Exploring of information transmission function of vehicle interior lights

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ABSTRACT

This study focuses on how real-time vehicle light language assists drivers in acquiring peripheral information. It first investigates the perceptibility of interior lighting at different positions within the peripheral field of view, then analyses the applicability and effectiveness of colour and dynamic changes in information cues. The research aims to establish a foundational framework for interior lighting with information cueing capabilities, clarifying its specific positioning, luminaire configuration, colour effects, and efficacy assessment. This lays the groundwork for subsequent in-depth exploration of specific light colours, dynamic designs, and interaction patterns.

KEYWORDS

Vehicle interior lighting, Peripheral vision, Intelligent cockpit

1 Introduction

With the advancement of autonomous driving technology, vehicles themselves can now provide greater takeover capabilities, relieving drivers of the need for constant, undivided attention. [1] As automotive cockpits become increasingly intelligent, the convergence of screen interfaces, Head-Up Displays (HUDs), and other visual information systems [2] can overwhelm drivers with excessive visual complexity, heightening the risk of distraction. Consequently, in scenarios requiring driver intervention or monitoring, operators may fail to react promptly to emergencies. Thus, enabling drivers to access critical vehicle surroundings information despite such distractions has become a key research focus.

Simultaneously, the evolution of vehicle interior lighting represents a growing trend, with embedding information within these lights emerging as a viable development direction. [3] By varying brightness, position, colour, and dynamic effects, interior lighting can convey distinct information to the driver. [4] This constitutes light language – an emerging multimodal interaction method that employs real-time, differentiated lighting effects to form a language system with specific meanings, thereby conveying reliability. [5] Its principle lies in peripheral vision—the broader observation and manipulation within an observer's visual field, centred on the head and line of sight. [6]

Thus, drivers can perceive lighting changes without shifting their visual focus from their primary or non-primary targets, enabling rapid information recognition. [7]

This study explores how real-time vehicle lighting language can facilitate drivers' access to peripheral information. Research will commence by examining the perceptibility of interior lighting at different positions within the peripheral visual field, then extend to the suitability and effectiveness of colour and dynamic changes for information alerts. The aim is to establish a foundational framework for interior lighting with information alert functionality, defining its specific positioning, luminaire configuration, colour effects, and efficacy. This will lay the groundwork for subsequent in-depth research into specific lighting colours, dynamics, and interactive design.

2 Related Works

2.1 Visual Attention and Cognitive Load

A driver's attentional resources are finite. Cognitive load diminishes visual attention during driving, thereby reducing sensitivity and confidence. [8] Increases in both cognitive and visual load prolong reaction times for driving tasks, with visual load diminishing peripheral sensitivity and thus causing certain levels of interference. [9] Current research on reducing driver cognitive load remains limited. For instance, an AR HUD prototype system featuring an AI co-pilot function reduces cognitive load by selectively displaying infotainment data on the windscreen.[10] More prevalent are purely design-oriented interfaces or visual cognitive load reduction schemes for vehicle interiors, alongside certain design commonalities. For instance, colour schemes must adhere to universally recognised conventions (e.g., red = danger/stop, yellow = warning, green = normal/proceed, blue = information) to minimise learning curves and misinterpretation risks. Beyond reducing cognitive load, enhancing peripheral visual sensitivity—through explicit visual cues—is equally vital. Consequently, utilising interior lighting to achieve this function is justified. Nevertheless, such lighting must be positioned within the driver's peripheral vision, avoiding the primary field of view to prevent visual competition with core driving tasks.

2.2 The Informational Function of Vehicle Interior Lighting

Vehicle interior lighting can fulfil an informational role, with research in this area steadily increasing. For instance, ambient light displays within the interior can convey short-term driving plans or intentions to passengers. [3] Furthermore, pixelated road sign-style information and theatrical welcome/farewell messages exemplify outstanding user experience design. [11] Consequently, vehicle interior lighting can fulfil further functionalities.

Safety alerts and status indications represent the most fundamental and critical functions of lighting language, directly integrated into ADAS and vehicle safety systems. Their design principle lies in rapidly and unambiguously capturing the driver's attention while conveying the severity of risk.[12] This design principle also serves as a model for warning-based lighting design. For instance, collision warnings employ intense red flashing lights in the direction of the hazard source (such as the A-pillar or corresponding door) to alert drivers to imminent frontal collisions, lane departures, or vehicles in blind spots. This design is exemplified in Mercedes-Benz's MBUX system, where blind spot monitoring triggers red alerts displayed on the corresponding rear-view mirror icon and door ambient lighting. This design principle also exemplifies lighting employed for warning notifications. Other instances involve system status indication. Utilising soft hues (e.g., blue/green) and dynamic patterns (e.g., steady illumination/breathing flashes) displays vehicle conditions, including autonomous driving mode activation, battery charge levels, or cruise control engagement.

Navigation and guidance functions constitute another vital component, predominantly realised through Head-Up Display (HUD) systems. Lighting can augment visual navigation, reducing driver reliance on central display maps. For instance, when approaching a turn, light can flow from the vehicle's centre towards the turning direction (manifested as dashboard illumination shifting left or HUD projection), providing directional cues. Employing LED matrix lighting within the driver's peripheral vision similarly aids visual navigation, offering a more economical and widespread solution. [13] This exemplifies utilising peripheral lighting for informational cues, though it clearly extends beyond merely enhancing navigation functionality.

2.3 Interaction Methods Between Vehicle Interior Lighting and Drivers

Future vehicle interior lighting will increasingly adopt more physical and contactless interaction methods. Physical integration means merging with tangible interfaces such as steering wheels and physical surfaces, rather than relying solely on virtual buttons. This is particularly evident when displays like Head-Up Displays (HUDs) and screens suffer from glare. Contactless interaction refers to light-guided interaction. For instance, when a hand approaches a touch-sensitive climate control panel, the relevant area illuminates to indicate operable zones, reducing visual distraction caused by searching for buttons. Thus, information can be perceived through contactless means and presented via physical interfaces.

3 Methodology

This study employs the Reflective Transformative Design Process (RTDP) as its core methodological framework [14]. Developed by the Industrial Design Department at Eindhoven University of Technology in the Netherlands, RTDP emphasizes the deep integration of design practice and research reflection through cyclical iteration, making it particularly suitable for exploratory interaction design projects. The method comprises five key phases—Envisioning, Integration, Fabrication, Verification, and Reflection—which progress cyclically, enabling design solutions to mature through continuous validation and refinement. This study selected RTDP because: no established paradigm exists for in-vehicle lighting information interaction, necessitating continuous iteration through rapid prototyping and user feedback; simultaneously, this method encourages researchers to maintain critical reflection, aiding in capturing new design opportunities during exploration.

