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The influence of LED road stud color on driver behavior and perception along horizontal curves at nighttime

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ABSTRACT

Scotopic lighting conditions (reduced level of natural light or presence of artificial lighting) may impair driving performance and, therefore, impact on road safety. Thanks to technological developments, low-cost light emitting diode (LED) studs are now being considered as an alternative and affordable pavement marking solution to assist drivers in these conditions. By helping them to maintain their vehicle within the marked lane, the studs should prevent any deterioration in driver performance when negotiating curves at nighttime. However, the few studies that investigated the impact of LED studs on driving performance produced inconsistent results, and the question of whether they actively improve driver performance remains open. Furthermore, while international road regulations allow the use of LED studs, they do not provide consistent prescriptions for their lighting color.

Here, we assessed the influence of different LED lighting colors (red, white, and unlit) on longitudinal and transversal driver behavior when negotiating road curves with different radii and sense of direction. In the study, thirty-six drivers drove a dynamic virtual scenario featuring twenty-four curves. After the driving simulation, participants completed a static perception test in which they assessed each curve in terms of the perceived levels of risk, pleasantness, and arousal they experienced while driving on it.

In comparison with the unlit and red lit curves, those marked with white lighting LED studs were perceived as less risky, less arousing, and more pleasant independently of the radii and curve direction. Furthermore, when entering these curves, participants tended to shift their driving trajectories towards the center of the road. This effect was most evident on the central part of the curve. Further studies are expected to corroborate these results by focusing on different road geometries and LED stud layouts, as well as testing driving behavior in controlled road field studies.

1. Introduction

Road fatalities per vehicle-miles driven are significantly higher at nighttime than during daytime, with a crash rate difference of

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around 60% (Owens & Sivak, 1996; Plainis, 2006). Furthermore, road crashes occurring at nighttime are typically more severe than those in daytime (Elvik, 1995; Goswamy et al., 2018). Consequently, the introduction of innovative solutions is of paramount importance when it comes to improving road safety while driving with reduced levels of natural light or in the presence of artificial light (i.e, scotopic lighting conditions; Babić & Brijs, 2021; Bassani et al., 2022; Calvi et al., 2019; Charlton, 2007; Plainis, 2006; Raimondo et al., 2022). Light Emitting Diode (LED) technology is commanding considerable attention as a road lighting solution (Lin, Chen, & Zhang, 2023; Pagden et al., 2020; Vicente et al., 2023; Ylinen et al., 2011).

LED active road studs are among the considerable number of LED devices available on the market. The major technological advantage of these active LEDs compared to current retro–reflective (passive) raised horizontal markers is that they do not need to be illuminated by the light of the vehicle's headlights. Active road studs offer a clear advantage in terms of visibility as they can increase forward visibility by up to 800 m more than passive retroreflective studs (Reed, 2006). Thus, active LEDs are able to provide better visibility of the road ahead in low light (e.g., night) conditions, giving drivers greater visibility over longer sections of horizontal curves and a keener perception of the curvature. Indeed, LED studs are currently used as alternative horizontal road delineators to enhance the visibility of the carriageway in low-light conditions (Villa et al., 2015), especially in non-urban curved sections (Bhatnagar, 1994; Johnston, 1982; NHTSA, 2008).

To date, several studies have agreed that LED studs might increase driver confidence at nighttime, perceived safety, and comfort (Llewellyn et al., 2020; Reed, 2006; Shahar et al., 2018). However, the few studies that investigated the impact of LED studs on driving performance produced inconsistent results (Llewellyn et al., 2021; Shahar et al., 2018; Shahar & Brémond, 2014; Zhu et al., 2021). Thus, the question of whether driver performance and road safety could be improved through these solutions remains open. Furthermore, although it is well known that color affects driver behavior (for a review, see Calvi, 2018) and emotional state (for a review, see Jalil et al., 2012), requirements for the design of LED studs almost never include definitive specifications on the choice of color lighting to be displayed (Llewellyn et al., 2020; Shahar et al., 2018; Zhu et al., 2021). Indeed, to date, only one study has parametrically manipulated the color of studs (among other factors) and measured their effects on driver personal preference and perceived visibility, legibility and level of glare (Bacelar, 2004). Results indicated that drivers preferred bluish/white studs to yellow (ish) or orang(ish) ones. However, because other factors – such as luminous intensity, device surface, spacing, and stud height – were simultaneously manipulated, a straightforward conclusion is not possible. Thus, starting from Bacelar's pioneering observations (ibidem), we designed an experimental simulator–based study to investigate the influence of LED road stud color on driver behavior and perception.

