Using interior lighting design to enhance the driver's perception of key information around the vehicle

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(7355 words)

ABSTRACT

As autonomous driving technology progresses from Level 3 conditional automation to Level 5 full autonomy, the role of the driver is shifting from that of an active operator to a passive monitor. During this transition, how to effectively enhance the driver's perception of key information regarding the vehicle's surroundings without increasing cognitive load has become a key challenge in human-machine interaction design. This study focuses on the potential of in-vehicle lighting as a medium for conveying information, exploring its effectiveness and comprehensibility within the peripheral visual field. The research first outlines the trend of in-vehicle lighting evolving from a purely illuminating function to an interactive one, and proposes a design solution by integrating colour semantics, dynamic patterns and cognitive load theory. Through two rounds of user testing, utilising video-simulated driving scenarios, the study compared participants' reaction times to pedestrians in different positions around the vehicle under conditions with and without lighting. The results indicate that the average reaction time of test subjects was significantly improved under lighting conditions, with pedestrians ahead being identified more effectively than those on either side, and those on the right slightly more effectively than those on the left. Blue lighting performed particularly well in rapid-response scenarios, whilst red lighting proved more effective as a warning signal in slow-response scenarios; the effectiveness of lighting cues was higher in night-time environments than during the day. This study validated the feasibility of in-vehicle lighting as a human-vehicle interaction medium characterised by low cognitive load and high perceptual efficiency. It also proposed a design paradigm to guide practical implementation, providing both theoretical grounds and empirical support for the interaction design of smart cockpits.

KEYWORDS

Interior lighting, Peripheral vision, Smart cockpit, Human-machine interaction

1 Introduction

1.1 The Development of Autonomous Driving Technology

The classification standards for autonomous driving are established by the J3016 standard developed by SAE International. First published in 2014, the standard was adopted by the US Department of Transportation in 2016 as a global industry reference standard and has since been widely adopted by the global automotive industry. [1] The standard classifies driving automation into six levels, ranging from L0 to L5, where L0 represents no automation, L1–L2 constitute driver assistance, and L3–L5 fall within the category of 'autonomous driving'. Level 3 represents conditional automation. At this level, the Automated Driving System (ADS) can sustainably perform all dynamic driving tasks within its Operational Design Domain (ODD), including lateral and longitudinal control, as well as environmental monitoring and response. This means that in specific scenarios (such as motorway congestion or designated closed sections), the driver may divert their attention from driving tasks to engage in other activities, such as reading or watching videos. However, for safety reasons, the driver is still required to keep their hands on the steering wheel, ready to take control should the rare need for intervention arise. At Level 4, driving tasks no longer require driver intervention; in the event of system failure or situations outside the design scope, the system automatically executes a strategy that minimises risk. Level 5 represents fully autonomous driving, where driving tasks no longer require human intervention; at this stage, there is no longer a need for a driver in the vehicle, and everyone on board can be a passenger.[2]

In December 2025, China's Ministry of Industry and Information Technology formally approved applications for the market entry of certain Level 3 autonomous driving products, marking a crucial step in the transition of Level 3 autonomous driving in China from the testing phase to commercial application.[3] Level 4 autonomous driving is already commonplace in the robotaxi sector. In the foreseeable future, autonomous driving will become increasingly widespread and advanced.

1.2 Background and Social Needs

In terms of policy, the concept of smart cities has gained significant traction in China. Within this framework, smart transport is an indispensable and high-priority component.[4] On the market front, China's transport sector demonstrates a strong focus on technological innovation. New technologies that enhance the user experience for the majority of people are highly sought after by the market, a trend reflected in sales figures.[5]

Some roads in Chinese cities are narrow, with a complex mix of road users and a marked presence of mixed traffic. A combination of factors, including historically inherited irregular junctions, high-density plot openings, the intermingling of motor vehicles and electric bicycles, on-street parking, construction hoardings, and pedestrians jaywalking, creates a complex road environment, increasing the uncertainty and danger of the transport system. [6, 7] Many of China's old urban districts were developed before the widespread adoption of motor vehicles; consequently, road widths are limited, buildings line the streets densely, and side streets and minor arterial roads are generally narrow. Furthermore, blind spots pose a safety hazard. These issues will not be resolved simply by advancements in autonomous driving technology. While people place their hopes in autonomous driving to make all decisions, they will still harbour doubts regarding the external environment. Therefore, although this study selects China as its research setting, it is not limited to this country and is equally applicable to other nations or regions facing similar challenges.

1.3 Driving Safety and Problem Identification

Driving safety has always been a central concern in research on human-vehicle interaction. In manual driving scenarios, blind spots pose a constant threat to drivers. Bicycles or electric scooters that appear suddenly are often difficult to spot in time. This not only causes psychological stress for the driver but may also lead to serious traffic accidents. At the same time, objects in the vehicle's surroundings that fall outside the driver's field of vision are highly likely to cause scrapes and dents to the vehicle body, which is equally worthy of attention. It is worth noting that this problem has not been resolved by the increasing level of driving automation. Research indicates that, in the case of current mainstream semi-autonomous vehicles, drivers are actually more prone to distraction due to a reduction in operational tasks and the complexity of visual information.[8] In emergency situations requiring manual intervention, the issue of delayed reaction times is even more pronounced than in manual driving.

These two scenarios, the limited field of vision in manual driving and the cognitive disengagement in autonomous driving, both point to a core issue: how can we effectively enhance drivers' ability to perceive critical information? The common approach to addressing this lies in providing appropriate cognitive stimulation; that is, reminding, warning and guiding drivers in the right way at critical moments. Based on this assessment, this study has selected lighting as the medium for conveying information. This choice not only aligns with the researchers' longstanding academic interests but also offers a potential design solution to the aforementioned problem.