Envisioning Phase: This phase establishes preliminary design directions and gathers foundational attitudes and needs from potential users. Data was collected via an online questionnaire designed based on literature review and the researcher's own driving experience insights. The questionnaire covered: drivers' challenges perceiving the vehicle's surroundings, shortcomings of existing information acquisition methods, and acceptance of in-vehicle lighting as a warning medium (see Appendix for full questionnaire). The questionnaire was distributed via social media and driving communities, yielding 15 valid responses primarily from experienced drivers. Descriptive statistics and thematic analysis of the data provided directional guidance for subsequent design phases (e.g., lighting position preferences, color semantic expectations).

Integration Phase: The core of the integration phase was translating user insights from the ideation phase into concrete design concepts and scenario definitions. This study employed storyboards to construct typical hazardous driving scenarios, including: cyclists appearing in blind spots during low-speed driving, sudden obstacles moving within parking lots, and emergencies requiring manual takeover during autonomous driving mode. These scenarios focused on Level 2-3 autonomous driving situations where driver monitoring remains essential. Based on questionnaire results, the research team organized brainstorming sessions to preliminarily define key lighting design variables: light source form (point/line), mounting location (A-pillar/window sill/dashboard), color (red/yellow/blue/green, etc.), and dynamic mode (static/flashing/breathing/flowing). The integration phase yielded a set of actionable design hypotheses and preliminary sketches.

Production Phase: This phase transforms concepts into testable physical prototypes. An iterative prototyping strategy was adopted. First-round Prototype: A simplified cockpit model constructed from cardboard and foam board, embedded with programmable LED strips (WS2812B) controlled by an Arduino Uno. This prototype primarily tested the visibility and distractiveness of different light source forms and mounting positions. Second Prototype: Based on feedback from the first prototype, the structure was optimized using brighter LED strips. A Bluetooth module (HC-05) was added to enable remote control of lighting modes via a mobile app, providing flexibility for subsequent user testing. During prototyping, researchers concurrently developed Arduino control code to implement various dynamic effects (e.g., breathing, flowing, strobing) and intensity changes linked to distance sensors.

Validation Phase: Feedback was gathered through multiple user research methods to evaluate design effectiveness and user experience.

Workshop: The initial validation employed a small workshop format, inviting 5 potential users (3 attended) to experience the prototype in a simulated driving environment followed by semi-structured interviews. The workshop focused on dimensions like light source form, brightness, installation location, and functional logic to collect qualitative feedback.

User Testing: The second validation round recruited 8 participants with valid driver's licenses (ages 24-50, driving experience 2-15 years) for controlled testing in a laboratory setting. Tasks included: identifying hazard directions corresponding to different light modes, evaluating reaction times under light prompts, and assessing system usability. The testing process was fully recorded and supplemented with observation notes.

Interviews: One-on-one interviews were conducted after each testing phase to gain in-depth insights into participants' subjective perceptions regarding light color, dynamic frequency, intelligent adaptability, and other details.

Reflection Phase: Reflection is not a standalone phase but an ongoing process throughout the research. After each validation, researchers reviewed design objectives against test results, identified successes and areas for improvement, and adjusted design hypotheses for subsequent iterations accordingly. For instance, after the first workshop, reflection revealed unclear directionality of point light sources, prompting enhanced flow effects for line light sources in the second prototype iteration. Following the second round of testing, reflection indicated that excessive color variety might increase cognitive load, leading to an iterative direction of simplifying the color palette. Reflection outcomes were documented in research logs and served as the basis for the final design guidelines.

Through the cyclical iteration of these five phases, this study progressively converged on an in-vehicle lighting information interaction solution with high user acceptance. It also established an empirical foundation for in-depth design research in related lighting design studies.

4 Design Research Process

4.1 Survey

4.1.1 Survey Objectives. This research seeks to gather foundational perspectives, namely pre-existing intentions. It aims to explore the feasibility of this design in terms of initial impressions among potential Testers, alongside fundamental views and acceptance levels regarding usage scenarios. The questionnaire commences by examining whether vehicles are easily overlooked in their surroundings, inquiring about commonly employed perception methods, and assessing willingness to utilise alternative means for perceiving external vehicle information—particularly through lighting. The detailed questionnaire is provided in Appendix.

4.1.2 Survey result. The results are shown in the tables below. Note that the data in the table represents the number of mentions, not the exact number of individuals. 15 participants completed the questionnaire, predominantly those with driving experience. The majority affirmed that vehicle surroundings are easily overlooked. Common methods for perceiving peripheral vehicle information included rear-view mirrors and displays, alongside collision systems, assistance from others, map navigation, and direct observation through windows. These methods exhibit numerous shortcomings in alerting drivers, with blind spots being the most frequently cited issue. Consequently, virtually all participants expressed a desire for more convenient means of perceiving external vehicle information and indicated willingness to utilise interior lighting for external alerts.

Table 1. Driver's license and driving experience

Answer	Amount
Licensed + Experienced Driver	11
Licensed + No/Little Driving Experience	3
Unlicensed + No Driving Experience	2

Table 2. Find it easy to overlook the vehicle's surroundings

Answer	Amount
Easy/Very easy	6
Average	6
Not easy	2
No clear indication	1

Table 3. Common methods for perceiving peripheral vehicle information

Method	Amount
Interior/exterior rear-view mirrors	13
Screens/displays	6
Collision avoidance systems/sensors	2
Assistance from others	1
Maps/navigation	1
Direct observation through windows	2

Table 4. Shortcomings in alerting drivers

Shortcoming	Amount
Blind spots/dead angles (repeatedly mentioned) Requires proactive observation; cannot provide automatic alerts Information is scattered, making comprehensive awareness difficult Limited field of view prevents simultaneous monitoring of multiple directions Inability to judge distance (e.g., rear-view mirror lights only indicate vehicle presence) Rapidly changing road conditions; attention shifts easily leading to missed information Novice drivers are prone to oversight	Consider it insufficient 14
Do not consider it insufficient	1

Table 5. Want a more convenient way to perceive external

Answer	Amount
Very much so	7
Yes	7
Neutral/Undecided	1

Table 6. Willing to try using interior vehicle lighting to signal information to the outside

Answer	Amount
Very willing	6
Willing	7
Neutral/Depends on effectiveness	1
Unwilling	1

4.1.3 Analysis. It is evident that overlooking the vehicle's surroundings during driving constitutes a genuine problem. Common methods for perceiving peripheral information remain significantly inadequate. Participants overwhelmingly expressed positive views towards employing interior lighting for external alerts. Issues such as blind spots, the need for active observation, information fragmentation, and novice driver oversight can all be mitigated through lighting solutions. Lighting stimuli can reduce reliance on active observation, while peripheral illumination can expand visual coverage. Furthermore, limited observation ranges necessitate the use of directional lighting to convey information beyond the field of view. Rapidly changing road conditions require varying frequencies and colours to communicate differing levels of urgency.

