarios. We manipulated ALRMs appearance (color: green, red, and unlit), size (width: conventional and wide), and road geometry (curve direction: left and right and radius: 120m and 440m). After the driving simulation, participants completed a video-based perception task rating their perceived levels of risk, speed estimation, valence and arousal. The lateral position was significantly affected by ALRMs features, resulting in changes in the driving trajectory toward the right side of the vehicle's lane in response to color, width, and curve radius. Green ALRMs showed higher variability for vehicle position, indicating reduced vehicle control. Curve radii also affected driving behavior, with narrower curves leading to reduced speeds. Subjective measures revealed that green ALRMs were perceived as brighter but less comfortable. Furthermore, curve radius significantly influenced arousal and speed estimates, with narrower curves eliciting lower activation and slower speed perception. Our study might offer valuable information that transportation engineers, road designers, and transportation psychologists can use to implement smart road technologies and improve road safety when designing new traffic lighting solutions.

INTRODUCTION

Road safety is a major issue in our society, especially as roadways become increasingly congested with vehicles, users, and pedestrians (Barodi et al., 2021). It relies on the dynamic interplay among three fundamental factors: the characteristics of the vehicle, the human factor, and the intricate road infrastructure (Babić et al., 2022). Therefore, to enhance road safety, increasing attention is paid to implementing new international safety standards (e.g., Euro-NCAP), formulating innovative driving regulations (e.g., point-based driving license system), and improving road infrastructures (e.g., smart roads). The latter being the topic of the study presented here.

Safe driving encompasses a broad spectrum of visual, manual, and cognitive resources for drivers due to the dynamic and complex nature of the road environment (Babić et al., 2022; Di Stasi et al., 2022). One crucial aspect of safe driving is the ability to scan the road effectively, which means being attentive to one's surroundings, identifying potential hazards, and reacting appropriately. Distractions, fatigue, and reduced visual guidance contribute significantly to traffic accidents (Lee, 2008; Mosböck & Burghardt, 2016). This is particularly true during nighttime when road fatalities and road crashes are reported to be significantly higher and more severe than in daytime (Plainis, 2006; Goswamy et al., 2018), or in sub-rural areas where insufficient lighting environment, dust, and debris are present (Mosböck et al., 2018). In this sense, road infrastructure plays an essential role, with road markings serving as a crucial, even if yet frequently underestimated, component to improve driving safety. In fact, road markings and road signs are indispensable tools for conveying essential information to drivers, improving optical guidance (using lines, text, and symbols), regulating traffic flow, and indicating restrictions (Mosböck & Burghardt, 2016). These markings are meticulously designed, each with unique features, such as shape, width, and colors (Babić et al., 2022).

Road markings can be considered as the minimum required for visual guidance (Babić et al., 2020; Babić et al., 2022) as one of the most basic, low-cost, and common safety measures used in road safety strategies. Since 1911, when the initial use of road markings was documented along the Trenton River Road in Michigan (Babić et al., 2020), road markings have evolved over the years to meet the functional and environmental prerequisites for traffic management (Lin et al., 2023). Traditional road markings rely on headlamp retroreflection to be seen at night, but factors such as water or dirt can reduce the luminance and the distance from which the road marking can be seen (Boyce, 2008), leading to tun-off-the-road accidents (Park et al., 2021). To address these challenges, the use of new technologies has begun to be explored (Anders, 1995; Siegel, 2001; Zhu et al., 2019).

One of the potential solutions examined in this study is to implement Active Luminous Road Markings to improve the shape and color as distinguishing features between the road markings. They are installations on the road, with which drivers can interact passively and that promote appropriate road users' behavior and awareness (Angioi et al., 2023). Active Luminous Road Markings are primarily comprised of two classifications: photoluminescence road markings (PRMs) and electric luminous road markings (ELRMs). PRMs are made of phosphorescent material; the luminous time can last from nanoseconds to ten hours, and they do not have an effect on the original road structure after being implemented; on the other hand, ELRMs use lamps such as LEDs or gas discharge lamps to maintain a stable and persistent light output. However, this solution requires changes to the original road structure, resulting in a higher cost of implementation and maintenance, and significantly higher energy consumption (Lin et al. 2023, Figure 1).

a)

b)

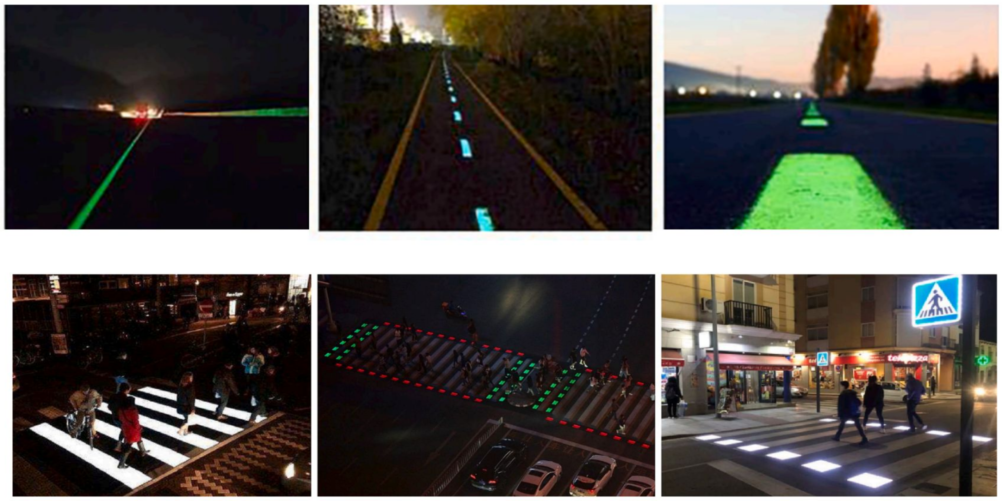

Figure 1 *Application cases of ALRMs. a) PRMs application in South Korea and Hungary. b) ELRMs application in China and Spain (Lin et al., 2023).*

Active Luminous Road Markings based on photoluminescence

In the present study, we designed and implemented –through a controlled driving simulation–, PRMs (hereafter, referred to just as ALRMs), which exploit photoluminescence. This phenomenon occurs when a substance absorbs energy through high-energy radiation (such as ultraviolet rays, β-rays, etc.) resulting in luminescence (Lin et al., 2023; Blasse, 1989). The self-luminous traits of PRMs are achieved primarily through the incorporation of luminescent substances, thereby creating a favorable visual environment for individuals in traffic due to their self-illumination (Park et al., 2014; Yi et al., 2016). In places with limited access to electricity, such as rural or suburban roads, ALRMs can emit light independently without electric rely on electricity, leading to advantages like lower carbon emissions and environmental protection (Lee et al., 2017; Lin et al., 2023).

As already mentioned, the crucial role of lighting within the context of driving encompasses its fundamental purpose: facilitating the transmission of information, whether through direct or indirect means. To effectively achieve this, the foremost prerequisite is the visibility of the conveyed information, intrinsically linked to the illuminance received by the human eye (Boyce, 2008). The concept of luminance assumes a central role in understanding the emission of light from a stimulus; however, it does not fully account for the role of the different wavelengths' composition in the perceived color.

Curiously, instances arise where a stimulus, despite possessing negligible illuminance contrast, remains discernible owing to its divergence in color from the background, as highlighted by Eklund (1999).

The influence of lighting becomes even more pronounced when considering light sources with varying spectral content. The spectral composition of the lighting source can notably modify the color distinction between the stimulus and the background, further underscoring the multifaceted role of lighting in shaping perceptual dynamics (Boyce, 2008). The most significant alteration in night vision occurs when luminance levels decrease to 3-5cd/m^2 or lower. During this phase, retinal cone cells become less sensitive, while retinal rod cells start to influence visual signals (Wanar & Mantiuk, 2014). This phenomenon, known as mesopic vision, leads to a gradual decline in both visual clarity and color recognition (Wanar & Mantiuk, 2014).

However, despite the complexity and importance of the driver's perceptual system in road contexts, the effect of color and its influence on driving behavior remain understudied (Portera et al., 2023; Llewellyn et al., 2021; Zhu et al., 2021; Díaz-Román, et al., 2015). Notably, color plays an important role in influencing individuals' comfort experiences and their understanding of environmental conditions. It can also guide behavior and cognition by impacting psychophysiological states, as investigated in existing research (Calvi, 2018; Jalil et al., 2012), as well as grab people’s attention, convey information, and exert persuasive influence (Ou et al., 2004). In this study, ALRMs colors were chosen based on their traditional use in road environments (Chiu & Lin, 2005; Autelitano & Giuliani, 2021). Specifically, red, green, and unlit (white) were selected. Red is the color with the longest wavelength in the visible spectrum and can be seen from a greater distance without losing a significant amount of intensity. It is the least scattered by fog, cloudy weather, and translucent situations. Red is also used as a symbol of danger in various contexts, such as traffic signals and signs (Pravossoudovitch et al., 2014), and appears to convey impulsiveness, speed, and danger (Zedda et al., 2013; Díaz-Román et al., 2015).