1.4 Research question

The research question is therefore: how can in-vehicle lighting design be used to effectively enhance drivers' perception of key information regarding the vehicle's surroundings? Specifically, this study aims to: (1) explore the effectiveness of the spatial positioning, colour language and dynamic patterns of in-vehicle lighting in conveying information; (2) validate the comprehensibility and usability of the design proposals through user testing; and (3) establish a design paradigm for in-vehicle lighting information interaction that can guide practical applications.

2 Related Works

2.1 Research on Vehicle Interior Lighting

Over the past few decades, vehicle interior lighting systems have undergone significant functional evolution. In the early days, interior lighting primarily served practical purposes, such as reading lights that activated automatically when a door was opened, or overhead lights used to locate items. Such systems were characterised by simple, static functional modes. With the widespread adoption of LED technology, vehicle lighting has entered a new phase of dynamic control. The brightness, colour and sequence of changes of LED lights can all be adjusted independently. This has enabled lighting systems to evolve from mere practical tools into interactive media with the potential to convey information, thereby driving research into the interactive capabilities of in-vehicle lighting. [9] This integration of information transmission constitutes 'light language'. As an emerging form of multimodal interaction, it utilises differentiated lighting effects to form a language system with specific meanings, thereby conveying reliability. [10] Through lighting variations in brightness, position, colour and dynamic effects, different messages are conveyed to the driver. [11]

Dynamic lighting is highly effective as a carrier of information. Bullough's research systematically summarised the fundamental coding principles of traffic lights, pointing out that dynamic characteristics (such as flashing frequency) can be used to convey supplementary information, including the level of urgency. [12] Löcken et al. investigated the auxiliary role of ambient light bands in lane-change decisions and found that the direction of light flow can effectively guide the driver's visual attention. Pfromm et al., meanwhile, explored how spatially referenced optical information can enhance the effectiveness of driver assistance systems. The spatio-temporal characteristics of dynamic lighting effects—such as the direction, speed and rhythm of light flow—are capable of conveying semantic information. In their research, dynamic effects such as blinking, jumping blocks and fading from left to right each demonstrated distinct advantages.[13] Case studies examined the information-conveying capabilities of different dynamic lighting effects on the front of a vehicle. Although the research objectives differ, these lighting effect case studies can also be referenced in this study for the design of lighting effects.

Light colour is one of the core coding dimensions for information communication within a vehicle; its effectiveness is based both on collective consensus regarding colour semantics and on relevant regulatory frameworks. A cross-national empirical study conducted by Weirich et al. systematically examined the emotional associations and semantic perceptions of ten colours in automotive contexts. The results indicate that, for the key warning semantic of 'attention', European participants exhibited significant hue dependence. Specific colours (such as red and yellow) were more strongly associated with warning meanings. However, Chinese participants, conversely, demonstrated a high level of attention towards blue. This suggests that cross-cultural differences may exist in the perception of colour semantics.[9] Consequently, in this study, red and blue were selected as the primary test colours for investigation.

2.2 Visual Attention and Cognitive Load

A driver's attentional resources are limited. Cognitive load reduces visual attention whilst driving, thereby diminishing alertness and confidence. [14] Increases in both cognitive and visual load lead to longer reaction times during driving tasks. Visual cognitive load reduction strategies for interfaces or vehicle interiors, when approached purely from a design perspective, require certain design conventions; for example, colours must adhere to universally recognised colour conventions (red = danger/stop, yellow = warning, green = normal/go, blue = information, etc.) to reduce the learning curve and the risk of misjudgement.

Ambient lighting systems are defined as a class of systems operating at the periphery of human attention, using light as a medium to convey information in a non-intrusive manner in the vast majority of cases.[9] The principle behind this lies in Peripheral vision, which involves broader observation and interaction within the observer's field of view, centred on the head and line of sight. [15] Drivers can perceive changes in lighting without having to shift their visual focus away from their current point of focus or unfocused area, thereby enabling rapid cognitive processing of the information.[16] Increasing the sensitivity of Peripheral vision—that is, providing clear visual cues—can also be achieved through interior lighting, allowing information to be perceived through passive observation.

2.3 In-car information display functions – active and passive

Interior lighting in vehicles can serve an informational purpose, and research in this area is growing. For example, displays within the vehicle interior can be used to convey the vehicle's immediate driving plan and surrounding information to passengers. Safety alerts and status indicators are the most fundamental and critical functions of lighting language; their design principles are based on quickly and clearly capturing the driver's attention whilst conveying the severity of the risk. [17] This design principle also serves as a model for lighting designed to provide warnings. Another example is collision warning; for instance, in Mercedes-Benz's MBUX system, when blind spot monitoring is triggered, a red warning is displayed on the corresponding rear-view mirror icon and the door ambient lighting. [18] System status indicators are also present in other cases. Soft colours (such as blue or green) and dynamic modes (such as steady illumination or pulsating flashes) are used to display vehicle status, including the activation of autonomous driving mode, battery charge level, or the engagement of cruise control.

Furthermore, in January 2026, a multimodal interactive method and system for in-vehicle ambient lighting throughout the entire automated parking process officially entered the public disclosure phase. The system establishes a vehicle coordinate system and divides the in-vehicle ambient lighting into independently controllable zones. By integrating obstacle coordinates with real-time parking status, the system quantifies collision risk levels and generates flowing or pulsating lighting effects during safe operation. When a high-risk situation is detected, the system triggers an interruption protection mechanism and, based on the principle of minimum angular deviation, precisely projects warning light effects onto the corresponding illuminated zones, thereby enhancing the directionality of the warning. Once the risk has been resolved, brightness is restored to normal operating levels through the adjustment of a smooth recovery coefficient. [19]

However, it is worth noting that such designs require the driver's active attention; they are proactive in nature. In the scenarios examined in this study, which involve advanced autonomous driving technologies (Levels 3–5), the driver is not fully focused on driving; indeed, they may not even be performing any driving actions. Consequently, this study has opted to utilise peripheral vision for observation, thereby providing alerts and information to the driver in a manner that does not require their active attention.