4.2 Scenario

When driving normally, drivers may overlook emergencies, potentially creating dangerous situations. By implementing this design solution, drivers can perceive the location and severity of emergencies through visual cues when they occur. This is the intended outcome.

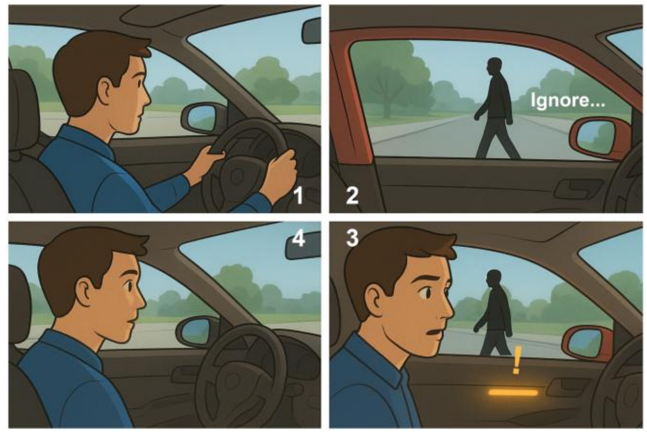


Figure 1. Storyboard

4.3 Iteration 1

4.3.1 Design. The design for Iteration 1 utilizes commonly available LED strips with adjustable brightness. These strips are placed within cardboard and filled with plastic foam to prevent direct visibility of the strips themselves.

Figure 2. Iteration 1 with adjustable brightness

4.3.2 Evaluation: Workshop. The prototype was placed in five common areas within the vehicle where ambient lighting is typically located (driver's left, upper left, front right, upper front right, lower right), with the light strip's intensity adjusted. Testers were asked to assess whether they could perceive the light strips' presence and the effectiveness of their alerts while visually interacting with a simulated manual driving dashboard and engaging in entertainment activities (simulating driver distraction during autonomous driving). Additional feedback and suggestions were collected. The testing was conducted via a workshop format, with 5 participants recruited and 3 attending in person. The results are in the following tables.

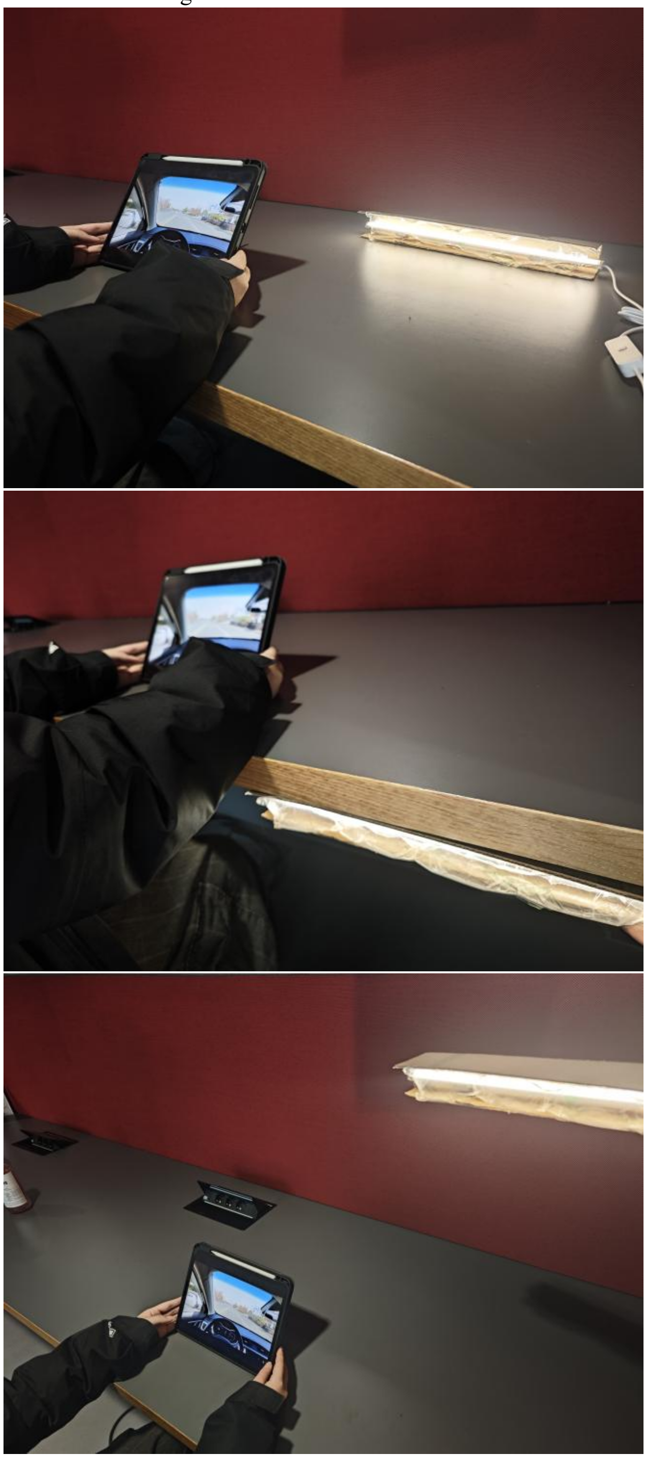


Figure 3. Workshop picture

Table 7. Results of the workshop

View Category	View	Amount
Light Source Shape Preference	Linear light sources are preferable to point light sources.	3
Brightness Preference	Medium brightness is most suitable; the lowest setting is insufficiently noticeable, while the highest is overly bright.	2
Distinguishing Between People and Objects	No differentiation is needed—it should illuminate whenever an object approaches.	3
Warning Light Position Preference	No differentiation is needed—it should illuminate whenever an object approaches.	2
Entertainment Functionality for Warning Lights	Placement around the windows (e.g., A-pillars, side windows) is more conspicuous than positioning on the center console or below.	1
Usefulness in Autonomous Driving	Not required—maintain pure functionality.	1
Brightness Adjustment Based on Distance	Still useful during autonomous driving, though Testers won't be using phones in the driver's seat.	1
Low-Brightness Breathing Lights as Normal Prompts	Brightness should adjust based on obstacle proximity (brighter as objects approach).	1
Potential Differences Between Daytime and Nighttime Effects	Low-brightness breathing pattern normally; localized high brightness when obstacles are present.	1
Importance of Location Information	Effectiveness under varying light conditions requires field testing. Warning lights should indicate obstacle direction (left/right).	1

Light Source Form: Linear light sources proved more popular: Most Testers felt linear light sources (e.g., light strips) more clearly indicated an object's movement trajectory than point light sources, providing more intuitive directional and dynamic perception.