On the other hand, green’s high sensitivity makes it valuable to be used to convey safety-related information, reducing the likelihood of accidents when placed on green-colored hazard signs compared to other colors (Sheikholeslami et al., 2020). In road environment, it is usually used to indicate ‘go’ signals and appears to be associated with restoration from mental fatigue, stress, and negative moods when driving in natural environments (Kaplan & Kaplan, 1989; Ulrich et al., 1991). The crucial role of these colors in nighttime vision has also been taken into account, aiming to potentially enhance safe driving by ensuring better and appropriate nighttime color vision. Green and red are preferred to bright white lights at night due to their physical characteristics (Wanar & Mantiuk, 2014). These colors find applications in various contexts. For instance, green lights are extensively employed in night-vision devices, as they are regarded as the most comfortable color for prolonged viewing in low-light situations (Chrzanowsky, 2013). Conversely, red light, associated with the longest wavelengths, is commonly used in several transportation domains to ensure optimal visibility of critical information, thereby minimizing confusion and conveying essential actions (Rash & Manning, 2003).

AIMS OF PRESENT RESEARCH

This research aimed to enhance our understanding of the effects associated with the incorporation of ALRMs in future road designs. We focused on examining the effects of ALRMs colors (red, green, and unlit), as well as their widths (conventional vs. wide), on both driver performance and subjective perceptions. Furthermore, we investigated the curve directions (left and right), as well as their radii (120m and 440m), as road features that could play a role in modulating drivers' behavior. To create a controlled and safe environment for manipulating these variables while simulating realistic driving conditions, we adopted a simulator-based approach (recognized for its effectiveness by Moroney & Lilienthal, 2008). The use of driving simulations not only allows us to explore intricate driving dynamics but also facilitates the examination of psychological metrics that could be expensive or risky to study in more naturalistic settings. Participants completed two experimental tasks: (1) the driving simulation, which aimed to evaluate driving performance and the subjective perception of the task, and (ii) the video-based perception task, which investigated the effects of ALRMs on arousal and valence levels, as well as perceived risk levels and estimated speed values.

Hypothesis and Expected Results

We hypnotized that the ALRMs colored road markings will contribute to an overall enhancement of road safety compared to conventional unlit road markings, supporting driver's vision in low-visibility traffic scenarios and by making the horizontal markings visible beyond the vehicle headlight beams (Angioi et al., 2023). In particular, the use of green color will positively influence the driver's perception of brightness, driving comfort, and feeling of safety in night driving. Furthermore, we anticipate that these subjective responses would affect drivers' performance in terms of both longitudinal and transverse vehicle control, speed, and stability. Finally, we posit that risk perception, emotional responses such as pleasantness, and levels of arousal, as well as speed estimation, will align with the established psychological association between green and a feeling of comfort and relaxation.

MATERIAL AND METHODS

1.1 Ethical approval

The present study was conducted in accordance with the Granada Research Ethics Committee Code (CEI / CEIM) and was approved by the Institutional Review Board of the University of Granada (IRB approval 1528/CEIH/2020). Written informed consent was obtained from all participants prior to the study.

1.2 Participants

Thirty-five active young adult drivers participated in the study. Power calculations were not performed due to the lack of applicable pilot data. This sample group included drivers aged 21 to 54 years, with an average age of 26 years old (standard deviation [SD] = 6.71).

All participants had normal or corrected-to-normal vision and possessed a valid 'B' driving license for a minimum of 12 months. Their driving experience ranged from 1 to 300 months with an average of 5.2 years. Their mean annual mileage was 5000 km/year, and the reported percentage of night driving was less than 25% in a year. Before the experimental session, participants were asked to abstain from consuming alcoholic beverages within the preceding 12 hours (as detailed in the Section 1.7). Furthermore, all participants exhibited an adequate level of alertness before the driving session, as indicated by a score below 3 on the Stanford Sleepiness Scale (SSS) (Connor et al., 2002; Diaz-Piedra et al., 2019; Hoddes et al., 1972), thus confirming the absence of fatigue and/or sleepiness.

Eight individuals were excluded from the initial sample due to abnormal trichromatic color vision ($n = 1$), inadequate arousal levels ($n = 3$), noncompliance due to motion sickness ($n = 2$), and technical problems ($n = 2$). This resulted in a conclusive group of 27 participants (mean age ± SD = 24.74 ± 4.31, range 21 - 42; 15 women), with only one individual choosing not to disclose his gender information. All drivers were unaware of the hypotheses under investigation and received an economic compensation of 20€ for their participation in the present study.

1.3 Experimental design

The study followed a 3x2x2x2 within-subject design with Active Luminous Road Markings (ALRMs) color (i.e., 3 levels: green vs. red vs. unlit), ALRMs widths (i.e., 2 levels: Conventional [centre-line = 10 cm; edge-line = 15 cm] vs. Wide [centre-line = 30 cm; edge-line = 30 cm]), curve radius (i.e., 2 levels: 120 vs. 440 m) and curve direction (i.e., 2 levels: right vs. left) as independent variables for both the experimental tasks (the

Driving simulation task and the video-based perception task). Thus, each driver underwent six experimental driving conditions and viewed twenty-four different videos for the secondary perception task (see 1.7 section).

The main dependent variables considered in the driving simulation were as follows: Driving performance, measured by (i) longitudinal speed at the Tangent-to-Spiral (TS) and Curve Center (CC, Figure 2); (ii) Lateral position, which refers to the distance between the vehicles' center of gravity and centerline of the lane, measured at the termini of TS and CC, (iii) Standard deviation of the lateral position (SDLP) between the termini of TS and ST, (iv) Standard deviation of the longitudinal speed (SDS) between the termini of TS and ST, (v) Subjective evaluation, which encompassed factors such as the level of brightness of the mark roads, uniformity of brightness, luminous comfort in the driving environment, sense of security, satisfaction, and level of concentration during the task.

For the video-based perception task, we recorded the participants' (i) degree of arousal, (ii) degree of pleasantness, (iii) perceived level of risk, and (iv) car speed estimation. We used four separate 9-point Likert scales from 1, very low, to 9, very high (see Section 1.5 for more details).

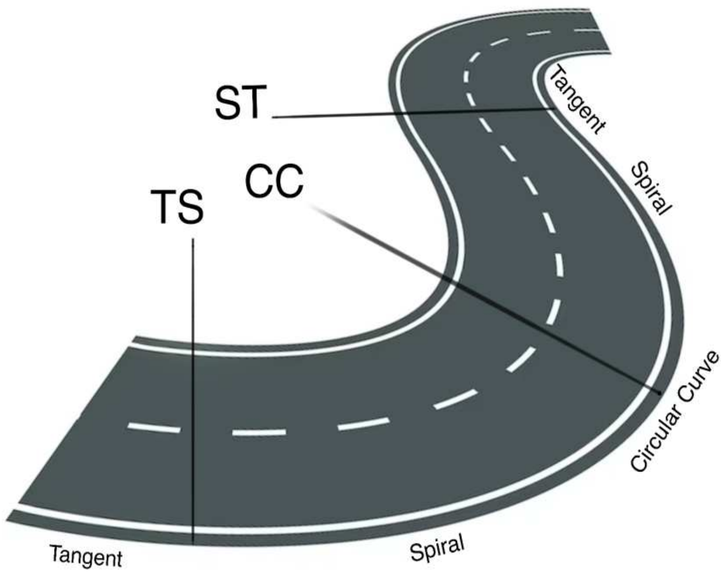

Figure 2 *Reference sites that indicate the curve termini Tangent-to-Spiral (TS), circular curve center (CC), and spiral-to-tangent (ST).*

1.4 Driving simulator and scenarios (Behavioral data)

To carry out the driving simulations, we developed six two-lane (each 3.5 m wide) rural highway scenarios using the SCANeR studio DT 2.5 software (AVSimulation, Boulogne-Billancourt, France). All the scenarios had the same road environment, nighttime lighting conditions, and road alignment. Each road scenario was ∼ 16 km long with a 1.5 wide shoulder on both sides of the carriageway (Orden FOM/273/2016, de 19 de Febrero), and it was surrounded by an empty and monotonous grassy meadow.

The road alignment included 24 spiraled curves differentiated for curves and directions. We investigated curves with radii equal to 120 m and 440 m for both directions (right and left), and each condition was repeated three times (2 radii x 2 directions x 3 times = 12 curves). The remaining 12 curves had radii ranging from 210 m to 300 m and were designed to guarantee gradual road alignment. The length of the tangents ranged from 150 m to 300 m. The six road scenarios were different in terms of ALRMs color (i.e., unlit, green, red), and width (conventional, wide), and this technology was only applied to the carriageway edge lines.