3 Methodology

3.1 Participants

The aim of this study is to verify the reaction times of participants in various vehicle-surrounding scenarios under both lit and unlit conditions, thereby determining whether the designed lighting is effective in improving participants' perceptual efficiency. The study comprised two rounds. The first round was a preliminary test involving 10 participants. A rough prototype was used for this round, with the aim of conducting a basic feasibility assessment. The second round involved 26 participants.

G*Power was used to estimate the sample size. G*Power is a flexible statistical power analysis programme designed for the social sciences, behavioural sciences and biomedicine. [20] The t-test was selected because the primary objective of the study is to compare two conditions—with and without lighting, whilst comparisons of other conditions are merely supplementary. In G*Power, the effect size was set to 0.5, representing a medium effect size, which is widely adopted as the standard default value in behavioural and social science research. [21] It is suitable for situations where prior data is lacking, the research field is relatively new, and a robust design is sought, thereby avoiding an excessively large or small sample size. Other parameters selected: α (error probability) = 0.05, Power = 0.88. This yields a total sample size of 26 participants as appropriate. This determined the number of participants for the second round of testing.

3.2 Simulator

This preliminary test was conducted to explore feasibility; however, further factors must be considered before the design can be effectively implemented within a vehicle. Consequently, testing was not carried out in an actual vehicle or a vehicle simulator, but was instead conducted using video simulations. Test subjects were required to watch several videos filmed from the driver's perspective. They sat in a seat, kept their eyes on the video, and provided their responses. The aim of maintaining focus on the video was to simulate the situation where a driver or passenger's attention wanders after a period of autonomous driving. In the first round of testing, observations were made using both a focus box embedded within the video and the test subject's own mobile phone; however, discrepancies were still observed. In the second round of testing, observations were made using a standardised collection of embedded videos, thereby achieving greater consistency.

3.3 Driving scenario in experimental sessions

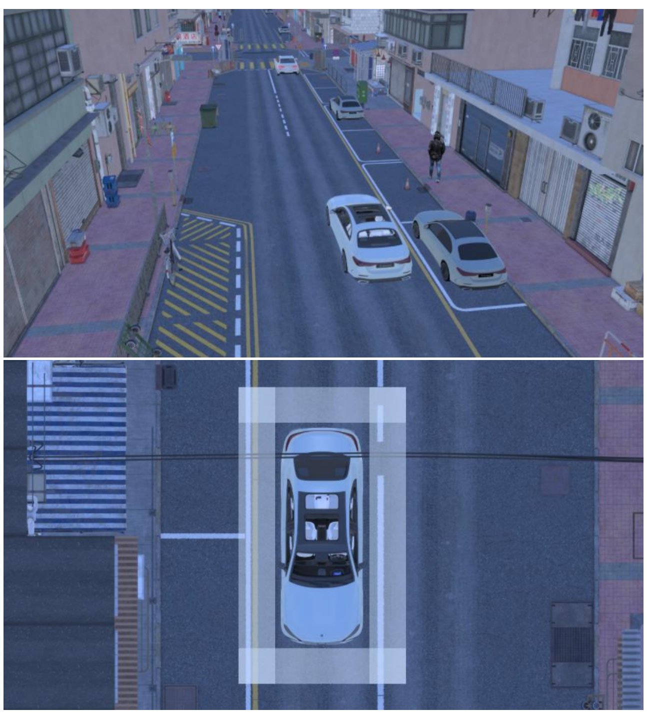

Figure 1. Driving scenario

The scenes in the video were selected from the streets of Hong Kong (as shown in Figure 1), with the following adjustments made: (1) The street layout was redesigned to conform to the road standards of mainland China; (2) A certain number of moving vehicles and pedestrians were added; (3) Day and night sky conditions were simulated. Consequently, the test video retains the problem scenario, namely, narrow streets combined with complex traffic conditions, thereby better addressing the issues within the design context. In the first round of testing, during the phase requiring a response from the tester, pedestrians will appear from four different positions: to the left, right, and just ahead to the right of the vehicle, with the latter scenario involving a pedestrian very close to the vehicle. In the second round of testing, during the phase requiring a response from the tester, pedestrians will appear from three different positions: directly in front, to the left, and to the right of the vehicle. On this basis, variations in lighting conditions were then introduced.

In the video, the vehicle maintains a speed of 30 km/h, which is a suitable speed for narrow streets. According to Article 45 of the Regulations for the Implementation of the Road Traffic Safety Law of the People's Republic of China, on urban roads without a centre line, the maximum speed of motor vehicles shall not exceed 30 kilometres per hour. [22] The 30 km/h limit also stems from national standards for the functional classification of urban roads, with different road categories having corresponding design speed ranges: arterial roads: 40–60 km/h; collector roads: 30–50 km/h; and local roads: 20–40 km/h. This is the case in most countries. Furthermore, a report by the World Health Organisation (WHO) indicates that speeds of 30 km/h or lower can mitigate the consequences of accidents.[23] Consequently, 30 km/h is the typical design speed for secondary arterial roads and has been selected as the speed standard for testing purposes.