Brightness Settings: Medium brightness proved most suitable. The lowest brightness setting was difficult to notice during daytime or in bright light conditions, while the highest setting risked distracting the driver's vision. Medium brightness achieved a good balance between warning effectiveness and visual comfort.

Installation Position: Peripheral areas around windows are preferable to the centre console or lower positions: Testers generally agree that warning lights placed in peripheral vision areas like the A-pillars or side windows provide directional information (left/right) while being less likely to be overlooked. Positions on the centre console or lower down are less effective as they divert attention away from the road.

Functional Logic: No need to distinguish between people and objects: Testers unanimously agree that warnings should trigger upon detecting any obstacle, without distinguishing object type, as 'any collision is unsafe'.

Brightness should dynamically adjust with distance: Testers suggest warning light intensity should increase as obstacles approach, enhancing the warning's sense of urgency and layering.

Manual driving mode: The system effectively assists drivers in perceiving moving objects in lateral and rear blind spots, proving particularly valuable in scenarios such as car parks and pedestrian-traffic areas. Autonomous driving mode: In certain autonomous driving levels (e.g., L2-L3), the system can still serve as an auxiliary warning measure before driver intervention. However, Testers emphasise that non-driving activities (such as using mobile phones) should not occur in the driver's seat, potentially limiting the warning system's effectiveness in such scenarios.

Environmental Adaptability: Testers note that system performance may be affected by ambient lighting conditions (day/night), recommending subsequent multi-scenario validation in real driving environments.

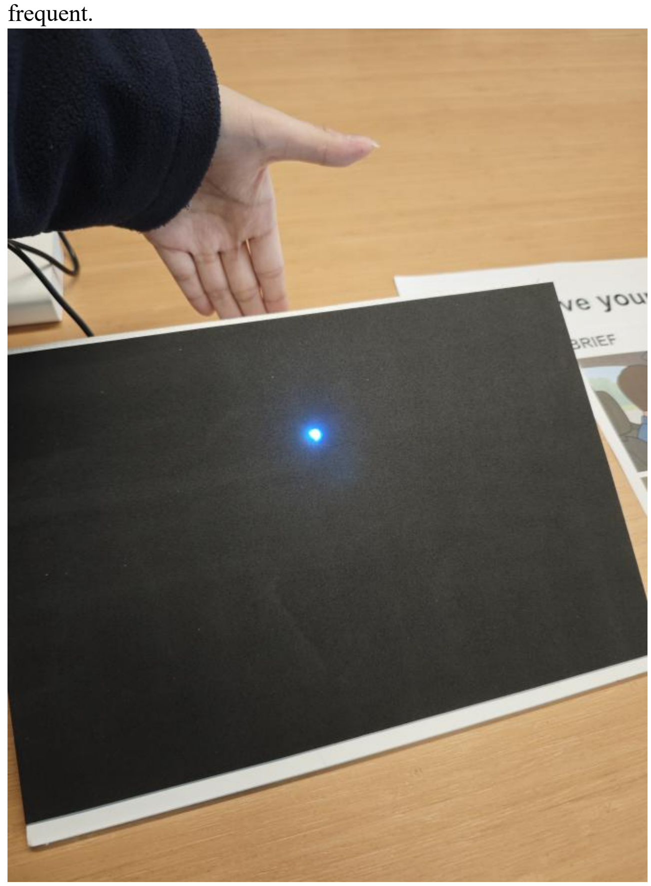
Opposition to Entertainment-Oriented Design: Testers generally prefer the system to remain purely functional, advising against incorporating entertainment or non-essential interactions to avoid distracting from driving tasks.

This experiment, through Tester interviews conducted in simulated driving scenarios, has preliminarily validated the feasibility and acceptance of an in-vehicle dynamic warning light system in enhancing drivers' perception of surrounding obstacles. The majority of participants held a positive attitude towards the system, recognising its potential as an auxiliary warning aid in complex traffic environments. It was deemed particularly practical in scenarios such as low-speed driving, parking, and distracted driving.

4.3.3 Reflection. The first iteration workshop preliminarily validated the feasibility of the design concept, but more crucially revealed multiple areas requiring deeper exploration. User preference for linear light sources made me realize that directional coding holds core value in warning systems—not just indicating "where danger is," but also "where danger comes from." The consensus on medium brightness reminded me that warning design must strike a delicate balance between perceptibility and intrusiveness, a balance that may dynamically shift with ambient lighting. Users' explicit rejection of entertainment features reinforced my commitment to the system's purity: the primary mission of an alert system is to convey safety information, and any redundancy risks becoming a liability. However, the limited workshop participation (only 3 users) may have resulted in underrepresented perspectives, necessitating a larger sample size in future iterations. Additionally, users suggested "dynamic brightness adjustment based on distance," which though not implemented this round, provides clear direction for the functional logic of the next prototype iteration.

4.4 Iteration 2

4.4.1 Design. The second iteration design incorporates LEDs. The LEDs are embedded within the cardboard, and a proximity sensor detects whether an object passes by. When an object passes, the LEDs flash. Over time, the flashing becomes increasingly frequent.