The color effect was implemented with SCANeR Studio DT 2.5 software. The brightness and visibility of the ALRMs were designed to be as realistic as possible and controlled by the visual mode. Furthermore, the rendering mode was set to “Advance”. We chose to assign the characteristics of color as “emitting”, resulting in self-illuminating colored road markings. The colors were defined by the following RGB color values: red RGB (207, 39, 5), green RGB (0, 248, 120), and unlit RGB (182, 182, 182). The RGB color values for white was each set to 182, aiming to reproduce the effect of the conventional road marking visible at night. Additionally, the attribute “emitting” was not assigned to this color, resulting in it being purely retroflecting, only illuminated when exposed to vehicle headlights. The simulation software managed the level of luminance according to the principles of light propagation, reducing the level of luminance when the distance between the driver and the road marking increased. In terms of visibility, the ALRMs were visible throughout the entire scenario, including beyond the vehicle’s headlights, due to sufficient self-illumination and the absence of any visual obstacles.

Participants drove a mid-sized automatic vehicle without any other traffic present, and they were asked to drive in the right lane throughout the experiment, with the posted speed limit set at 90 km/h. Moreover, following the Spanish regulation (Orden FOM/273/2016, de 19 de Febrero), we placed the recommended speed sign 150 m before each curve, according to its radius (e.g., 90 km/h for 440m radius, 60 km/h for 120m radius). The driving simulator recorded the driving performance indicators at 125 Hz.

The experimental scenarios and the video-based perception test were performed in a dynamic driving simulator (Nervtech™, Ljubljana, Slovenia; Figure 3) located in the Neuroergonomics & Operator Performance Lab (CIMCYC, Universidad de Granada, Spain).

The simulator was situated within a specialized octagonal dome and operates using a motion platform with four degrees of freedom to replicate the physical sensation and

forces (longitudinal, back, and forth; and lateral movements) experienced during real driving intensifying the participant's immersion in the scene.
The driving simulator system included three 49″ screens (Samsung Electronics, South Korea) with a 130° field of view; a fully equipped car seat, a dynamic force feedback steering wheel, a speed dashboard, three pedals (gas, brake, clutch pedals), manual gearbox, vibration pads to return pavement roughness, wheel rolling, and shocks (Figure 4). Moreover, the simulator also incorporated a simulated rear-view mirror, allowing drivers to observe traffic flow in their surroundings, and a sound system that reproduced the sounds of the car engine, of the environment, and of the road according to the car speed.
Lastly, to prevent any increase in heat and audio disturbances, the computer that managed the simulation was placed outside the simulator room.

Figure 3 *Dynamic driving simulator (Nervtech™, Ljubljana, Slovenia) located at the Neuroergonomics & Operator Performance Lab (CIMCYC, Universidad de Granada, Spain).*

Figure 4 *Inside of the dynamic driving simulator (Nervtech™, Ljubljana, Slovenia) located at the Neuroergonomics & Operator Performance Lab (CIMCYC, Universidad de Granada, Spain). Three 49"*

screens, a car seat, a dynamic force feedback steering wheel, a speed dashboard, three pedals (gas, brake, clutch pedals), a manual gearbox, vibration pads to return pavement roughness, wheel rolling, and shocks.

1.5 Video-based perception test

During the video-based perception test, participants were asked to rate 24 video-displayed curves on the central screen of the simulator, using four separate 9-point Likert scales. At the end of each video, the participants had to verbally indicate (i) the degree of arousal, (ii) the degree of pleasantness, (iii) the perceived level of risk, and (iv) the estimated speed velocity, while the experimenter reported the responses in an online survey from the control room (see Section 1.7 for more details).

These videos were obtained by recording the central screen of the simulator. Each curve was recorded using the autonomous simulator's driving mode , where the vehicle adhered to the recommended speed limits (90 km/h or 60km/h) indicated by the road signs placed at the beginning of each curve (Figure 5).

The 24 curve videos were acquired by combining the ALRMs color condition, the ALRMs width condition, the two radii, and the two curve directions (3 colors x 2 width x 2 radius x 2 directions). Each of the videos had a duration of 10 seconds.

Figure 5 *Central screen of the simulator and recommended speed limits (90 km/h or 60km/h) placed at the beginning of each of the curves displayed for the video-based perception task. In yellow: the training video; in green, red, and unlit: the experimental curves.*

1.6 Questionnaires (Subjective data)

At the beginning of the experimental session, we screened participants for their sociodemographic (e.g., age, sex, education), health (e.g., eye impairments, medication, and alcohol use), and driving history (e.g., driving license, amount of driving per year/at night, number of accidents) information. Then, participants were asked to fill in the following pre-driving questionnaires: the *Standford Sleepiness Scale* (SSS, Hoddes, et al., 1973) and *the Borg Rating of Perceived Exertion (RPE) scale* (Borg, 1982).

To evaluate any changes in subjective sleepiness levels before and after the driving simulation, participants were required to select one of seven statements from the SSS scale (Hoddes et al., 1973), each closely reflecting their current level of sleepiness. It comprises a series of statements, spanning from "Feeling active, vital, alert, or wide awake" (rated as 1) to "No longer resisting sleep, on the verge of sleep onset, experiencing dream-like thoughts" (rated as 7). The reliability of this assessment method is evidenced by a strong test-retest consistency (Cronbach's alpha coefficient of 0.88; Miró et al., 2002).

Lastly, participants were asked to assess their level of exertion and sensation of fatigue both prior to and after engaging in the driving simulation. This evaluation was accomplished using the BORG - RPE numerical scale. Within this scale, a rating of ‘6’ corresponds to ‘No fatigue at all’, while a rating of ‘20’ corresponds to ‘Maximal fatigue’. This assessment was designed to discern the intensity of all sensations and perceptions of physical stress and fatigue linked to the task. The reliability of the BORG - RPE test has been well established, as evidenced by a Cronbach's alpha coefficient of 0.85, as reported by Buckley et al. (2009). This coefficient is a measure of internal consistency, implying that the items within the test exhibit strong correlations with each other, indicating a reliable measure of perceived exertion.

Then, after performing each of the six experimental conditions, drivers verbally filled in the *NASA Task Load Index* (TLX; Hart & Staveland, 1988) questionnaire and the *Subjective Evaluation questionnaire*. The NASA-TLX questionnaire aimed to assess the workload of each experimental scenario across six bipolar dimensions: Mental demand, Physical demand, Temporal demand, Effort, Performance, and Frustration level. Participants provided their assessment on an interval scale ranging from 1 to 100 (higher values indicate a higher perceived task load; Hart, 2006).

In addition, they were asked to fill out a modified version of the Subjective Evaluation Questionnaire (revised from the original by Yu et al., 2023). Specifically, we selected subjective evaluation items related to the space and lighting (brightness, comfort, sense of security, and satisfaction), and only one item pertaining to the evaluation of task and body (concentration) was included. The scale was adapted to a 9-point Likert scale.

Upon completion of the final scenario, participants were asked to complete post-drive questionnaires, which included the post-driving BORG questionnaire, and the *Motion Sickness Assessment Questionnaire* (MSAQ; Gianaros et al., 2010) chosen to evaluate the self-reported simulation sickness symptoms. The MSAQ includes 16 statements that outline the most common symptoms of motion sickness, such as “I felt dizzy.” (Gianaros et al., 2010). For each statement, participants were required to provide their response using a Likert scale that ranged from "not at all"(1) to "severely" (9).

After completing the experimental driving scenario, participants were asked to complete the video-based perception task. After watching each video, they were required to rate how pleasant or unpleasant they found it, on a 9-point rating scale. They had to indicate whether their experience was positive or negative, with “1” representing the lowest valence (or level of pleasantness) and “9” corresponding to the highest. In terms of arousal evaluation, participants were instructed to indicate how activated or stimulated they felt while watching the videos. The scale also ranged from 1 to 9, where 1 represented the lowest arousal level and 9, the highest. Both measures utilized a 9-point rating scale that was adapted from the Spanish version of the Self-Assessment-Manikin-Scale (SAM) developed by Lang in 1980. Furthermore, participants were asked to assess the perceived level of risk associated with each driving scene using a 9-point Likert scale. The scale ranged from 1, indicating "Not risky at all," to 9, representing "extremely risky". Lastly, participants were required to estimate the speed of the car depicted in each video. They did this using a 9-point rating scale that ranged from 50 km/h to 130 km/h.

These evaluations and ratings were collected as part of the video-based perception task, and they allowed us to assess the participants' subjective experiences and perceptions of the driving scenes presented to them.