3.4 Variables

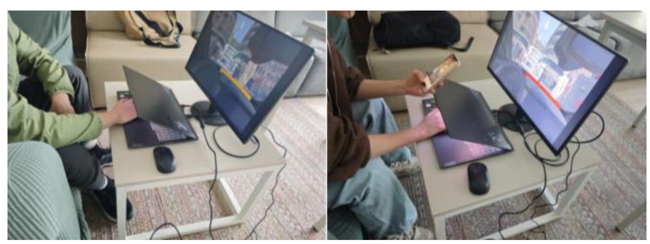

Figure 2. Test picture 1

In the first round of test videos (as shown in Figure 2), the proposed variables included the presence or absence of lighting, as well as four specific lighting scenarios. These corresponded to: a pedestrian on the left with a blue light on the left; a pedestrian on the right with a blue light on the right; a pedestrian ahead on the right with a red light ahead; and a pedestrian very close ahead on the right with a light changing from red to amber ahead. In the second round of test videos (as shown in Figure 3), the proposed variables were day and night, with or without lighting, two light colours (blue and red), and three scenarios involving lighting. As shown in Figure 4, these correspond to: a pedestrian on the left with a light on the left, a pedestrian on the right with a light on the right, and a pedestrian ahead with a light ahead. Compared to the first round, the dynamics of fixed lights have been incorporated, and colour has also been included as a unifying factor. It is worth considering that, in addition to the specified lights, there are other variables, such as differences in the angle at which the mobile phone is held in the first round of testing, variations in the level of concentration among different testers, and differences in peripheral vision perception among testers, all of which are variables that could be explored in future research.

Figure 3. Test picture 2

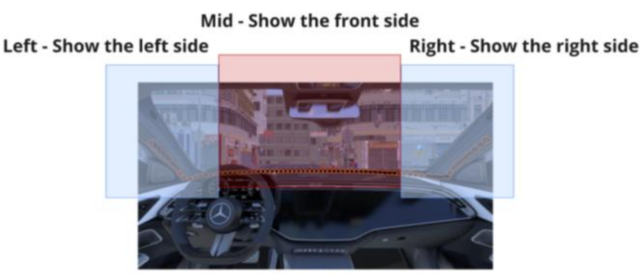

Figure 4. Positions of the designed lights

3.5 Secondary task

Test participants were asked to simulate a scenario in which their attention wandered after driving for a certain period whilst the video was playing. Therefore, in the first round of testing, participants were required to focus on a focus box embedded within the video or on their own mobile phones. In the second round, participants were required to read a novel embedded on the same mobile phone.

3.6 Procedures and instructions to participants

Participants were first briefed on the background and objectives of the study, followed by an explanation of the testing procedure and a Q&A session. During the test, participants were asked to watch the video out of the corner of their eye and press a button when they saw a light come on or a pedestrian come very close to the vehicle (whichever occurred first). The time at which they pressed the button was automatically recorded. After the test, participants were asked to complete a user experience questionnaire and a brief interview.

3.7 Statistical analysis

Once all the test data has been collected, it is processed as follows: (1) Irrelevant data (such as accidental button presses) is deleted; (2) In cases where a button is pressed multiple times, the first instance of the data is retained; (3) The data is rounded to two decimal places; (4) As the data is random, it is rearranged according to different scenarios. The data is then analysed using charts and graphs.

4 Iteration and test

4.1 Iteration 1

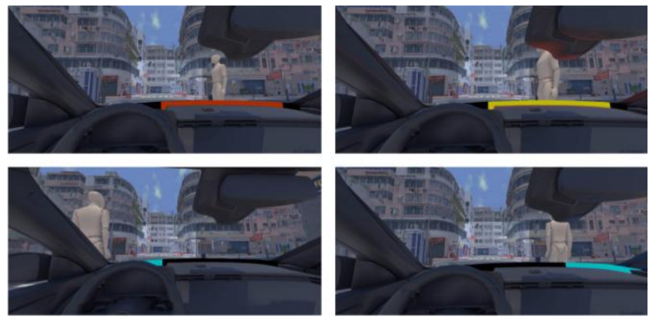

Figure 5. Lights in iteration 1

The lighting test videos are divided into four scenarios (as shown in Figure 5): pedestrians on the left correspond to the blue light on the left; pedestrians on the right correspond to the blue light on the right; pedestrians to the front and right correspond to the red light at the front; and pedestrians to the front and right who are very close correspond to the light at the front that transitions from red to amber. The reason for this is that red and amber convey a stronger sense of caution and warning, and pedestrians in front pose a greater danger. Blue is generally associated with conveying information; pedestrians on either side do not pose such a significant danger, and the information provided is sufficient. The lights are static and rely on proximity sensors to illuminate when a pedestrian approaches and switch off when the pedestrian moves away.

4.2 Test 1

4.2.1 Preparation. Participants were asked to watch 32 videos, each lasting 15 seconds. The 32 videos were divided into two sets of 16, which were played in a completely randomised order. The 16 videos comprised a cross-mix of scenarios involving lights on and lights off, as well as four different lighting conditions. Participants were instructed to focus on either the on-screen focus box or their own mobile phone, depending on the requirements of each video, whilst observing the video out of the corner of their eye. They were to press a button upon observing the lights come on or a pedestrian coming very close to the vehicle (whichever occurred first). Following the test, participants were asked to complete a user experience questionnaire and a brief interview. A total of 10 people took part in the test.