Here, we evaluated the effects of two different colored LED studs (red vs. white, and a control condition: unlit) on driver performance and driver subjective perception. Participants performed two experimental tasks: (i) a driving simulation and (ii) a static perception test. The first task aimed to evaluate the effects of colored LED studs on vehicle longitudinal and transversal behavior, while the second one was intended to investigate their effect(s) on the levels of risk, pleasantness, and arousal perceived by drivers. Since red is commonly used to convey danger in traffic signs and lights (Chapanis, 1994; Pravossoudovitch et al., 2014), we expected that red LED studs – perceived as a warning signal – would induce a safer driving style (i.e., a more stable longitudinal and transversal control). In addition, it was also expected that driver perception of risk, pleasantness and arousal would reflect this red–danger association.

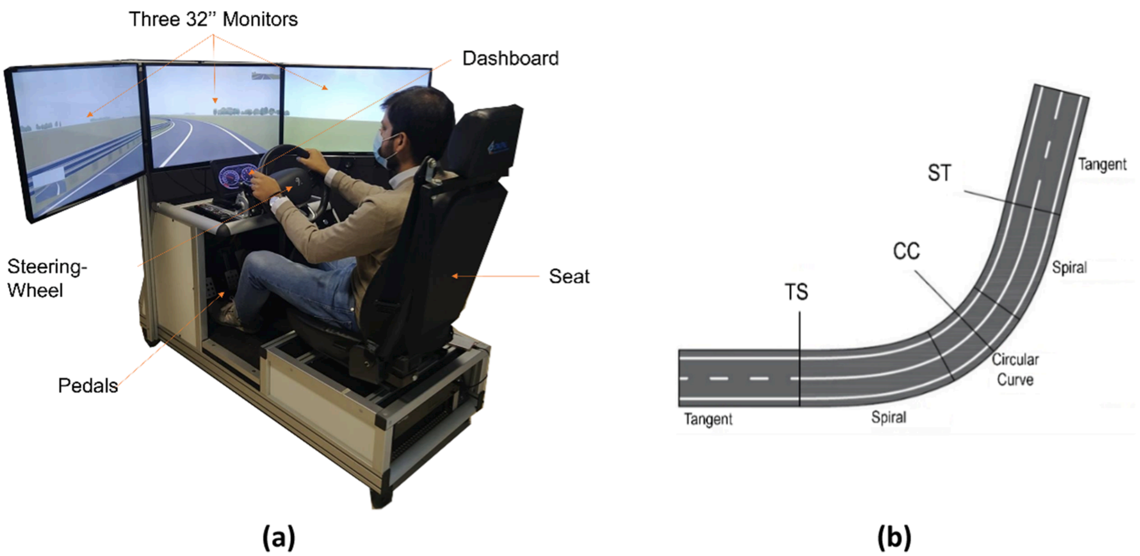

Fig. 1. (a) The fixed-base driving simulator used for the simulation task; (b) Reference sites correspond to curve termini TS (tangent-to-spiral) and ST (spiral-to-tangent), and to circular curve center (CC).

2. Method

2.1. Participants

Thirty-six participants (11 females) took part in the study. This sample included drivers with ages ranging from 19 to 63 (Mean [Standard Deviation, SD] = 31 [11.2] years). All participants had normal or corrected–to–normal vision and were asked to abstain from caffeine–based beverages in the 2 h before the experimental sessions. None of the drivers were aware of the hypotheses being investigated nor did they receive any monetary compensation. The experiment was conducted in compliance with the Code of Ethics of the World Medical Association (WMA, 2013).

2.2. Experimental design

Both experimental tasks (the driving simulation and the static perception) followed a within-subject design with *LED Stud* (3 levels: unlit, red, and white), *Curve Radius* (4 levels: 120, 210, 300, and 440 m), and *Curve Direction* (2 levels: left and right) as independent factors. It is worth noting that the four radius values were chosen so as to enable the participants negotiate the curves at different speeds. Therefore, to explore design speed interval, we selected the four values permitted by the Italian technical standards (Ministero delle Infrastrutture e dei Trasporti, 2001) for two–lane rural roads, which are 60, 75, 85, and 100 km/h. During the driving simulation task, we recorded the following longitudinal and transversal variables (Fig. 1b) for each investigated curve: (i) the longitudinal speed at TS (tangent-to-spiral) and CC (curve center) termini, (ii) the lateral position (i.e., the distance between the center of gravity of the