1.7 Procedure

The present study was conducted at the Neuroergonomics & Operator Performance Lab at the Mind, Brain, and Behavior Research Center (CIMCYC; University of Granada). The laboratory includes two adjacent windowless rooms: the driving simulator room and the control room. Once participants signed the informed consent form, we recorded sociodemographic, health, and driving history data (see *1.7 section).*

To complete the screening, participants filled in the SSS, and the BORG questionnaires (see 1.7 section) and then proceeded with the calibration of the Smart Eye Pro system (~10 min, data not reported in this work). Following the calibration phase, participants were informed that they were about to drive on a two-way rural highway with a speed limit of 90 km/h. They were instructed to drive safely and adhere to the speed limit indicated by the roadside sign. An overview of the experimental procedure is available in Figure 6.

Participants had a 5-minute driving training phase with the driving simulator (that is, training scenario) to familiarize themselves with the apparatus and virtual environment. Subsequently, they were asked to complete the six experimental scenarios. Road scenarios were randomly administered to the participants, in terms of the independent variable, such as color, width, and starting point (from start-to-end or end-to-start) to prevent the learning effect.

We asked participants to continue to drive following the usual traffic rules (the posted speed limit was set at 90 km/h) and to keep the car in the right lane. Between each scenario, the NASA-TLX and Subjective Evaluation questionnaires were administered by voice through the simulator audio (or microphone) system. Upon completion of the final scenario, participants were asked to fill out the post-driving questionnaires, which included the post-driving BORG questionnaire and the MSAQ to evaluate simulator sickness. Finally, the participants undergo the video-based perception task. Prior to the beginning of the task, participants were shown two training videos, in which the color of the marking road was deliberately set to yellow. This distinct color choice helped to differentiate it from the colors used in the perception task videos. Speed velocity remained consistent and was in line with the speed indicated by the road sign at the beginning of each video (e.g., 60 km/h vs. 90 km/h; see Figure 5). Shortly thereafter, they were instructed to view a total of 24 brief videos, each of a duration of about 10 seconds. These videos showcased different curves characterized by experimental variables of color, width, radius, and direction.

During this video-based perception phase, participants were asked to remain seated within the simulator and to watch the videos displayed on the central screen of the simulator. After viewing each video, including the training videos, participants were required to verbally express their responses on the SAM scales for factors such as arousal and valence, as well as the perceived risk, and their estimation of speed.

Moreover, to prevent the so-called end-spurt effect, occurring when people know they are approaching the end of a task (Bergum & Lehr, 1963), participants were blind about the exact duration of the driving simulation, and they were only told that the overall duration of the experiment was ~ 2.5h.

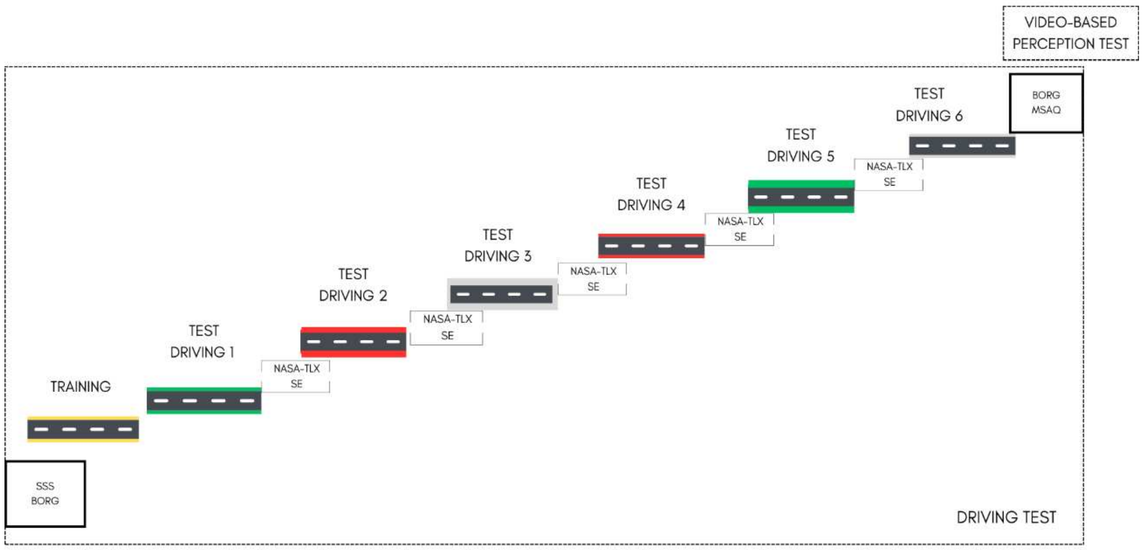

Figure 6 *Experimental procedure overview. The experimental procedure included: 1) the driving test, and 2) the video-based perception test. In the driving test: the pre-driving questionnaire (SSS and BORG questionnaire); a training phase (5 min); six different random-assigned test driving scenarios (green or red or unlit), (conventional or wide), (left or right); post-driving questionnaires (BORG and MSDI). The video-based perception test included: two training videos; 24 videos (10 seconds). After viewing each video, participants were required to verbally express their responses on the SAM scales for arousal, valence, perceived risk, and their estimate of speed.*

STATISTICAL ANALYSIS

JAMOVI 2.4.7 software was used for statistical analysis and repeated-measure analysis of variance (RM ANOVA) with significance < 0.05 was chosen. The sphericity assumption was met or corrected with Greenhouse-Geisser correction for all the variables. Moreover, we used Bonferroni corrections for multiple comparisons.

2.1 Driving simulator-based data analysis

To analyze the driving simulator data, we calculated two separate 3 × 2 × 2 × 2 repeated measure ANOVA to analyze the effect of color (3 levels: green vs. red vs. unlit), width (2 levels: conventional and wide), curve direction (2 levels: right and left), and radii (2 levels: 120 and 440) on the (i) Lateral position in TS and CC, (ii) Speed in TS and CC, (iii) Standard deviation of the longitudinal speed (SDS), (iv) Standard deviation of lateral position (SDLP). Three measurements were collected for each participant for each combination of the independent factors. For statistical analysis, we considered the average of these three observations.

2.2 Subjective rating-based data analysis

Initially, participants' alertness was assessed using the SSS scale, setting a predetermined threshold (score ≥ 4). This assessment served as a baseline measure and did not undergo formal statistical analysis.

The comprehensive evaluation of the workload across the experimental task employed repeated measures ANOVA with the NASA-TLX questionnaire, where data were utilized without regard for the dependent variable. Additionally, a 3 (color) × 2 (width) RM ANOVA measure was calculated on the drivers' performance task (NASA-TLX scores) in alignment with the dependent variables.

Expanding the analysis to the subjective evaluation questionnaire, a total of six separate 3 × 2 repeated measures ANOVAs were performed to analyze the effect of color (3 levels: green vs. red vs. unlit) and width (2 levels: conventional and wide) of the ALRMs on brightness, uniformity of brightness, comfort, feeling of safety, satisfaction, and concentration during driving simulation.

Finally, a repeated measures analysis of variance for the BORG scale was executed, focusing on the two distinct measurement sessions, pre- and post-driving. These sessions were treated as the repeated-measures factor, allowing an investigation of potential variations of physical stress and fatigue linked to the task. Similarly, the MSAQ data were analyzed, capturing both the general experience of motion sickness and the different dimensions labelled as gastrointestinal, central, peripheral, and sopite-related. The overall motion sickness score was derived by calculating the percentage of accumulated points out of a possible total, while subscale scores were obtained by analogous calculations within each specific factor and were used, as well as a threshold for motion sickness (Gianaros, et al. 2001).

2.3 Video-based perception test data analysis

Four different repeated measure ANOVAs were performed to analyze the video-based perception results. Specifically, we examine the effect of color (3 levels: green vs. red vs. unlit), width (2 levels: conventional and wide), direction of the curve (2 levels: right and left) and radii (2 levels: 120 and 440) on (i) arousal (SAM), (ii) valence (SAM), (iii) perceived risk, and (iv) speed estimation.

RESULTS

During a 2.5-h simulated driving session, we assessed the effect of the ALRMs' color and width on driver performance and driver behavior. At the beginning of the driving simulations, we collected subjective ratings of perceived alertness (used as a threshold) and fatigue (also collected at the end of the driving task). We analyzed the subjective ratings of workload, perceived level of brightness, uniformity of brightness, perception of safety, satisfaction, and concentration to assess driving behavior. For driving performance, we analyzed the results from the first task (driving simulation task). We also analyzed the outcome of the video-based perception task, exploring the effects of the dependent variables on levels of pleasantness, level of arousal experienced, perceived levels of risk, and speed estimations.

3.1 Driver Performance

Evaluation of drivers' performance included measuring (i) vehicle lateral position and standard deviation of the lateral position (SDLP); and (ii) speed and standard deviation of the speed (SDS).