4.2.2 Results and Reflections.

Figure 6. Test 1 – Result 1

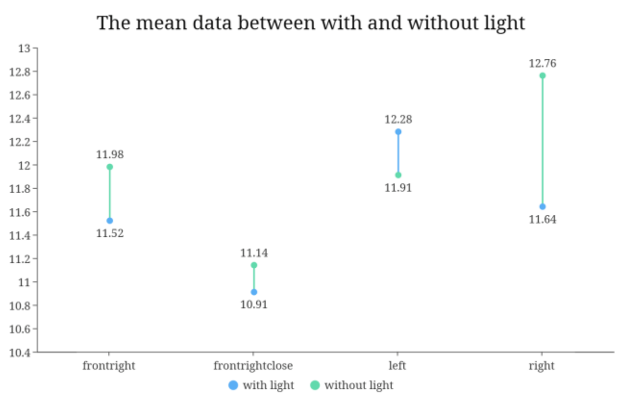

Figure 7. Test 1 – Result 2

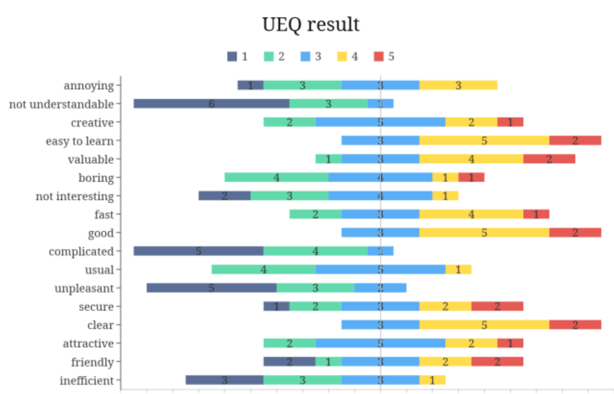

Figure 8. Test 1 – Result 3

As shown in Figure 6, this graph illustrates the relationship between the number of tests conducted during different reaction time intervals and the position of the light. It should be noted that the number of tests does not correspond exactly to the number of participants, as some tests were repeated. It can be observed that, for the right-hand side, when the light was present, the highest number of responses from participants occurred between 12 and 13 seconds, whereas when the light was absent, the highest number of responses occurred between 13 and 14 seconds. On the left-hand side, when lighting was present, the highest number of responses occurred between 13 and 14 seconds, whilst a proportion of participants failed to respond in time and were therefore not recorded. For the front-right position at close range, when lighting was present, the highest number of responses occurred between 11 and 12 seconds, whereas when lighting was absent, the highest number of responses occurred between 12 and 13 seconds. For the front-right position, the results with and without lighting were relatively similar. Overall, the time intervals in which the fastest reactions were recorded were consistently shorter when lights were present than when they were absent.

As shown in Figure 7, this chart compares the average reaction times with and without lighting under different conditions. With lighting, the average reaction times for the front right, front right (very close), left and right were 11.52s, 10.91s, 12.28s and 11.64s respectively. In the absence of lighting, the figures are: 11.98 s, 11.14 s, 11.91 s, and 12.76 s. With the exception of the left-hand side, reaction times were faster when lighting was present than when it was absent. It should be noted that, for situations where neither lighting nor pedestrians were observed, the maximum value of 15 s from the video was used for calculation purposes.

As shown in the figure 8, this is a user experience chart where scores range from 1 to 5, with higher scores indicating greater agreement with the statement. It can be seen that, among the positive descriptors, ‘easy to learn’, ‘valuable’, ‘good’ and ‘clear’ received the highest levels of agreement. Among the negative descriptors, ‘not understandable’, ‘complicated’, ‘unpleasant’ and ‘inefficient’ received the lowest levels of agreement. This points to a positive conclusion regarding user experience.

Table 1. Ideas from the interview

Answer	Amount
Lighting effectiveness	10
Colour preferences	
Reasonable or acceptable	7
Unreasonable or problematic	3
Consider blue to be more eye-catching	4
Consider red to be more eye-catching	1
Consider it to be related to brightness/contrast; the colour itself is unimportant	8
Using a single colour	1
Customise colours	2
Colour distinction	
Colour distinction is necessary	4
Unnecessary, position is sufficient	2
No preference	4
Attitude towards flashing	
Support flashing	4
Opposed to flashing	3
Neutral/no preference	3
Static vs dynamic	
In favour of flowing/slow motion	5
Prefer static (information is direct)	1

As shown in Table 1:

With regard to lighting effects, a total of 10 respondents mentioned this aspect, indicating that it is a key consideration for the vast majority. Lighting effects received the highest frequency of support, suggesting that factors such as light intensity, direction and uniformity have a direct impact on the user experience in interface or environmental design. Respondents generally agreed that good lighting enhances information readability and visual comfort, making 'lighting effects' the most widely recognised metric.

Regarding the assessment of colour scheme appropriateness, seven respondents deemed it "reasonable or acceptable", whilst three considered it "unreasonable or problematic". This distribution indicates that the majority hold a positive view of the current colour scheme, yet nearly a third raised concerns, suggesting that designers must address the pain points of minority groups, such as colour vision differences or issues with discernibility in low-contrast environments.

Regarding the perceived appeal of colours, four respondents felt that blue was more eye-catching, whilst only one felt that red stood out more; a further eight stated that the colour itself was unimportant, with the key factors being brightness or contrast. This indicates that the vast majority of respondents are not fixated on specific hues, but are more concerned with how colours convey information through variations in light and dark or the intensity of contrast. Consequently, in design strategy, prioritising sufficient brightness and contrast may be more practical than debating whether 'blue or red is better'.

Regarding colour usage strategies, only one person supported the use of a single colour, whilst two hoped for customisable colours. This suggests that minimalist colour schemes have a limited audience, and whilst there is a demand for personalisation, it is not particularly strong. The majority of respondents did not express a clear preference on this point, which may suggest that the current colour scheme already meets basic usage requirements.