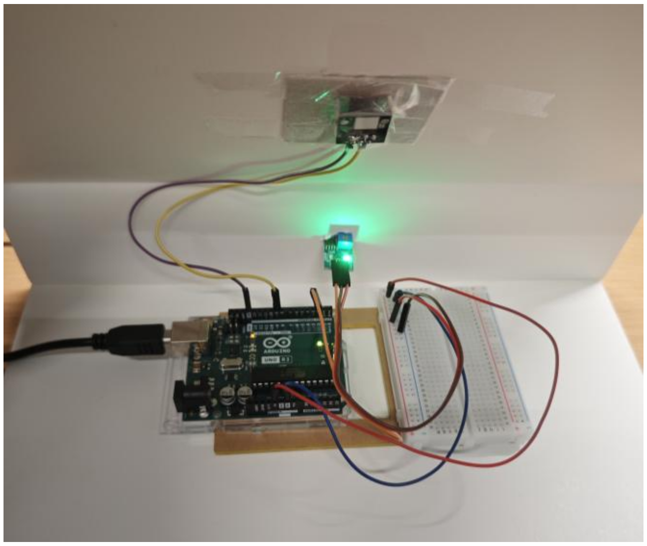


Figure 4. Iteration 2

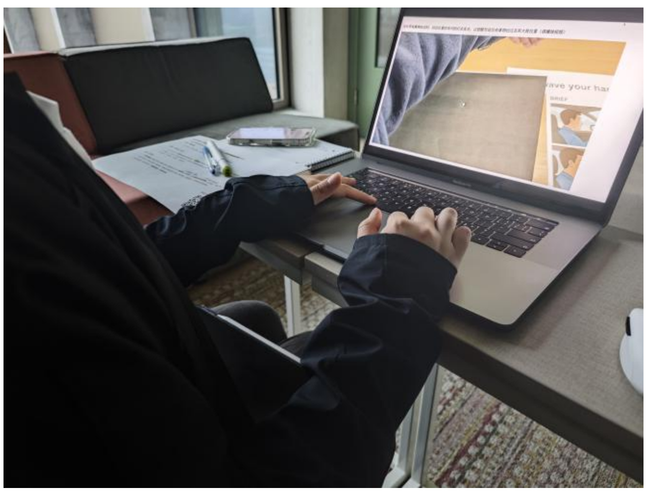


Figure 5. Test

4.4.2 Evaluation: Test. Test 2 employed an online experience and interview format. Participants watched videos of partial usage scenarios, answered a series of questions, and subsequently completed the UEQ questionnaire. A total of 16 individuals participated in the test. The results are in the following tables.

Table 8. Light Place

Place	Amount
Dashboard / Near Steering Wheel	6
Head-Up Display (HUD)	2
Ambient Lighting / Ring Light Strip	3
Side Windows / Near Rearview Mirrors people	5
Below Windshield / Near Center Console	4

Table 9. If can sense objects passing by

Sense objects passing by	Amount
Able	13
Not able	9

Table 10. If can indicate distance

Indicate distance	Amount
Yes	11
No	3

Table 11. Ideas about colour

Idea	Amount
Multiple colors attract attention, but avoid excessive use (recommended 2-3 colors)	10
A single color is sufficient; too many colors interfere with memory and reaction times	7
Red is suitable for emergency alerts, but must be distinguishable from other red elements inside the vehicle	4
Blue or green are suitable for general reminders	2

Table 12. Light Strips vs. Individual Light Modules

Idea	Amount
Complete light strips are more suitable (visually cohesive, easier to perceive)	10
Multiple individual light modules are more suitable (high flexibility, lower cost)	4
Both are acceptable, depending on design and location	2

Table 13. Brightness Preference

Brightness	Amount
Moderate Brightness	6
Dimmer Brightness	5
Brighter Brightness	2
Brightness should adjust automatically based on day/night	3

Table 14. Shortcomings and Concerns

Concern	Amount
Potential driver distraction	8
Requires learning and adaptation period	5
Excessive colors may cause panic or memory overload	6
Insufficient brightness during daytime, potentially too bright at night	4
Unable to distinguish object types (e.g., people, vehicles, animals)	9
Frequent flashing during traffic jams may induce anxiety	3
May interfere with passengers or other in-vehicle functions	2

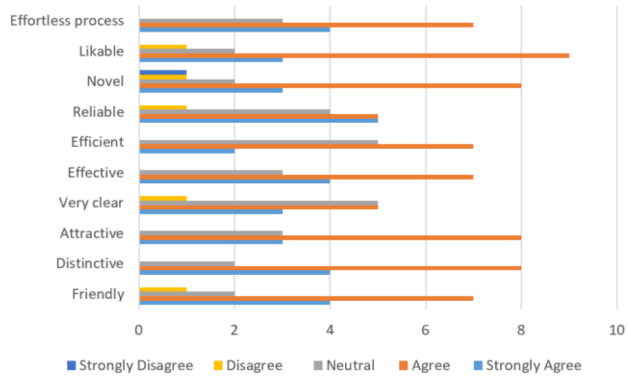


Figure 6. Result of UEQ

Overall system acceptance and effectiveness: Testers broadly acknowledge the system's practicality and Tester-friendliness. Most respondents deemed the system 'distinguishable,' 'effective,' and 'Tester-friendly,' indicating that in-car light prompts possess a solid foundation for positive Tester experience as an auxiliary driving aid. The system scored highly in "novelty" and 'appeal,' demonstrating that innovative interaction formats readily capture Tester interest.

There exists a certain learning and adaptation cost. Some Testers noted the system requires an initial learning period, potentially causing distraction at first, though prolonged use allows for natural peripheral perception.

Position Preference: Guided by principles of peripheral visibility and non-distraction. The most favoured locations are near the instrument panel/steering wheel and the side window/rear-view mirror areas, enabling drivers to perceive alerts without shifting their gaze. Circumferential light strips garnered favour among some Testers, aiding panoramic environmental awareness.

Colour Design: Simplicity over complexity. Most Testers advocated limiting colours to 2–3 varieties, as excess increases cognitive load. Red suits critical alerts but must contrast with existing red interior indicators; blue/green suit general reminders.

Brightness and Form: Moderate levels are optimal, with consistency being paramount. Most Testers prefer moderate brightness levels, ideally with automatic adjustment for day and night conditions. Continuous light strips are preferred over scattered individual lights due to their stronger visual continuity and more intuitive information delivery.

Testers generally acknowledge the system's ability to alert them to approaching objects, but its inability to distinguish between people, vehicles, animals, or other obstacles represents a key limitation in current designs.

Flashing frequency can convey proximity information. Most Testers agree that varying flash rates effectively express an object's approach, demonstrating strong potential for spatial cues. However, in congested or high-speed scenarios, frequent flashing may cause Tester anxiety or even interfere with normal driving.

Environmental adaptability must be considered. The system should feature automatic brightness adjustment for day and night, ensuring visibility during daylight hours without causing glare at night. Combining multimodal alerts is recommended. Some Testers suggested integrating light alerts with audible warnings to enhance warning effectiveness, particularly in emergency situations.

4.4.3 Reflection. During the second iteration, physical prototype testing provided deeper insights into the nuances of user interaction with the lighting system. User feedback regarding learning curves highlighted that even the most intuitive designs require an adaptation period, prompting me to incorporate progressive guidance or conservative default settings in the final solution. Regarding color coding, the crucial feedback that "red must be distinguishable from existing interior indicator lights" underscored that design cannot exist in isolation but must integrate into the vehicle's overall information ecosystem. The conclusion that continuous light strips outperform point light sources further validated the advantages of linear light sources in conveying continuous information, such as movement trajectories or distance changes. However, this round's prototype failed to fully demonstrate the intended effect due to LED hardware malfunction, exposing risks in technical implementation. Future iterations must prioritize contingency plan preparation. While users' disappointment over "unable to distinguish obstacle types" falls beyond the current design scope, it prompts reflection: Could multimodal combinations (e.g., sound) compensate for this limitation? This insight will guide my exploration of richer interaction dimensions in the Final Model Prototype (FMP).