3.1.1 Lateral Position

In the first section (TS), the influence of ALRMs color on the lateral position was significant, $F(1.59, 42.80) = 6.19$, $p = .007$ (Figure 7), as well as road marking width and curve radius, $F(1, 27) = 5.96$, $p = .02$ (Figure 8), and $F(1, 27) = 13.08$, $p = .001$(Figure 9), respectively. The first-order interaction (Direction ✻ Color) was found to be significant $F(2, 54) = 4.67$, $p = .013$, likewise the second-order interaction (Width ✻ Color ✻ Radius), $F(2, 54) = 3.28$, $p = .045$, and the third-order interaction (Direction ✻ Width ✻ Color ✻ Radius), $F(2, 54) = 3.\ 38$, $p = .041$. Post hoc comparison for the color factor ($p = .004$) showed a significant mean difference between the "Unlit" and "Green" conditions (mean difference = -.051, SE = .019 $t(27) = -2.59$, Bonferroni-adjusted-$p = .045$), as well as the "Unlit" and "Red" conditions (mean difference = -.049, SE = .016, $t(27) = -2.94$, Bonferroni-corrected $p = .020$). However, no significant differences were found between the comparisons of "Green" and "Red" (mean difference = .001, SE = .012, $t(27) = .15$, Bonferroni-corrected $p = 1.000$). In the estimated marginal means of the color factor, we observed that the "Green" and "Red" conditions tended to have higher mean values compared to the "Unlit" condition suggesting that ALRMs influenced drivers' behavior independently of color (Figure 7). Specifically, the results showed that only under the conditions in which ALRMs were present (green and red), and thus in which the edge of the carriageway stripes was more visible, as well as the lateral shoulder (1.5 m), and offered visual support to drivers who drove closer to the right lateral edge of the roadway.

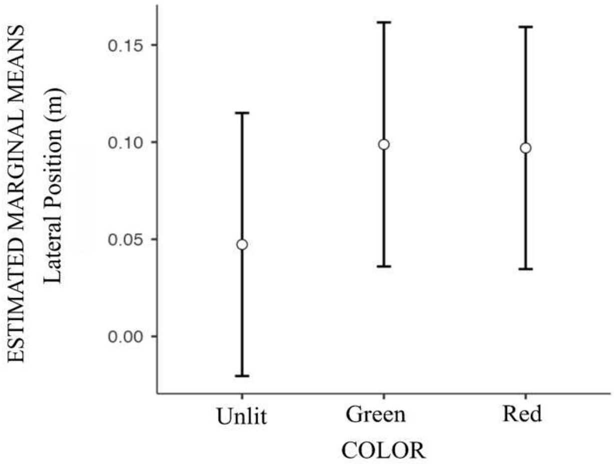

***Figure** 7 Estimated marginal means for the color factor associated with the lateral position at TS. The unlit condition showed lower marginal means (.04) with respect to the other two colors. As the 0.00 in the graph represents the center of the lane located in meters, it can be inferred that the drivers' only under conditions of red and green color tended to drive more at the right of the center of the road, thus maintaining the vehicle closer to the lateral edge of the road independently ALRMs from the color. The error bars represent the confidence interval of the data.*

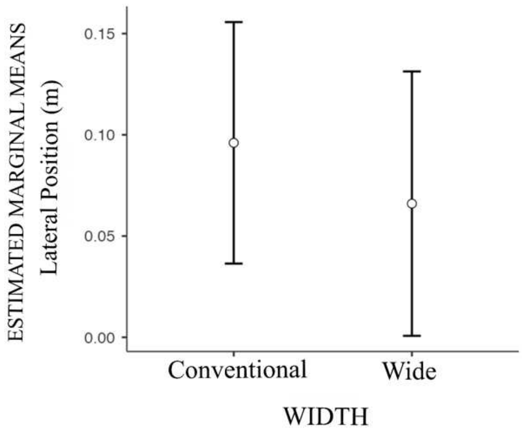

***Figure 8** Estimated marginal means for the width factor associated with the lateral position at TS. The conventional width of the road markings was found to have a higher lateral position value compared to the wide road marking conditions, suggesting that participants drove on average closer to the right side of the road in the presence of conventional road markings. The error bars represent the confidence interval of the data.*

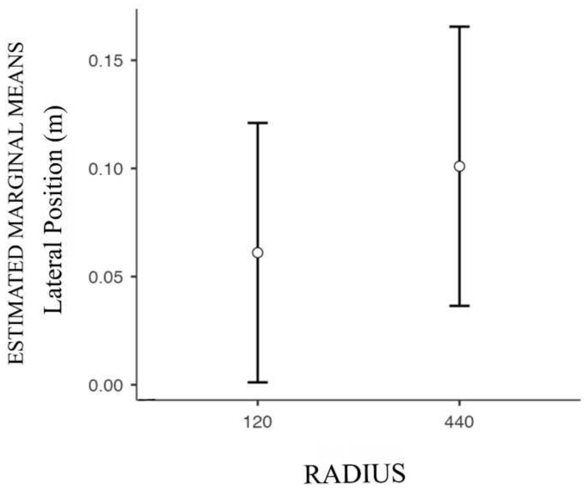

Figure 9 *Estimated marginal means for the radius factor associated with the lateral position at TS. The curve radius of 440 meters was found to have higher lateral position values compared to the narrower curve (120m), suggesting that participants drove on average closer to the right side of the road in the presence of wider curves. The error bars represent the confidence interval of the data.*

In the central section (CC), only the second-order interaction (Direction ✻ Width ✻ Radius) differed significantly for the lateral position, $F(1, 27) = 8.69$, $p = .007$.

SDLP was significantly affected by the color of the ALRMs, $F(2, 160) = 12.18$, $p < .001$ (Figure 10), by the width of the ALRMs, $F(1, 80) = 7.45$, $p = .008$ (Figure 11), and by the radius of the curve, $F(1, 80) = 5.16$, $p = .026$ (Figure 12). Nevertheless, the first-order interaction (Direction ✻ Color), $F(2, 160) = 3.37$, $p = .03$, and the second-order interaction (Direction ✻ Color ✻ Radius), $F(1.82, 145.60) = 3.22$, $p = .047$, exhibit significance. Post hoc comparison for the color factor ($p <.001$) showed a significant mean difference between the "Unlit" and "Green" condition (mean difference = -.021, SE = .004, $t(80) = -4.50$, Bonferroni-corrected $p < .001$), as well as the "Green" and "Red" condition (mean difference = .023, SE = .005, $t(80) = 4.62$, Bonferroni-corrected $p <.001$). However, no significant difference was found between the "Unlit" and "Red" comparisons (see Figure 8). The results on SDLP also produced interesting findings. In this study, SDLP was used as a measure to indicate the lateral control capability of the vehicle through the steering wheel (Verster & Roth, 2011; Portera et al., 2023). The estimated marginal means results presented below indicated that in the green condition, the SDLP had the highest values, compared to the other two conditions, which can be translated into greater trajectory corrections made by drivers in the green condition.

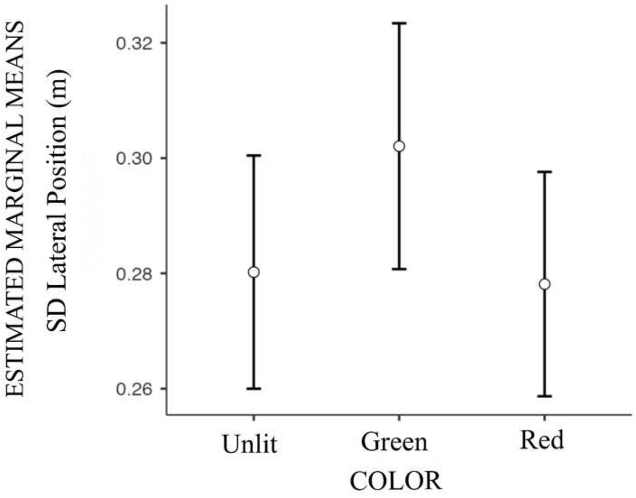

Figure 10 *Estimated marginal means for the color factor associated with the SD of the lateral position. Green: The estimated mean is 0.32, with a standard error of 0.01. The 95% confidence interval spans from 0.28 to 0.32. Unlit: The estimated mean is 0.28, with a standard error of 0.01. The 95% confidence interval span from 0.26 to 0.30. Red: The estimated mean is 0.27, with a standard error of 0.009 and a 95% confidence interval spans from 0.25 and 0.29. The error bars represent the confidence interval of the data.*