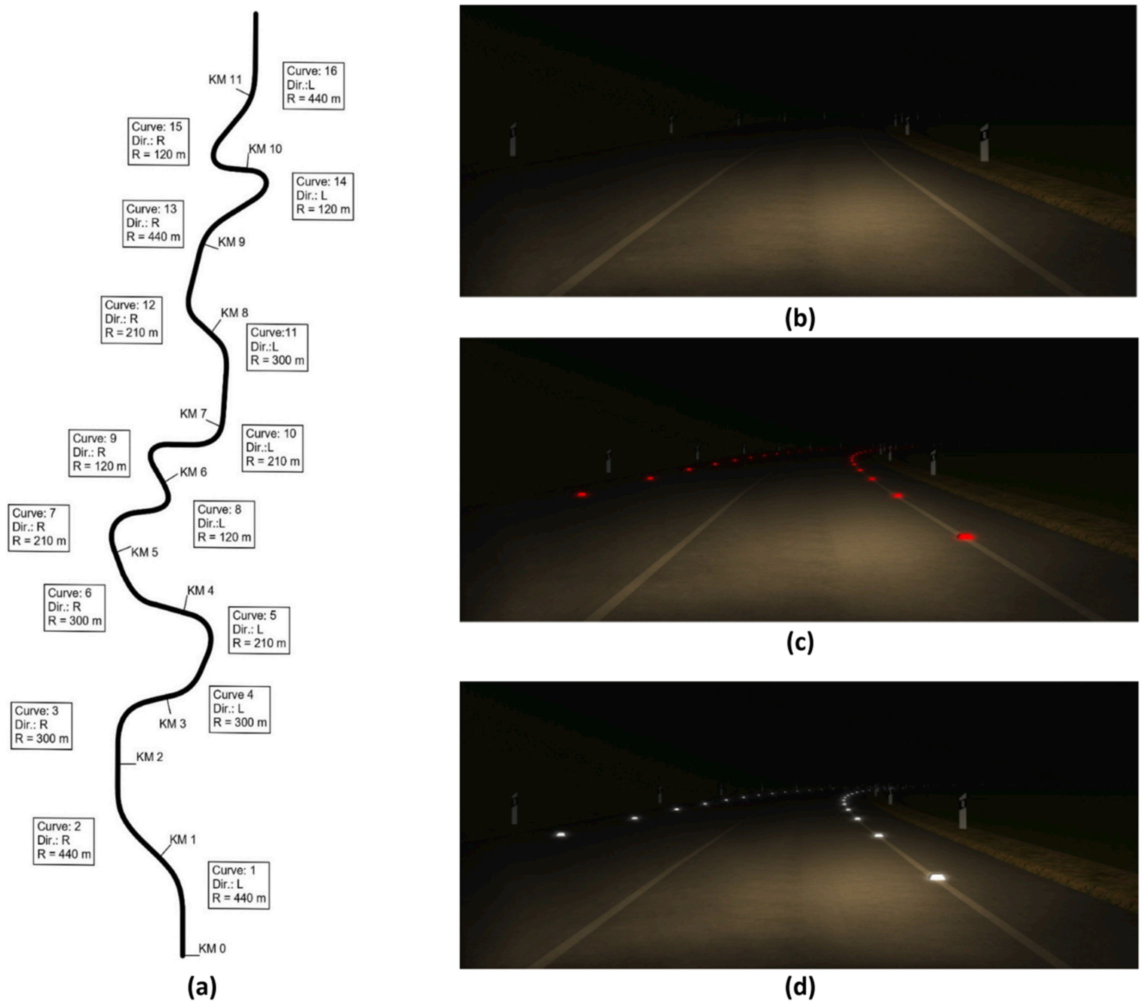

Fig. 2. Plan scheme (a) of the experimental track with curve details (16 curves: 2 curve directions × 4 radii × 2 repetitions), and frames taken from the driver point of view for (b) unlit condition, (c) red, and (d) white LED road studs in night-time driving conditions. Road studs were placed 8 m apart at the edges of the lanes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

vehicle and the lane centerline) at TS and CC termini, and (iii) the standard deviation of lateral position (SDLP) between TS and ST (spiral-to-tangent) termini (Fig. 1b). During the static perception test, we recorded participants' (i) perceived level of risk, (ii) the degree of pleasantness, and (iii) degree of arousal. We used three separated 9-point Likert scales (from 1, very low, to 9, very high), see 2.3 section).

2.3. Equipment, simulated scenario, and stimuli

For the driving simulation task, we used a fixed-base driving simulator (AV Simulation, France) located at the Road Safety and Driving Simulation lab (RSDS, Politecnico di Torino, Italy). The simulator is composed of three monitors with a 130° field of view, a fully equipped driving position with seat, dashboard, steering wheel with force feedback, pedals, manual gearbox, vibration pads to replicate pavement roughness, wheel rolling, and shocks (Fig. 1a). A sound system reproduced the sounds of the engine and the surrounding environment. The data acquisition frequency was set to 100 Hz. The SCANeR Studio® simulation software (https://www.avsimulation.com/scanerstudio/) was employed to develop the driving scenarios, run the simulation, and record the dependent variable values. The simulator had previously been validated for longitudinal (Bassani et al., 2018), transversal (Catani & Bassani, 2019), and passing (Karimi et al., 2020) behavior.