Regarding the necessity of colour differentiation, four respondents believed that 'colour differentiation is necessary', two felt that 'position alone is sufficient, with no need for colour differentiation', and a further four stated they had 'no preference'. This result presents a relatively balanced distribution: those in favour of colour differentiation hold a slight advantage, but there are still a significant number of users who believe positional information is sufficient for identification. Therefore, colour can serve as an auxiliary coding method, but should not be the sole means of distinguishing information.

Regarding feedback on flashing, 4 respondents supported it, 3 opposed it, and 3 were neutral or had no preference. It is evident that users' attitudes towards flashing are clearly divided. Supporters may believe that flashing is effective at attracting attention, whilst opponents are concerned that it may cause visual fatigue or discomfort. Consequently, flashing should be used with caution, preferably reserved for high-priority alerts, and options to disable or adjust the frequency should be provided.

Finally, regarding preferences for static versus dynamic presentation, five respondents favoured motion or slow-motion effects, whilst only one preferred static (direct information) displays. This indicates that dynamic visual presentation methods—such as gradients, slow movement or transition effects—are more popular, as they enhance user immersion and the information comprehension process. However, static presentations also have their place; for instance, when key figures need to be consulted quickly, a direct static display is more efficient.

In summary, respondents generally prioritise lighting effects and contrast, whilst the specific hue of the colour itself is not critical; the necessity of colour differentiation is debatable, but there is a slight leaning towards 'necessary'; flashing should be used with caution; and dynamic, slow-moving visual presentations are preferred. In design, priority should be given to ensuring good lighting and contrast, using colour coding moderately (without over-reliance), providing control options for flashing, and prioritising smooth dynamic effects to enhance the user experience.

Consequently, the following conclusions can be drawn: (1) Under normal circumstances, the presence of lighting does indeed improve the test subjects' reaction times. (2) Test subjects tend to notice pedestrians and lighting in front of them sooner than those on either side. (3) The effect of the distance to pedestrians in front is not particularly pronounced. (4) It is appropriate to incorporate smooth animation effects. (5) The user experience yields positive results.

There are also some points for reflection: (1) Within the same overall context, different areas should not be distinguished by colour; instead, tests should be conducted on the same position using different colours. Otherwise, it becomes unclear whether the results are due to differences in area or differences in colour. This will be corrected in the second round of testing. (2) Different testers held their mobile phones at varying angles and positions; whilst this reflects real-life usage (as people use their own devices), it significantly influenced the results. Consequently, a standardised approach was adopted for the second round of testing.

4.3 Iteration 2

The lighting test videos cover a variety of scenarios (as shown in Figure 9): pedestrians on the left correspond to the lights on the left, pedestrians on the right correspond to the lights on the right, and pedestrians ahead correspond to the lights in front. Both red and blue lights were tested. The lights are dynamic (as shown in Figure 10); they are activated by proximity sensors when a pedestrian approaches and deactivate when the pedestrian moves away. Subsequently, depending on whether the pedestrian changes direction or leaves, the lights either change position or remain off. The movement of the lights consists of a smooth, directional sequence, with the direction of the light aligning with that of the pedestrian.

4.4 Test 2

4.4.1 Preparation. Test subjects were asked to watch 36 videos, each lasting 74 seconds. The videos were divided into two sets of

18, which were played in a completely randomised order. The 18 videos were a cross-combination of daytime and night-time scenes, with and without lighting, and three different lighting scenarios. Participants were instructed to focus on a mobile phone displayed on a screen in front of them, reading a novel whilst observing the videos out of the corner of their eye. They were to press a button upon observing either a light switching on or a pedestrian coming very close to a vehicle (whichever occurred first). Following the test, brief feedback was collected from the participants. A total of 26 people took part in the test.