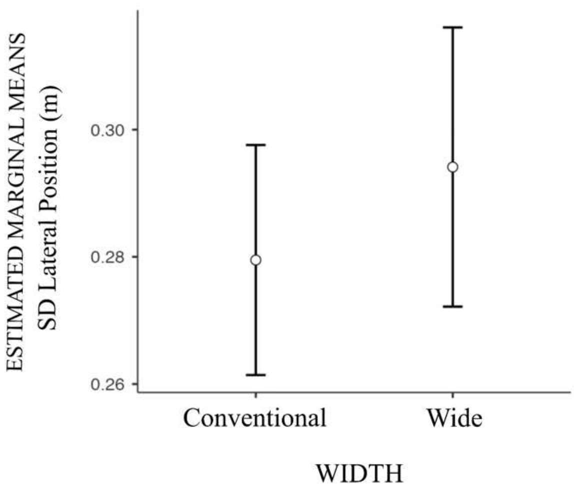

Figure 11 *Estimated marginal means for the width factor associated with the lateral position. The wide road markings condition was found to have a higher value in SDLP compared to conventional road markings conditions, suggesting that drivers made greater trajectory corrections in the presence of wider road markings. The error bars represent the confidence interval of the data.*

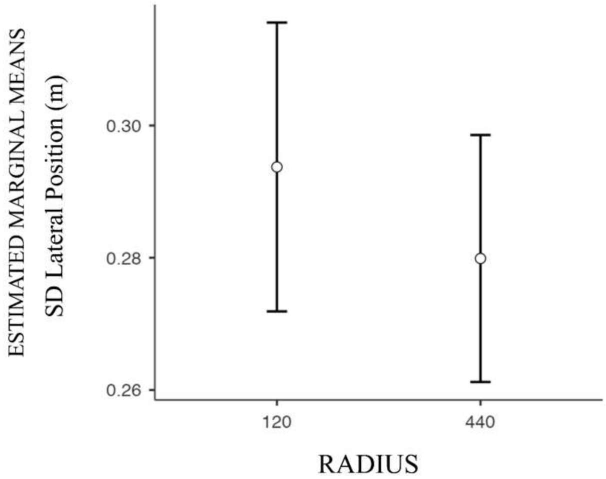

Figure 12 *Estimated marginal means for the radius factor associated with the lateral position. The curve radius of 440 meters was found to have lower values in the SDLP compared to the narrower curve(120m), suggesting that the drivers made fewer trajectory corrections in the presence of wider curves. The error bars represent the confidence interval of the data.*

3.1.2 Speed

In the first section (TS), the curve radius effect on the speed was significant, $F(1,80) = 248.66$, $p <.001$ (Figure 13), as well as the (Direction ✻ Width) interaction, $F(1, 80) = 8.87$, $p = .004$, and the (Width ✻ Color ✻ Radius) interaction, $F(2, 160) = 3.10$, $p = .04$.

In the central section (CC), color and width of the road markings did not statistically affect drivers' speed behavior. However, the radius of the curve was found to have a significant effect, $F(1, 80) = 905.00$, $p <.001$ (Figure 14).

Furthermore, the SDS, $F(1, 80) = 252.85$, $p < .001$, and the average of the means speed, $F(1, 27) = 305.45$, $p < .001$, were significantly affected only by the radius of the curve too (Figure 15). The results of the longitudinal behavior in both the first section (TS) and the central section (CC) of the curve revealed that the speed adopted by drivers was higher for curves with a larger radius than for those with a smaller radius (probably considered more complicated). In addition, the SDS was found to be greater in the curves with a smaller radius, indicating greater variability of speed in120m curves than in those with a 440m radius.

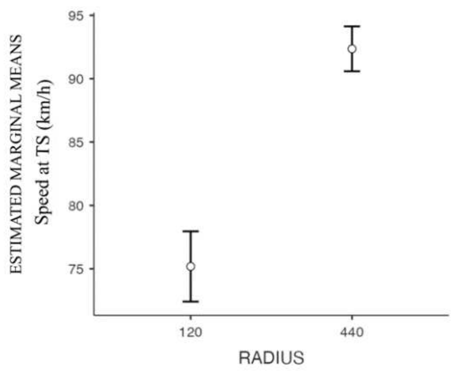

Figure 13 *Estimated marginal means of speed variable at TS measured in km/h. A higher speed average was found for the curves with 440m radius. The error bars represent the confidence interval of the data.*

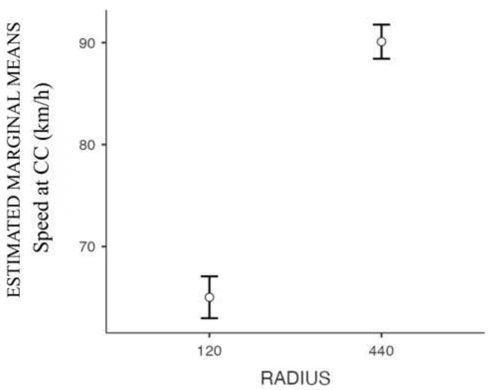

Figure 14 *Estimated marginal means of speed variable at CC measured in km/h. A higher speed average was found for the curves with 440m radius. The error bars represent the confidence interval of the data.*

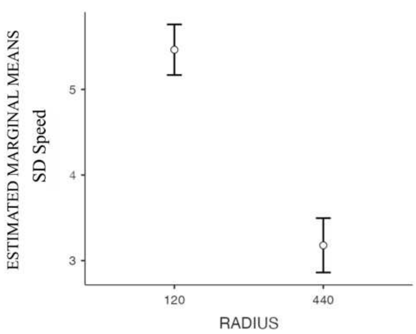

Figure 15 *Estimated marginal means of standard deviation of speed (SDS). Higher values of SDS were found for the curves with 120m radius. The error bars represent the confidence interval of the data.*

3.2 Subjective Measures

To examine the drivers' perceived level of fatigue, we analyzed changes in the BORG scores before and after the driving simulations. Perceived levels of fatigue differed significantly between the pre- and post-driving measurements, (average BORGpre ± SD = 8.9 ± 2.1 vs. BORGpost ± SD = 12.2 ± 3.0; $F(1, 29) = 24.3$, $p < .001$), suggesting that the subjective experience was affected by the driving simulation. No significant differences were found in the comprehensive workload assessment, as measured by NASA-TLX assessed by randomly assigned scenarios ($p = .69$), nor in the NASA-TLX scores measured considering all dependent variables (all p-values > .05, Table 1).

Table 1 *Mean and standard deviation (SD) for the NASA Task Load Index (TLX; Hart & Staveland, 1988). NASA-TLX averaged responses that were calculated by considering the dependent variables (ALRMs Color and Width). GC = Green, Conventional (120cm), RC = Red, Conventional, UC = Unlit, Conventional, GW = Green, Wide (440cm), RW = Red, Wide, and UW = Unlit, Wide.*

	Green		Red		Unlit	
	Conventional	Wide	Conventional	Wide	Conventional	Wide
	Mean (SD)					
NASA-TLX [0-100]	38.75 (34.58)	36.09 (29.58)	36.89 (33.75)	35.96; (38.33)	37.28 (36.67)	38.75 (32.50)

Although the subjective evaluation of brightness uniformity, safety perception, satisfaction, and concentration was shown to be unaffected by the color and the width of the ARLMs, our study established a significant link between the color of road markings and the perceived brightness evaluation, $F(2, 50) = 40.70$, $p < .001$, as well as the subjective evaluation of driving comfort, $F(2, 50) = 5.39$, $p = .008$. Post hoc comparison for the Color factor ($p < .001$) for the perceived brightness showed a significant mean difference between all the conditions (Bonferroni-corrected $p < .05$).

Estimated marginal means were calculated to provide insight into the average values of the dependent variable for each level of the color conditions. Green appeared to have a higher marginal mean than red and unlit colors, suggesting that it was the brightest color perceived on average by the participants across the driving sessions. However, it reported a wider confidence interval compared to the red and unlit color, suggesting greater variability in the data (Figure 16). Nevertheless, the interaction between color and driving comfort was no longer significant after Bonferroni's correction for the 'Green – Red' and the 'Red – Unlit' interactions (Bonferroni-corrected $p > .05$), but only for the 'Green – Unlit' comparison, (Mean Difference = -1.15, SE = .37, $t(25) = -3.09$, Bonferroni-adjusted $p = .014$). The estimated mean comfort level while driving in the presence of the green color condition is 5.58, with a 95% confidence interval ranging from 4.86 to 6.29; while for the unlit condition, it is 6.73, with a 95% confidence interval ranging from5.98 to 7.48 (Figure 17). This result could imply that on average drivers perceived moderate comfort when driving under the green conditions, while they perceived a higher level of comfort when driving in the absence of ALRMs illumination.