Three driving scenarios were designed to simulate the road alignment of a two–lane, 11.63 km long rural highway (Fig. 2a). The road cross-section presented one lane per direction, with a lane width of 3.75 m and a shoulder width of 1.50 m, in accordance with the Italian policy for road design (Ministero delle Infrastrutture e dei Trasporti, 2001). For all scenarios, we simulated a low volume of traffic on tangents to reflect real conditions as much as possible (Michael et al., 2014; Pinto et al., 2008), while free-flow conditions were simulated along curves. The scenarios were differentiated by the presence of LED studs at the curve roadside: (i) unlit, i.e., no LED studs (Fig. 2b), (ii) red (Fig. 2c), and (iii) white LED studs (Fig. 2d). Each scenario had the same characteristics in terms of landscape, environment, nighttime lighting conditions, and road geometric elements. The road alignment consisted of 16-spiraled curves, with different radii (120, 210, 300, and 440 m) and curve directions (left and right). Each condition was repeated twice (4 radii × 2 directions × 2 times = 16 curves). For the statistical analysis, we averaged out the observed values by referring to those curves having equal geometric characteristics (see Section 2.5). The length of the tangent was set in a range of 110 to 330 m. The road studs were placed on the left and right sides of the curves (Fig. 2), spaced 8 m apart, and not installed on tangents. We decided to install the active road studs exclusively at the edges of the carriageway because our objective was to support the passive retroreflective delineators, which are traditionally placed there to guide motorists and enhance safety.

The luminance and visibility of the simulated active road studs were managed by the SCANeR Studio software and were simulated to be as realistic as possible (i.e., light intensity of the studs decreased as the distance from the driver observation point increased). Furthermore, the road studs were visible along the entire length of the curve thanks to the adequate luminance of the studs and the absence of any sight obstructions (Fig. 2c and d).

For the static perception task, we randomly presented 24 images (obtained from the combination of 3 LED stud condition types × 4 radii × 2 curve directions) on a 24″ monitor positioned about 60 cm from the driver's face. Each image was displayed for 7 s. After seeing each image, participants assessed the perceived risk level of the driving scene using a 9-point Likert rating scale from 1 (not risky) to 9 (extremely risky). Then, they were asked to rate the levels of pleasantness (i.e., valence) and arousal (i.e., activation) they had experienced while viewing the image. We used a digital version of the Self-Assessment-Manikin-Scales – SAM – (Lang, 1980). Drivers were instructed to rate the level of pleasantness (i.e., valence), as positive or negative on a 9-point rating scale (e.g., one is the lowest valence and nine corresponds to the highest valence). For the arousal evaluation, drivers had to describe the activation induced by the presented image, from "lowest activating" to "highest activating" again on a 9-point rating scale (one is the lowest arousal while nine corresponds to the highest arousal).

2.4. Procedure

The experiment took place at the RSDS lab (Politecnico di Torino, Italy) during a one-day session organized as follows: (i) a pre-drive questionnaire, (ii) simulator training session, (iii) the three driving simulations, (iv) the static perception test, and, finally, (v) the post-drive questionnaire.

First, participants filled in a pre-drive questionnaire to collect demographic data, driving information, and information related to their health and physical condition. Subsequently, they conducted a five-minute training test at the driving simulator. After a 2-min rest period, participants were asked to drive the three experimental scenarios, which were fully counterbalanced to control the order effect (Keppel et al., 2001). Participants were given a 1-min rest time between driving scenarios. To increase the truthfulness of nighttime driving conditions, the experiment took place in a dimly lit laboratory. That is, the displayed image/simulation on the screen/s provided the only light inside the room. After that, we conducted the static perception test on the dedicated PC. Finally, the participants filled in a post-drive questionnaire about their driving simulation experience and any motion sickness experienced.

2.5. Statistical analysis

All the dependent variables were analyzed with a (3 × 4 × 2) repeated measures analysis of variance (RM ANOVA). For the dependent variables in the driving task, we averaged out the observed values by referring to those curves having equal geometric characteristics. The significance level (α) was always set to ≤ 0.05. The Bonferroni correction for multiple comparisons was applied. Two participants failed to complete the driving task because of simulation sickness. As a result, only data from 34 out of the 36 participants were analyzed.

3. Results

This study explored the effects of different LED stud colors on driver behavior and perceived levels of risk, levels of pleasantness, and arousal experienced, using both a simulator-based technology and a static perception test. To investigate the influence of the color manipulation on driver behavior, we first analyzed the outcomes of the second task (static perception task), after which we analyzed the driver performance results from the first task (driving simulation task).

3.1. Subjective measures

The risk perception of participants was affected by the color of LED studs, $F(2,66) = 16.28$, $p < .001$, as well as by curve direction, $F(1,33) = 9.44$, $p = .004$, and curve radius, $F(3,99) = 25.91$, $p < .001$. No significant interactions between these independent factors were found. Bonferroni post-hoc tests on the *LED stud* variable revealed a significant difference between the white and unlit conditions (mean difference = 1.07, corrected–$p < .05$), while the other comparisons did not prove to be significant (see Fig. 3).