Figure 9. Lights in iteration 2

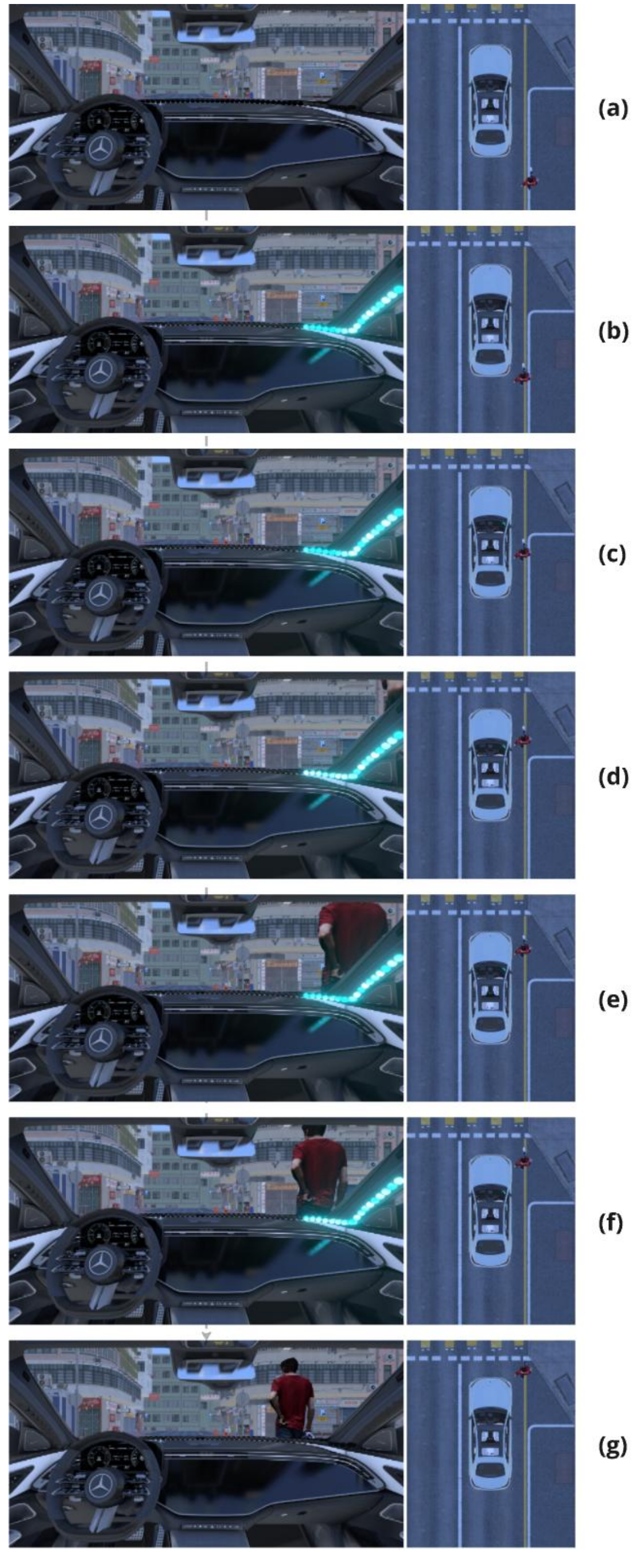

Figure 10. How the lights go

4.4.2 Results and Reflections. In the diagram below, the three letters denote different scenarios. In the first letter, 'W' stands for 'white day' and 'N' stands for 'night'. In the second letter, 'L' stands for 'left', 'F' stands for 'front' and 'R' stands for 'right'. In the third letter, 'B' stands for 'blue', 'R' stands for 'red' and 'N' stands for 'no lights'.

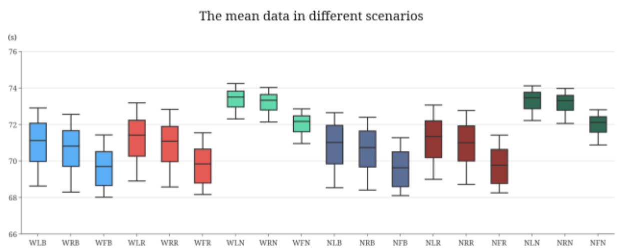

Figure 11. Test 2 – Result 1

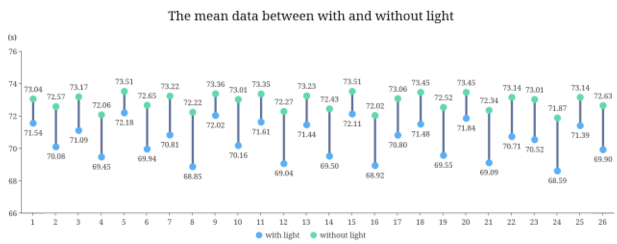

Figure 12. Test 2 – Result 2

As shown in Figure 11, this graph illustrates the relationship between different scenarios and the average reaction times of the test subjects. It can be observed that reaction times are significantly faster in well-lit conditions. There is little difference between day and night, and the trends observed across different scenarios remain consistent between the two.

As shown in Figure 12, this graph illustrates the relationship between individual test subjects and the average reaction time. It can be seen that whilst there are variations between test subjects, overall, the average reaction time is faster when lights are present.

As shown in Figure 13, this graph illustrates the relationship between the time of day (daytime or night-time) and the number of times the average reaction time was recorded. It can be seen that, in most cases, more people observed pedestrians or lights outside the vehicle at night than during the day.

As shown in Figure 14, this graph illustrates the relationship between different light colours and the number of instances of average reaction times. It can be observed that when people's reaction times are fast, blue lights are more effective as a warning. When people's reaction times are slow, red lights are more effective as a warning.

As shown in Figure 15, this graph illustrates the relationship between the position of the lights and the number of instances of average reaction time. It can be observed that pedestrians or lights in the foreground are most easily detected. The right and left sides exhibit different patterns across different reaction time intervals; for example, between 70 and 71 seconds, more people noticed the lights on the right first, whereas between 72 and 73 seconds, more people noticed those on the left. This also indicates that more people observed the lights on the right first.