5 Discussion

Through two rounds of design iterations and user testing, this study preliminarily validated the feasibility and user acceptance of in-vehicle dynamic lighting as an information alert medium.

5.1 Theoretical Significance of Findings

Re-validation of Peripheral Vision and Cognitive Load: This study found that drivers can perceive lighting changes at locations such as the A-pillar and lower window edges via peripheral vision while maintaining focus on the forward field of view. This result aligns with Berencsi et al.'s research on peripheral vision function [6] and Wolfe et al.'s study on brake light detection under distraction [7], further confirming the potential of peripheral vision in driving information transmission. Notably, users explicitly stated that "medium brightness is most appropriate."

Semantic Consistency of Light Language Encoding: User feedback on color reinforcement principles for warning signal design proposed by Cao et al. [12]: red should be reserved for the highest emergency level warnings, while blue/green is suitable for general reminders. However, this study also reveals new complexities: users pointed out that red warnings must be clearly distinguished from existing red indicators in the vehicle (e.g., engine malfunction lights, seatbelt reminders), as failure to do so could lead to semantic confusion. This finding suggests that in-vehicle lighting design cannot be conducted in isolation but must be considered within the overall dashboard information ecosystem.

Spatial Representation Capabilities of Dynamic Patterns: Users widely agreed that “flashing frequency can convey distance information,” supporting the potential value of dynamic lighting in spatial perception. The association between high-frequency flashing and rapidly approaching objects appears to be cross-culturally intuitive, offering potential for establishing universal light coding. However, users' concerns about “frequent flashing causing anxiety” in complex traffic scenarios remind designers to consider contextual adaptability—not all approaching objects require equally intense warnings.

5.2 Design Implications

Light Source Form and Installation Location: Two rounds of user testing consistently demonstrated that linear light sources outperform point light sources (offering clearer directionality), while placement around the windows proves superior to positioning below the center console (better aligning with peripheral vision). This finding provides empirical evidence for the hardware layout of in-vehicle warning lights. Notably, the advantage of linear light sources extends beyond visual continuity—they also encode the direction of threat sources through their “flowing direction.”

Principle of Simplicity: Users repeatedly emphasized that “too many colors are unnecessary—2-3 are sufficient” and “entertainment features should not be added.” This feedback converges on a core design principle: the purity of the warning system. In emergency situations, any redundant information can become a cognitive burden. This principle aligns with predictions from multi-resource theories like Wickens' [9]: when the visual channel is occupied by driving tasks, auxiliary information should be presented at minimal cognitive cost.

Intelligent Adaptability Requirement: User expectations for “automatic brightness adjustment based on distance” and “day/night mode switching” reflect demands for the system's “situational awareness capability.” Warning systems should not be static signal emitters but intelligent agents capable of understanding environmental changes and dynamically adjusting presentation intensity. This requirement also resonates with Figalová et al.'s research on “ambient light conveying reliability information” [5]—the presentation of light itself carries meta-information about urgency levels.

5.3 Research Limitations

Limitations of the Experimental Environment: This study employed a simulated driving environment for testing. While users could evaluate lighting perception effects, it lacked the risk pressure and multitasking distractions present in real driving scenarios. In actual road conditions, drivers' attention allocation and emotional states differ significantly from laboratory settings, potentially affecting perception thresholds and comprehension speed for light signals. Future validation should be conducted in driving simulators or real-vehicle environments.

Sample Size and Representativeness: Due to holiday scheduling, the workshop participation fell below expectations (3 participants). The second-round user testing sample was online-based, resulting in a small overall sample size. The generalizability of conclusions requires further validation through expanded sampling.

Technical Implementation Limitations: A third iteration was planned, but the prototype failed to fully demonstrate the intended effects due to LED strip hardware malfunction. While this did not affect users' evaluation of the design concept, it diminished the persuasiveness of the prototype demonstration. Future research should prioritize hardware debugging and contingency planning.

Unexamined Variables: This study focused on light position, color, and dynamic patterns without systematically investigating the impact of specific brightness levels or flicker frequency ranges on environmental adaptability. It also did not compare combined effects of light with other modalities (sound, vibration). These variables will be incorporated into future research.

5.4 Future Research Directions

Based on the above discussion, future research may explore the following avenues:

1) Some participants in user testing suggested that “combining light with sound alerts yields better results,” indicating that multimodal integration is a viable approach to enhance the robustness of warning systems. Subsequent studies could investigate synergistic presentation strategies combining light with auditory cues (directional alert tones) and tactile feedback (steering wheel vibration), evaluating their combined impact on reaction times and perceived workload.
2) This study preliminarily validated the feasibility of “dynamic frequency variation based on distance.” Future work could develop a more refined coding system—e.g., segmenting threat zones into “long-range indication (green pulsing) → mid-range warning (yellow flashing) → emergency alert (red high-frequency)”—and test user acceptance of different threshold settings for each segment.
3) While this study mentions potential applications in autonomous driving modes, it does not deeply explore the interference effects of light perception on non-driving tasks (e.g., watching videos, reading). Future research could test the perceptibility of light signals under varying cognitive loads by requiring subjects to perform secondary tasks within simulated autonomous driving environments.
4) Color semantics vary across cultures (e.g., red symbolizes good fortune rather than danger in some cultures). As participants were primarily Asian individuals from China and the Netherlands, future studies should expand to broader cultural contexts to validate the cross-cultural stability of light-based coding systems.

6 Conclusion

This study explores the potential of real-time interior lighting as an information interaction medium, with the core objective of enhancing driving safety. Through two rounds of design iterations and user testing, the research yielded the following key conclusions:

First, the interior lighting warning system demonstrates user acceptance and practical feasibility. Questionnaire surveys revealed that the vast majority of drivers are dissatisfied with existing information acquisition methods and are willing to try using interior lighting to obtain external environmental information. User testing further validated the effectiveness of light prompts in simulated scenarios, demonstrating their potential as a valuable supplement to existing ADAS systems.

Second, user preferences for key design parameters were identified:

1) Installation location: Peripheral visual areas like the A-pillar and lower window edges are preferred, avoiding positions requiring significant visual shifts (e.g., below the center console);
2) Light source form: Linear light sources are preferred over point sources, as they more intuitively convey directionality and motion trajectories;
3) Color coding: 2-3 colors recommended—red for highest urgency (distinguishable from other red interior indicators), blue/green for general alerts;
4) Dynamic patterns: Flashing frequency effectively conveys distance information; high-frequency flashes should correlate with high urgency;
5) Brightness settings: Medium brightness is optimal, with automatic day/night adjustment required.