The valence level of participants was significantly influenced by LED studs, $F(2,66) = 13.42$, $p < .001$, and curve radius, $F(3,99) = 8.90$, $p < .001$, albeit no significant interactions were found. Post-hoc comparisons revealed a difference between the white and unlit condition (mean difference = 1.05, corrected-$p < .05$). A post-hoc test on curve radius showed a significant difference between the sharper radius (120 m) and the wider (440 m) one (mean difference = –0.48, corrected-$p < .05$).

Participant arousal levels were significantly influenced by the LED studs, $F(2,66) = 14.120$, $p < .001$, as well as by curve direction, $F(1,33) = 11.880$, $p = .002$, and curve radius, $F(3,99) = 6.789$, $p < .001$. The interaction between LED studs and curve direction was statistically significant, $F(2,66) = 3.33$, $p = .042$. The post-hoc tests on the interaction (*LED stud*Curve Direction*) confirmed a significant difference between white and unlit studs for both directions of the curve. Moreover, no significant differences between the red and unlit conditions were detected. A significant difference between the red LED stud condition on left and right curves was found (mean difference = 0.38, corrected-$p < .05$).

Overall, the manipulation of the color had a marginally significant effect on the participants' subjective perception of the road. The white LED condition was perceived as less risky, less arousing, and more pleasant than the unlit condition. The red LED condition was perceived as similar to the unlit LED condition, while also tending being perceived as different from the white LED condition (see Fig. 3). We did not find significant differences between the red and unlit conditions.

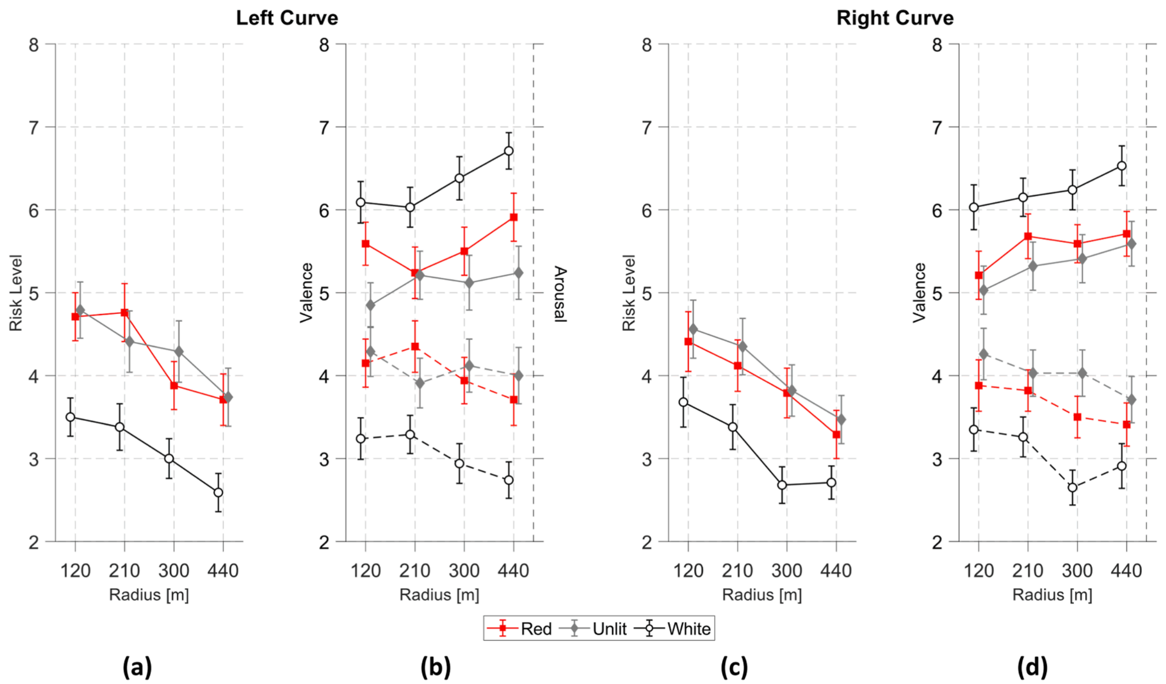

Fig. 3. Average perceived risk, valence, and arousal levels recorded during the static perception test. Graphs are split for curve direction (i.e., left, and right). Solid lines refer to valence, the dashed ones refer to arousal. The error bars represent the standard error of the mean (SEM). Valence and arousal are represented on the same scale. Note that, for graphic purposes, the range of the y-axis always ranges from 2 to 8, while the variables were measured in a scale from 1 to 9.