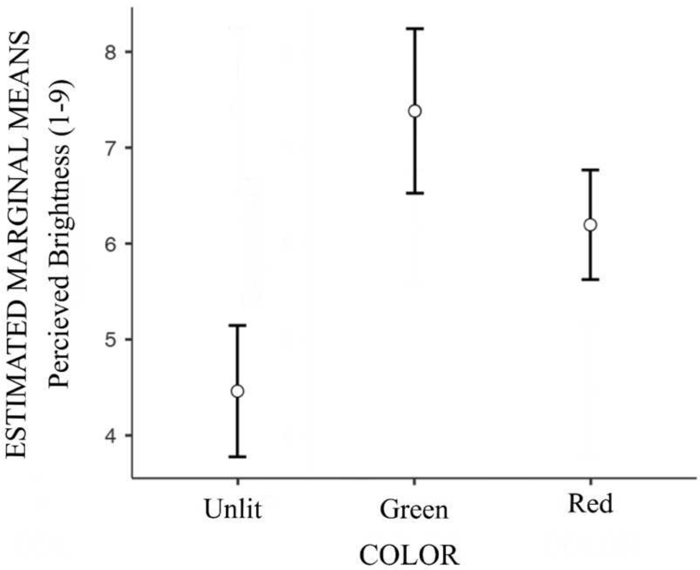

Figure 16 *Estimated marginal means for the color condition associated with the perceived brightness. Green appears to have a higher marginal mean (7.38) than red (6.28) and unlit (4.46) colors, suggesting that it is the brightest color perceived on average by participants in driving sessions. However, Green reported a wider confidence interval (range from 6.53 and 8.24) compared to the red color (range from 5.62 and 6.24) and the unlit color (range from 3.78 and 5.15) suggesting greater variability in the data. The error bars represent the confidence interval of the data.*

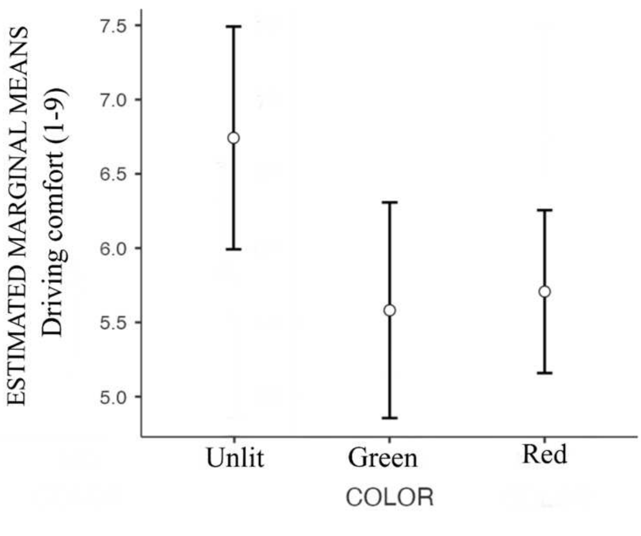

Figure 17 *Estimated marginal means for the color condition associated with perceived comfort. The interaction between color and driving comfort was no longer significant after Bonferroni's correction for*

the 'Green – Red' and the 'Red – Unlit' interactions (Bonferroni-corrected p > .05), but just for the 'Green – Unlit' comparison, (Mean Difference = -1.15, SE = .37, t(25) = -3.09, Bonferroni-adjusted p = .014). On average, drivers rated their comfort level higher when confronting unlit conditions compared to the green and red colors conditions. The error bars represent the confidence interval of the data.

3.3 Video-based perception task

Drivers' perceived level of arousal, as measured by the SAM scale during the video-based perception phase, was found to be significantly affected only by the radius of the presented curves, $F(1, 26) = 4.37$, $p = .046$ (Figure 18), and by the interaction (Width ∗ Color ∗ Radius), $F(2, 52) = 4.28$, $p = .019$. However, the other comparisons did not yield significant results. Only the ALRMs color showed a significant effect on valence, $F(2, 52) = 3.31$, $p = .044$, and on participants' perceived level of risk, $F(1.54, 37.64) = 3.81$, $p = .044$. Nevertheless, these differences were no longer significant after applying the Bonferroni correction ($p > .05$, Figure 19).

Finally, neither the color nor the width of ALRMs showed significant interactions with the estimated velocity of the simulated vehicle ($p > .05$) suggesting that the ALRMs width and color did not affect the perception of the estimated speed velocity while watching the videos. Conversely, the curve radius was found to be statistically significant, $F(1, 26) = 40.47$, $p < .001$, along with the first-order interaction (Width ∗ Color), $F(2, 52) = 4.87$, $p = .012$, indicating that for curves with a radius of 120m, the estimated speed of the car was lower compared to curves with a radius of 440 meters, where a higher speed was perceived (Figure 20).

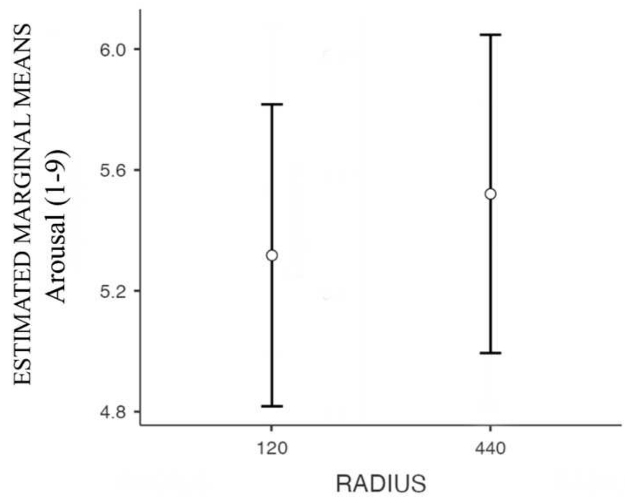

Figure 18 *Estimated marginal means for the radius factor associated with arousal. Higher arousal ratings were found to be associated with wider curves (440m). This could suggest that narrower curves were perceived to be less activating. The error bars represent the confidence interval of the data.*

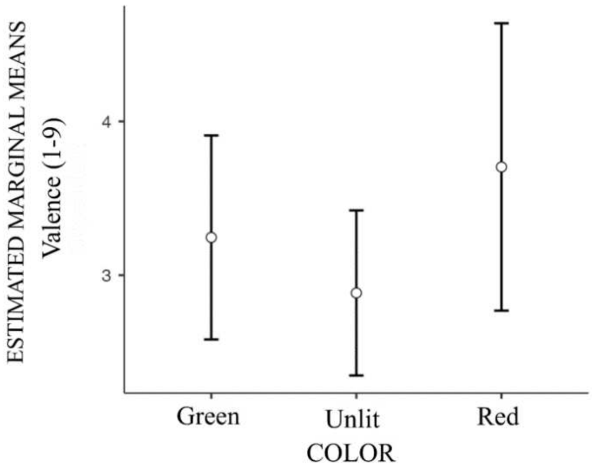

Figure 19 *Estimated marginal means for the color factor associated with valence. Green: The estimated mean is 3.25, with a standard error of 0.32. The 95% confidence interval spans from 2.58 to 3.91. Unlit: The estimated mean is 2.88, with a standard error of 0.26. The 95% confidence interval spans from 2.35 to 3.42. Red: The estimated mean is 3.70, with a standard error of 0.45 and a 95% confidence interval span from 2.77 and 4.64. However, the post hoc comparison showed no significant difference after the Bonferroni correction (p >.05). The error bars represent the confidence interval of the data.*

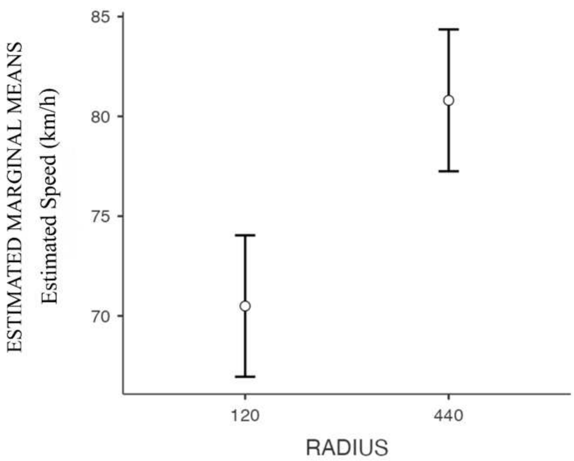

Figure 20 *Estimated marginal means for the radius factor associated with estimated speed. A higher estimated speed was found to be associated with wider curves (440m). This could suggest that the speed estimation for narrower curves was lower than the one estimated for curves of 440 meters. The error bars represent the confidence interval of the data.*

DISCUSSION

This study aimed to examine participants' behavior and performance within a driving simulation environment that incorporates Active Luminous Road markings (ALRMs). We investigated the impact of the ALRMs colors (green, red, and unlit), their width (conventional or wide), curve directions (left and right), and the two distinct radii (120m and 440m) on various behavioral and subjective measures. These measures included driving performance (lateral position, speed, and their SDs), as well as perceived level of brightness, uniformity, feeling of safety, concentration, driving comfort, subjective levels of fatigue, and task complexity. Furthermore, we analyzed the subjective evaluation of arousal and valence levels, along with perceived risk level, and estimated speeds, obtained during the video-based perception task.