Third, the fundamental principles for warning system design were established:

1) Simplicity: Information coding should be concise and intuitive, avoiding cognitive overload;
2) Purity: The system should maintain functional focus, avoiding entertainment elements;
3) Contextual Adaptability: Brightness and dynamic intensity should dynamically adjust based on environmental conditions and threat levels;
4) Learnability: Although an initial learning curve exists, users can develop natural peripheral awareness after brief usage.

Fourth, the applicability of the Reflective Transformative Design Process (RTDP) in in-vehicle interaction design research was validated. This method employs a cyclical iteration of "Envision-Integrate-Prototype-Validate-Reflect," enabling design solutions to progressively converge through user feedback.

This study completed exploratory validation of fundamental parameters for in-vehicle light-based information interaction. Future research will deepen the mapping between light colors, dynamic patterns, and specific scenarios. Through larger-scale user testing and physical prototype validation, it aims to establish a guiding design paradigm and comprehensive scenario demonstration animations. These findings are expected to provide novel insights for intelligent cockpit HMI design and contribute practical solutions to enhance driving safety.

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I hereby declare that the DEEPL tool was used to translate certain Chinese terms into English within this research. I acknowledge that I used ChatGPT-generated images as a foundation and then refined them during the storyboard design process.

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APPENDIX

Preset Intentions

1) Have you obtained a driving licence? Do you possess driving experience?

2) When driving, do you find it easy to overlook the vehicle's surroundings?
○ Very easy – ○ Easy – ○ Average – ○ Not easy – ○ Very difficult

3) What is your most frequently used method for perceiving vehicle surroundings? (e.g. rear-view mirrors, in-screen displays)

4) Do you consider these methods inadequate for alerting drivers? If so, where do the shortcomings lie?

5) Would you prefer more convenient methods for perceiving external vehicle information?
○ Very much so – ○ Somewhat – ○ Neither – ○ Not at all – ○ Not at all

6) Would you be willing to try using interior lighting to indicate external vehicle surroundings?
○ Very willing – ○ Willing – ○ Neither – ○ Unwilling – ○ Not at all

UEQ

Do you agree that this method of perceiving external information via interior lighting is:

1) User-friendly?
○ Strongly agree – ○ Agree – ○ Neutral – ○ Disagree – ○ Strongly disagree

2) Distinct?
○ Strongly agree – ○ Agree – ○ Neutral – ○ Disagree – ○ Strongly disagree

3) Appealing?
○ Strongly agree – ○ Agree – ○ Neutral – ○ Disagree – ○ Strongly disagree

4) Extremely clear?
○ Strongly agree – ○ Agree – ○ Neutral – ○ Disagree – ○ Strongly disagree

5) Effective?
○ Strongly agree – ○ Agree – ○ Neutral – ○ Disagree – ○ Strongly disagree

6) Efficient?
○ Strongly agree – ○ Agree – ○ Neutral – ○ Disagree – ○ Strongly disagree

7) Reliable?
○ Strongly agree – ○ Agree – ○ Neutral – ○ Disagree – ○ Strongly disagree

8) Novel?
○ Strongly agree – ○ Agree – ○ Neutral – ○ Disagree – ○ Strongly disagree

9) Liked?
○ Strongly agree – ○ Agree – ○ Neutral – ○ Disagree – ○ Strongly disagree

10) Effortless process?
○ Strongly agree – ○ Agree – ○ Neutral – ○ Disagree – ○ Strongly disagree

Welcome to the test!
Pre-test preparations

1) Please complete the informed consent form by filling in the grey-shaded sections of the document Consent form-X.L. Signatures must be in English. You may either paste a signed image directly or convert the form to PDF before signing.

2) This test is to be completed on a computer. Please sit facing the screen.

3) Activate your recording device (either via computer audio capture or a separate mobile recording app) to record your responses.

Background

As the cabin environment of autonomous vehicles becomes increasingly intelligent, the proliferation of visual information from diverse systems—including infotainment and HUD—has grown more complex, potentially distracting drivers. Consequently, in scenarios still requiring driver intervention, there exists a risk that drivers may fail to respond promptly when necessary. How to enable drivers to extract information from such contexts has thus become a focus of research.

Dynamic cabin lighting offers a potential solution, conveying environmental information to the driver through variations in brightness, position, colour, and motion effects. The research objective is therefore to investigate how real-time cabin lighting language can assist drivers in more readily acquiring information about their surroundings.

The purpose of this test is to evaluate the appropriateness and effectiveness of colour and dynamic changes in relation to the information cues being conveyed.

Test part 1

When an object passes by externally, the corresponding interior light illuminates to alert the driver of the object's passage and its approximate location (please play the video).

1) Where or in which locations within the vehicle would you consider this light most suitable?

2) Do you believe this method would enable you to detect objects passing through the corresponding area?

3) Do you perceive any shortcomings in these methods regarding alerting the driver?

Test part 2

When objects pass by or linger near the vehicle, the corresponding interior lights illuminate. Initially, the light changes gradually; as proximity increases, the flashing becomes more frequent. (Please play the video).