3.2. Lateral and longitudinal driver behavior

The transversal behavior of the drivers was measured by determining the lateral position (Fig. 4) and the SDLP (Fig. 5) of the vehicle. At the TS section, the LED stud effect on lateral position was significant, $F(2,66) = 15.30$, $p < .001$, as well as the curve direction and radius, $F(1,33) = 6.75$, $p = .015$ and $F(3,99) = 5.57$, $p = .001$, respectively. The second-order interaction (*LED Stud*Curve Radius*Curve Direction*) was also found to be significant, $F(6,198) = 2.65$, $p = .017$. The post-hoc test of the second order interaction revealed significant differences between the lateral position with left curves and a sharp radius (120 m) and the other three curves (210, 300, and 440 m), for the same road stud condition (corrected–$p < 0.05$). No significant differences were found among lateral positions in the lane on left curves with 210, 300, and 440 m, for the same road stud condition. On left curves, there were significant differences between the unlit condition and that of the white LED stud even though the mean difference was small (-0.20 m).

At the CC section, the lateral position differed significantly across the three road stud conditions $F(2,66) = 24.74$, $p < .001$. Significant differences were also found for curve direction, $F(1,33) = 14.00$, $p < .001$, and curve radius, $F(3,99) = 6.27$, $p < .001$. The second-order interaction (*LED Stud*Curve Radius*Curve Direction*) was also found to be significant, $F(6,198) = 7.47$, $p < .001$. A post–hoc comparison of road studs showed significant differences between the unlit and white LED conditions (mean difference = − 0.32, corrected-$p < .05$), the red and unlit LED conditions (mean difference = 0.20, corrected-$p < .05$), and the red and white LED conditions (mean difference = − 0.12, corrected-$p < .05$).

SDLP was significantly affected by LED road stud and curve radius, $F(2,66) = 4.23$, $p = .019$, $F(3,99) = 27.28$, $p < .001$, respectively, while the curve direction was non–significant. Nevertheless, the interaction between road stud condition and curve direction was significant, $F(2,66) = 7.43$, $p = .001$. Post–hoc comparisons between road stud and curve direction revealed significant differences between the red and unlit condition (corrected-$p < .05$) and between the white and unlit conditions albeit only on right curves (corrected-$p < .05$).

Our study did not establish any link between the color of LED studs and curve direction, and speeds at the TS section of curves under white, red, and unlit conditions. However, we did find that the curve radius had a significant effect on speed, $F(3,99) = 77.76$, $p < .001$. We also found the first order interaction between curve direction and radius to be significant $F(3,99) = 15.97$, $p < .001$.

At the CC section, color LED studs did not statistically affect drivers' speed behavior. Significant differences were found for curve direction, $F(1,99) = 9.51$, $p = .004$, and radius, $F(3,99) = 207.08$, $p < .001$. We found the first order interaction between road stud condition and direction to be significant too, $F(2,66) = 5.72$, $p = .005$. Post hoc comparisons between color LED stud and curve direction revealed significant differences only for the unlit condition between left and right curves (corrected-$p < .05$). The outcomes for speed are shown in the Supplementary Material 1.

4. Discussion and conclusions

We examined the effect(s) of the color (unlit, red, and white) of LED road studs, placed at curve carriageway edges in correspondence with the horizontal markings visible in nighttime driving conditions, on subjective measures and driver performance. We considered curves with four different radii (120, 210, 300, and 440 m) and in both directions (left and right).

Based on the results we obtained from the static perception task, the white LED studs induced a lower perception of risk than the