4.1 The effects of ALRMs solutions on driving performance: lateral position, speed, and their SDs

ALRMs did affect driver performance in terms of the lateral position adopted during the driving simulation. In the first section (TS) of the curves, both color, width, and curve radius affected the driver performance. In the ALRMs green and red color conditions, participants adjusted their behavior compared to the unlit condition driving significantly closer to the lateral edge of the carriageway (and thus maintaining a greater distance from the centerline) independently by the color. This result suggests that ALRMs visibility offered greater visual support to drivers who anticipated the road design (Lehtonen et al. 2012) and reflected the better performance of visual recognition at night already found in Zhu et al. (2021). Moreover, it is plausible to assume that the presence of the shoulder (1.5m) on the right side of the road could have had an effect on this behavior. Specifically, as observed in other studies, the presence of the lateral shoulder (even if of moderate size), has a positive effect on driving safety, especially in two-lane roads with two-way traffic directions, as in our case (Ahmed, 2013; Zegeer et al., 1981). It can be hypothesized that in conditions where the shoulder is more visible (e.g., ALRMs conditions) drivers tend to move closer to the right side of the road compared to when it is less visible, and thus more unpredictable. However, this finding is inconsistent with earlier studies that showed opposite behavioral changes. Driving with advanced road technologies led to driving closer to the centerline compared to the unlit condition of the lateral marking (Portera et al., 2023; Shahar et al., 2018; Lehtonen et al. 2012).

In our study, it becomes evident that drivers adapted not only their lateral position before starting the curve in response to ALRMs colors, but also in relation to their width and radius. Specifically, they drove closer to the lateral edge of the carriageway in the presence of the conventional width and of the wider curve (440m). This reflects the dynamic adaptation in driving behavior according to the ALRMs features and environmental factors.

Notably, ALRMs color did influence the standard deviation of the lateral position (SDLP), an indicator of how well drivers maintain control and stability of the vehicle during lateral movements (Verster & Roth, 2011). However, while previous studies found that SDLP was affected by fewer trajectory corrections in scenarios involving the studded and LED stud layout compared to the unlit condition (Shahar et al., 2018, and Shahar & Brémond, (2014); Portera et al., 2023, respectively), here the ALRMs green condition reported significantly higher SDLP values with respect to the unlit and red conditions. It is plausible to assume that brighter but not comfier conditions (e.g., green conditions) resulted in greater lateral corrections and worsened vehicle control (Verster & Roth, 2011; Portera et al., 2023).

Additionally, the ALRMs width and radius of the curve were also found to significantly influence SDLP. In the conditions where the road markings were presented with conventional width, lower levels of trajectory corrections were reported, just as in the condition of curves with a wider radius (440m). This result could be explained by the established inverse correlation between the radius of the curve and the SDLP, according to which as the radius of the curve decreases, the SDLP increases, as found in Portera and Bassani (2021). It is plausible to suppose that ALRMs features interactions can effectively reflect how drivers simultaneously integrate and process different types of information.

Consistent with earlier studies (Llewellyn et al., 2021; Portera et al., 2023), ALRMs color did not affect the behavior of the drivers in terms of speed. However, the curve radius appeared to be extremely relevant in terms of speed behavior, both in the first and central sections of the curve (Bassani et al., 2019; Portera et al., 2023). This finding could be explained by the perception of a narrower curve (smaller radius) as more complex, leading to a decrease in driving speed (as previously observed in Bassani et al., 2019). As expected, before starting the curve (at TS termini), participants drove at a speed that reflected the recommended speed signs placed on the side of the road (e.g., 60 km/h for a 120m radius and 90km/h for a 440m radius). At the CC termini, divers tended to observe the speed limit (90 km/h) regardless of radius. Moreover, it is plausible to assume that the curve radius had a significant effect even on how drivers maintain average speed during curves due to its significance in SDS and mean speed, showing greater variability of speed in narrower curves than in wider ones. It is plausible to assume that in curves with smaller radius, drivers tended to enter the curve at higher speed and then slow down during the curve. However, in curves with a larger radius, drivers did not adjust their speed once navigating the curve, as the speed limit was the same as the one prescribed at TS, resulting in less speed variability.

4.2 The effects of ALRMs on drivers' subjective measures

Perceived task complexity levels (measured using NASA-TLX) did not show any significant differences. The very low values could reflect the simplicity of the driving scenarios used in our experiment: the limited external stimuli, the absence of other vehicles, and the repetitive nature of the curves suggest once again that mental workload is affected by conditions involving high-traffic density compared to situations where the traffic is reduced, as in this case, minimized (Fallahi et al., 2016).

As expected, the ALRMs significantly influenced the perception of brightness compared to the unlit condition. Specifically, the green ALRMs condition was perceived to be brighter in contrast to the red and unlit conditions. However, it was associated with a lower level of perceived driving comfort than the unlit condition (which does not differ in terms of comfort with the red condition). These results could be explained by the fact that the subjective ratings of the green color could have been perceived as an uncomfortable brightness of a light shining into the eyes, impairing proper vision, and resulting in higher ratings of visual discomfort and worsened driving behavior. Our results did not reveal any significant difference in the perceived level of safety between the ALRMs and unlit conditions, in contrast to previous studies where the LEDs stud conditions were associated with a more pleasant, non-hazardous, and less alarming perception (Horberry et al. 2006; Portera et al., 2023).

Unlike previous studies that identified differences in SAM components between different colors of the road markings (Portera et al., 2023; Kensinger, 2004), our analysis of the video-based perception task revealed that all color conditions produced comparable levels of arousal. The marginal effects of ALRMs red color were also initially found to be significant in valence and perceived level of risk; however, these effects did not remain significant after applying the Bonferroni correction in opposition to Portera et al. (2023).

In addition, the curve radius significantly influenced the arousal level along with the estimated speed velocity. Our findings suggested that narrower curves (120 m) were perceived as less aroused (activating), resulting in lower scores for speed estimation. According to these results, it is not possible draw clear conclusions about the ALRMs technology on driving behavior. The findings need future studies employing ALRMs to understand the complex interplay between visual cues, driving safety, and subjective experience in the domain of new smart on-road technology.

4.3 Limitations

Some issues must be posed when considering the practical outcomes of this study. Firstly, it is worth noting that road accidents result from an intricate interplay of factors that extend beyond mere lighting conditions, such as fatigue, weather, and other vehicles. Indeed, drivers reported a significant increase in the perception of fatigue (pre- and post-BORG scores) following the driving simulation. It is reasonable to suppose that fatigue could have been induced by the monotonous road (Farahmand & Boroujerdian, 2018), and visually uninteresting the scenarios (Merat et al., 2013). Furthermore, in the present simulation, the absence of external elements (chosen to minimize the impact of other variables on the driver response) could be considered as a limitation on the validity of the results. Furthermore, another technical limitation of our study is that we designed and examined only road configurations with the lateral standard lateral shoulder (1.5m). However, it should be considered that the alternative configurations (e.g., larger shoulder, smaller shoulder, or inexistent shoulder) could potentially influence the lateral position of the drivers. Furthermore, the implementation of ALRMs encounters obstacles both in considering financial implications and in the limited availability of driving simulation laboratories that investigate them. In addition, the demographic of the participants primarily included young individuals, excluding from the results the impact of ALRMs on older populations. Lastly, it is important to note that driving behavior is profoundly influenced by cultural and social factors and, for this reason, is essential to be cautious in assuming the universal applicability of these findings (Özkan, 2006).

4.4 Future directions

Future studies aimed at improving road safety and creating a more effective road environment should consider these findings as a starting point to examine the psychological and perceptual aspects of colors in road environments. Specifically, this research may offer some guidance on how ALRMs color combination and contrast on road safety would affect drivers mood and behavior through the implementation of physiological measures such as eye tracking and EDA (Zhu et al., 2021; Doudou et al., (2020).

CONCLUSIONS

To conclude, this study aimed to enhance our understanding of the potential benefits associated with the use of Active Luminous Road Markings (ALRMs) in road designs. We evaluate the effects of ALRMs' color, widths, and curve geometri features of the curves (radii and directions) on driver performance and subjective perceptions. The findings showed that ARLMs significantly influenced driving behavior, in terms of lateral position and speed, based on color, width, and curve radii. Specifically, green ALRMs led to poorer vehicle control, and narrower curve radii resulted in reduced speeds. Subjective responses indicated that while the green ALRMs were perceived as brighter, they were considered less comfortable than the unlit white road markings. These outcomes provide a starting point for investigating the potential impact of ALRMs on driving behavior and highlight the need for deeper consideration in their implementation due to the lack of existing strong research background (Angioi et al., 2023). Additionally, this study offers valuable information that transportation engineers and road designers could use to implement ALRMs and improve road safety by increasing driver awareness through developments in traffic lighting (Portera et al., 2023). As driving behavior is indeed influenced by different factors, further research should investigate the applicability of these findings considering the effectiveness of ALRMs on driving behavior and road safety.

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