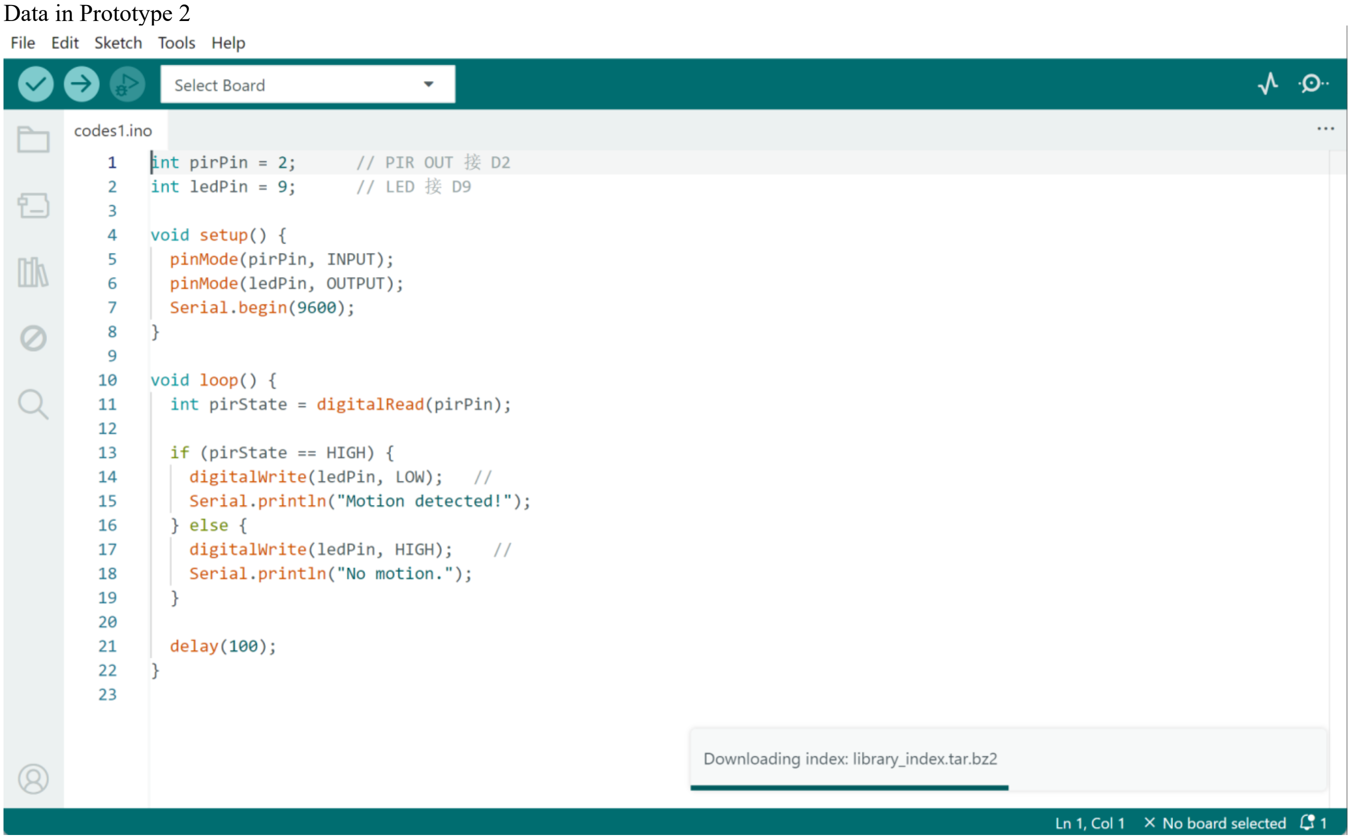
1) Do you believe that variations in flashing frequency could indicate the passage of objects at corresponding locations and changes in their relative distance?

2) In your view, would multi-coloured flashing animations effectively capture a driver's attention?
If feasible, would you consider this overly complex? Or would a single colour be more appropriate? If so, which colour would be preferable?
If not feasible, what colour or animation effect would you consider more suitable? (Note: This could also involve changes to the light strip's animation effect.)

3) Do you believe different colours should correspond to different scenarios? If so, what distinctions in external information would need to be made to justify using different colours?

4) Do you perceive any shortcomings in these methods for alerting drivers?

Data in Prototype 2



Information sheet for research project "Exploring of information transmission function of vehicle interior lights"

1. Introduction

You have been invited to take part in research project Exploring of information transmission function of vehicle interior lights, because you are invited by personal network.

Participation in this research project is voluntary: the decision to take part is up to you. Before you decide to participate we would like to ask you to read the following information, so that you know what the research project is about, what we expect from you and how we deal with processing your personal data. Based on this information you can indicate via the consent declaration whether you consent to take part in this research project and the processing of your personal data.

You may of course always contact the researcher Xinyue Liu via *x.liu2@student.tue.nl*, if you have any questions, or you can discuss this information with people you know.

2. Purpose of the research

This research project will be managed by Xinyue Liu.
The purpose of this research project is to fidure out how real-time vehicle interior light language can make it easier for drivers to gain information from surrounding areas.

3. What will taking part in the research project involve?

You will be taking part in a research project in which we will gather information by:

- Asking you to visit a location 1 time so we can interview you about experience after each projected content or different scenarios in test
- Interviewing you about experience after each projected content or different scenarios in test and to write down/record your answers via audio/video. Also, we will make a transcript of the interview.
- Observation
- ......

This study will be completely anonymous, and the data obtained from the study will not be traceable to you.

For your participation in this research project you will not be compensated.

4. Potential risks and inconveniences

Your participation in this research project does not involve any physical, legal or economic risks. You do not have to answer questions which you do not wish to answer. Your participation is voluntary. This means that you may end your participation at any moment you choose by letting the researcher know this. You do not have to explain why you decided to end your participation in the research project. Ending your participation will have no disadvantageous consequences for you.

If you decide to end your participation during the research, the data which you already provided up to the moment of withdrawal of your consent will be used in the research. Do you wish to end the research, or do you have any questions and/or complaints? Then please contact Xinyue Liu via *x.liu2@student.tue.nl*.

5. Confidentiality of data

The raw and processed research data will be retained for a period of 2 years. Ultimately after expiration of this time period the data will be either deleted or anonymized so that it can no longer be connected to an individual person. The research data will, if necessary (e.g. for a check on scientific integrity) and only in anonymous form be made available to persons outside the research group.

This research project was assessed and approved on 18-11-2025 by the ethical review committee of Eindhoven University of Technology.

<u>* Scroll down for the consent form ***</u>**

EINDHOVEN UNIVERSITY OF TECHNOLOGY

Consent form for participation by an adult

By signing this consent form I acknowledge the following:

1. I am sufficiently informed about the research project through a separate information sheet. I have read the information sheet and have had the opportunity to ask questions. These questions have been answered satisfactorily.

2. I take part in this research project voluntarily. There is no explicit or implicit pressure for me to take part in this research project. It is clear to me that I can end participation in this research project at any moment, without giving any reason. I do not have to answer a question if I do not wish to do so.

Name of Participant:

Signature:

Date:

Name of researcher:

Signature:

Date:

Severens, Marjolein 代表 Ethics

收件人: Liu, Xinyue

☺ 答复 全部答复 转发 ...

周二 2025/11/18 11:56

此消息的语言为 英语

翻译至 中文 (简体)

始终不翻译 英语

Dear Xinyue,

Your application (ERB2025ID541) with project title “Exploring of information transmission function of vehicle interior lights” has been approved by the ERB.

We assume that you have answered all questions correctly. We will perform regular spot-checks so you need to keep your documentation (ERB form, informed consent forms, surveys/interview questions, description of experiment/prototype etc.) available for at least 6 months.

We wish you the best of luck with your research and a pleasant day.

Best regards,

Marjolein Severens
ERB student assistent

...

答复 转发