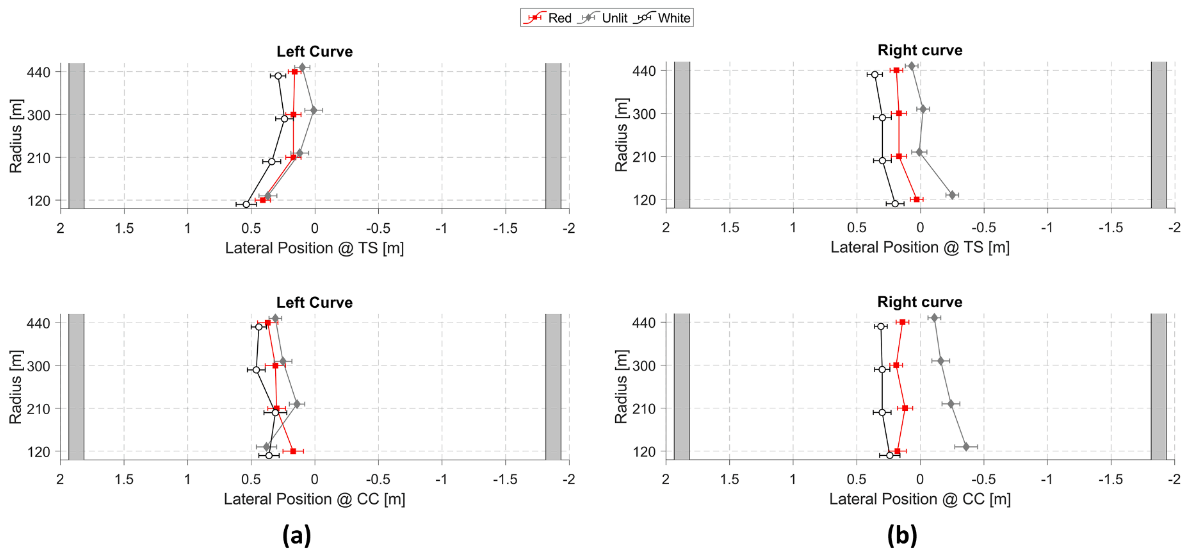

Fig. 4. Average lateral position maintained by drivers at (a) the beginning of the curve (TS section), and (b) at the center of the curve (CC section). The upper part of the figure shows the behavior on left curves, and the lower part on right curves. The two grey vertical bars in each graph represent the horizontal road markings, and the white area is the lane width. The error bars indicate the standard error of the mean (SEM).

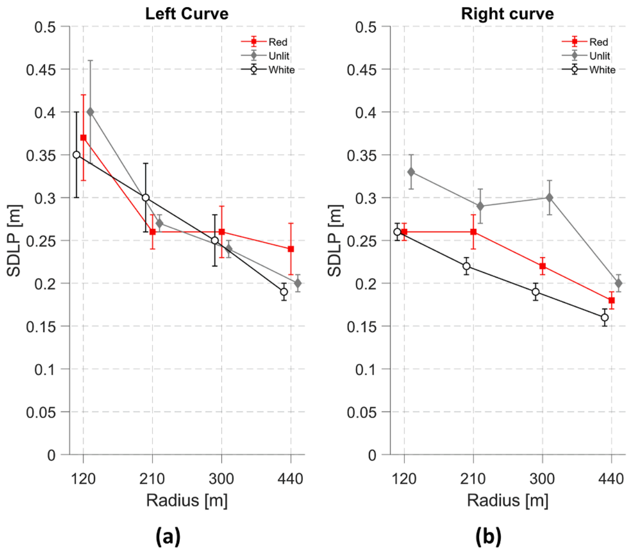

Fig. 5. Average standard deviation of lateral position (SDLP) between the beginning of the curve (TS) and the transition end (TE) sections for (a) left and (b) right curves. The error bars indicate the standard error of the mean (SEM).

unlit LED studs. The white LED stud condition increased valence and decreased arousal with respect to the unlit condition; in other words, white LED studs induced a less aroused (activating) state (Kensinger, 2004). In contrast, the red and unlit stud conditions produced comparable valence and arousal levels. Therefore, in terms of a subjective response, white LED studs are perceived as non–hazardous, pleasant, and less alarming delineators of the carriageway when driving at nighttime. We contend that the effect of white LED studs on driver perception enables the driver to benefit from a more pleasant and safer driving experience (Paxion et al., 2014). Moreover, our results indicate that the greater the radius, the lower the perceived level of risk. This result (from a subjective measurement) reflects the actual behavior of drivers (Bassani et al., 2019; Chen et al., 2007; Othman et al., 2009), as the authors determined that a decrease in the radius of the curve was accompanied by an increase in the objective level of risk. We also found significant differences in the perceived levels of risk between left and right curves. Although we cannot extrapolate too much from a single result, our findings provide further support for the hypothesis that a difference in risk perception can influence driving behavior (Jing et al., 2022; Song et al., 2021).

The analysis of lateral position revealed significant differences in driving behavior along curves of different directions. On right curves with red and white road studs, participants drove closer to the carriageway centerline compared to the unlit condition of the lateral marking (Fig. 4). However, we found no significant differences in the case of left curves, as the lateral positions were all close to the unlit condition (Fig. 4a). We conjecture that this different behavior is a consequence of the specific road stud layout we adopted. We only put the road studs at the edge of the carriageway, which inevitably makes the behavior asymmetrical when the driver uses the "tangent point" mechanism for lateral control. Land & Lee (1994) as well as Lehtonen et al., (2012) observed that most drivers regard the point of apparent inversion of the inner road marking, and towards which the driver's line of sight is oriented, to be tangent to the marking itself. Since they were almost visible to the driver (see Fig. 2), all left curves in the three scenarios offered the same visual support to drivers, as the road centerline was always free of LED studs.

The analysis of SDLP also produced relevant results, used here as an indicator of the vehicle's lateral control capability through the steering wheel (Verster & Roth, 2011). Based on previous considerations, it is not surprising that the effect of LED studs on SDLP was significant on right curves only. As previously said, the LED studs render the lane boundaries more visible to drivers who, consequently, performed fewer trajectory corrections, resulting in lower SDLP values with respect to the unlit condition. Once again, the white LED stud condition resulted in the best vehicle control. These results are consistent with those of Shahar et al. (2018) and Shahar & Brémond (2014), who observed lower SDLP values in the studded condition than in the unlit one. In these previous works, different conclusions were drawn for left and right curve maneuvers with respect to this study, again due to the different LED stud layout. Shahar et al., (2018) observed driver behavior on two-lane rural roads where, in addition to being placed on the edge of the carriageway, road studs were also used to mark the solid line dividing the two opposing traffic lanes. Moreover, as expected, the SDLP decreased as the radius increased. This result reflects that of Portera & Bassani (2021) who also established an inverse correlation between curve radius and SDLP.

Results for longitudinal behavior revealed that speed values entering and along the curve were not influenced by the presence nor by the color of the LED stud. This is certainly a good result in favor of the use of road studs, and is in line with the results obtained by Llewellyn et al. (2021) who did not find a significant variation in speed between the LED studded and unlit conditions on real roads. This implies that although the drivers' ability to predict road curvature improved dramatically, it did not translate into the adoption of riskier behavior in terms of higher speeds.

Our results are also consistent with previous studies (e.g., Shahar et al., 2018; Shahar & Brémond, 2014) in which speed was influenced by the presence of LED studs along straight sections only, a condition which we did not consider in this study. Nevertheless, our results combined with those from Shahar et al. (2018) clearly indicate that the longitudinal performance of drivers does not deteriorate with the use of road studs along curved sections only. In addition, the radius had an impact on longitudinal behavior. As the radius increased the speed increased too. This result was already found by Bassani et al. (2019).

Finally, the presence of red LED studs during nighttime driving in free-flowing conditions produces perceptions of hazard, pleasantness and arousal similar to those of the unlit condition. Moreover, along right curves with red LED studs, the lateral control of drivers improved with respect to the unlit LED studs but regressed with respect to the white ones. While this result is neither positive nor negative, it does suggest that it might be preferable to avoid the use of any red(ish) color which is typically used to signal work zones and/or situations of danger (Bacelar, 2004; Chapanis, 1994; Pravossoudovitch et al., 2014).

Taken together, our results demonstrate that white LED studs have a positive influence on nighttime driving. We found that a more pleasant, non-hazardous, and less alarming perception enabled the driver to exercise better lateral control, with significantly fewer steering corrections. This result appears to be extremely relevant for the design and implementation of road lighting solutions and would seem to favor the use of white devices over red ones. However, we also observed an asymmetrical behavior which was certainly influenced by the LED stud layout that we did not consider here. Therefore, we were able to appreciate the benefits of LED on right curves only.

Notwithstanding the above, our results should be viewed in the context of four shortcomings. First, LED studs were installed along the carriageway edges only. Our outcomes confirm that this decision led to a difference in results between right and left curves. Future research should compare all possible layouts resulting from a different arrangement of LED studs along the available lane markings. Second, the simplicity of our road scenario (free-flow conditions involving only horizontal curves) with constant meteorological and favorable visibility conditions (e.g., dry road surface, no fog, see Villa et al. 2015) could in part limit the external validity of our results, so further studies should address our research hypothesis in a more ecological way. Third, the explication based on the tangent point vision mechanism is just an assumption based on relevant previous studies. Future studies must also include eye–tracking measurements to confirm the effective adoption of this mechanism. Finally, although the study aimed at analyzing psychological (i.e., level of risk, valence, and arousal) and behavioral (i.e., speed, lateral position and SDLP) aspects, there is a possibility that the results were also influenced by physiological factors outside of our control, e.g., individual differences in color perception or in physiological responses to light (Boyce, 2009). Indeed, we did not specifically check the environmental levels across the different experimental conditions. Considering the absence of any oncoming vehicles or other road lighting devices, the variation in environmental luminance was determined by the led emitting lights themselves. Therefore, the findings should be interpreted with caution and future studies should aim to address this potential limitation by reducing the impact of confounding variables.

To conclude, our study on the influence of LED road stud color on driver behavior and attitude yielded promising results when white was used to provide guidance while driving at nighttime. Our investigation can offer transportation engineers, as well as road designers, some guidance on how to enhance traffic lighting developments, which serve to increase driver awareness of the conditions of oncoming curves, and to improve traffic safety.

Author contributions

The authors confirm contributions to the paper as follows:
(1) study conception and design: Portera, A., Angioi, F., Di Stasi, L.L., Bassani, M.
(2) data collection: Portera, A., Angioi, F., Muzzioli, L.
(3) analysis and interpretation of results: Portera, A., Angioi, F., Muzzioli, L., Di Stasi, L.L., Bassani, M.
(4) draft manuscript preparation: Portera, A., Angioi, F., Di Stasi, L.L., Bassani, M.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2023.06.007.

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