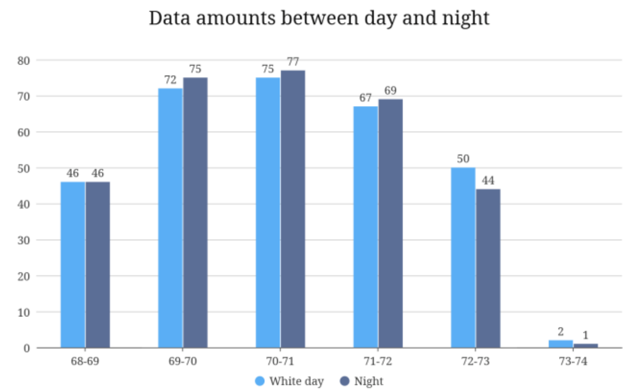

Figure 13. Test 2 – Result 3

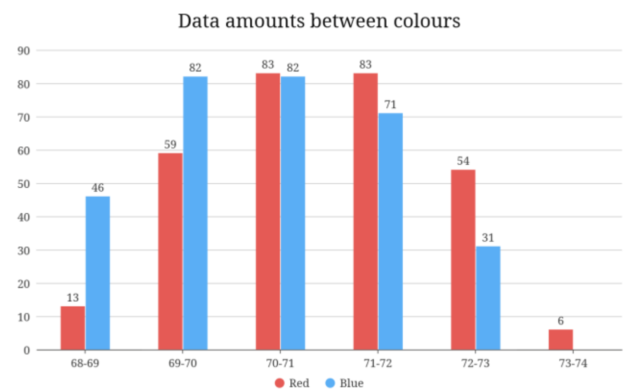

Figure 14. Test 2 – Result 4

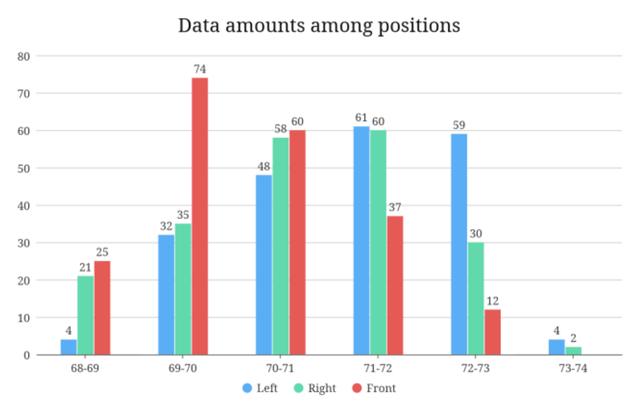

Figure 15. Test 2 – Result 5

Therefore, taking into account the results of the simple questionnaire, the following conclusions can be drawn: (1) The presence of lighting did indeed improve the test subjects' reaction times. (2) There was little difference in the results regarding colour; it would be more appropriate to incorporate personalisation. (3) Test subjects tended to notice pedestrians and lights ahead of them sooner than those on either side, with those on the right being noticed earlier than those on the left. (4) The test was more effective at night than during the day.

5 Conclusion

This study conducted a systematic review of the theory and empirical research centred on the core question of how to effectively enhance drivers' perception of key information in the vehicle's surroundings through the design of interior lighting. Through two rounds of user testing, the study reached the following main conclusions:

Lighting significantly improves perceptual efficiency. In comparative tests with and without lighting, participants' average reaction times to pedestrians in front of the vehicle, on the left and on the right were all faster under lit conditions than under unlit conditions, validating the effectiveness of in-vehicle lighting as a medium for conveying information.

There are differences in the recognition efficiency of lights positioned in different locations. Lights positioned ahead were recognised most quickly, whilst those on the right were recognised slightly faster than those on the left. This indicates that a driver's Peripheral vision exhibits spatial asymmetry; therefore, design should prioritise alerts in high-risk directions.

The semantic meaning of colours varies depending on the usage context. Blue lights perform better in rapid-response scenarios, whilst red lights are more effective in slow-moving, high-alertness scenarios. Colour preferences differ across cultural contexts, suggesting that design should account for personalisation and localisation.

Dynamic patterns influence user experience. Smooth, directional dynamic lights achieve high user acceptance, whilst high-frequency flashing may trigger negative emotions. Dynamic patterns should be matched to risk levels and the direction of the warning.

Ambient lighting affects the effectiveness of warnings. Light warnings are more effective at night than during the day, indicating that ambient contrast is a key factor influencing light perception; designs should therefore incorporate adaptive adjustment capabilities.

User acceptance is favourable. Results from user experience questionnaires and interviews indicate that participants generally found the lighting system easy to learn, clear, effective and valuable; negative feedback centred on colour recognition and discomfort caused by flashing.

In summary, this study has demonstrated the feasibility of a peripheral vision-based in-vehicle lighting information alert system and has provided a preliminary basis for its design for use in autonomous driving scenarios.

6 Discussion

6.1 Contributions and Insights

This study offers valuable contributions and insights at the theoretical, methodological and practical levels.

Integration of qualitative insights and quantitative validation: This study employs a closed-loop process comprising qualitative insights (user interviews), quantitative testing (reaction time measurements) and iterative optimisation (two rounds of testing), thereby retaining the depth of user understanding characteristic of design thinking whilst incorporating the rigour of laboratory testing.

Expanding the interaction paradigm of in-vehicle lighting: Whilst traditional in-vehicle lighting primarily serves illumination and decorative purposes, this study expands its role to that of an interactive medium capable of encoding information, exploring the coding rules of colour, position and dynamic patterns in non-verbal communication. This paradigm is not only applicable to driving safety scenarios but can also be extended to broader smart cockpit interaction scenarios such as in-vehicle entertainment, health alerts and system status feedback.

The universal value of low-cognitive-load warning systems: The core question of this study—how to convey critical information with minimal cognitive load in emergency situations—is equally relevant in fields such as medical monitoring, industrial control and aviation. The findings from this research on in-vehicle lighting interaction can serve as a reference for these sectors, offering transferable value particularly in the areas of multi-channel information presentation and cognitive load optimisation.

The Integration of Design Studies and Human Factors Engineering: This study combines the creative thinking of design studies with the empirical methods of human factors engineering, demonstrating the practical value of human-centred design principles within complex systems and providing a practical case study for the further development of design disciplines in the field of human-computer interaction.

6.2 Limitations of the Study and Future Directions

This study has the following limitations: (1) The tests utilised video simulations rather than real-world driving or high-fidelity simulators, and therefore did not account for factors such as multitasking distractions and emotional fluctuations in real driving environments; (2) The sample consisted primarily of Chinese participants, and the cross-cultural generalisability of the findings requires further verification; (3) The coding scheme for colours and dynamic patterns remains relatively rudimentary, and the optimal configuration of multidimensional parameter combinations—such as brightness, frequency and direction—has not been systematically explored; (4) Individual differences among drivers, such as age, driving experience and attention levels, were not taken into account; (5) The study did not investigate whether in-vehicle screens could also serve as part of Peripheral vision.

Future research could be conducted in the following areas: (1) validating the effectiveness of the lighting cue system in real-vehicle environments; (2) conducting cross-cultural comparative studies to explore differences in colour semantics and dynamic preferences across different cultural contexts; (4) exploring the differences and potential integration of lighting with other interaction modalities (such as sound and vibration).

ACKNOWLEDGMENTS

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I hereby declare that the DEEPL tool was used to translate some 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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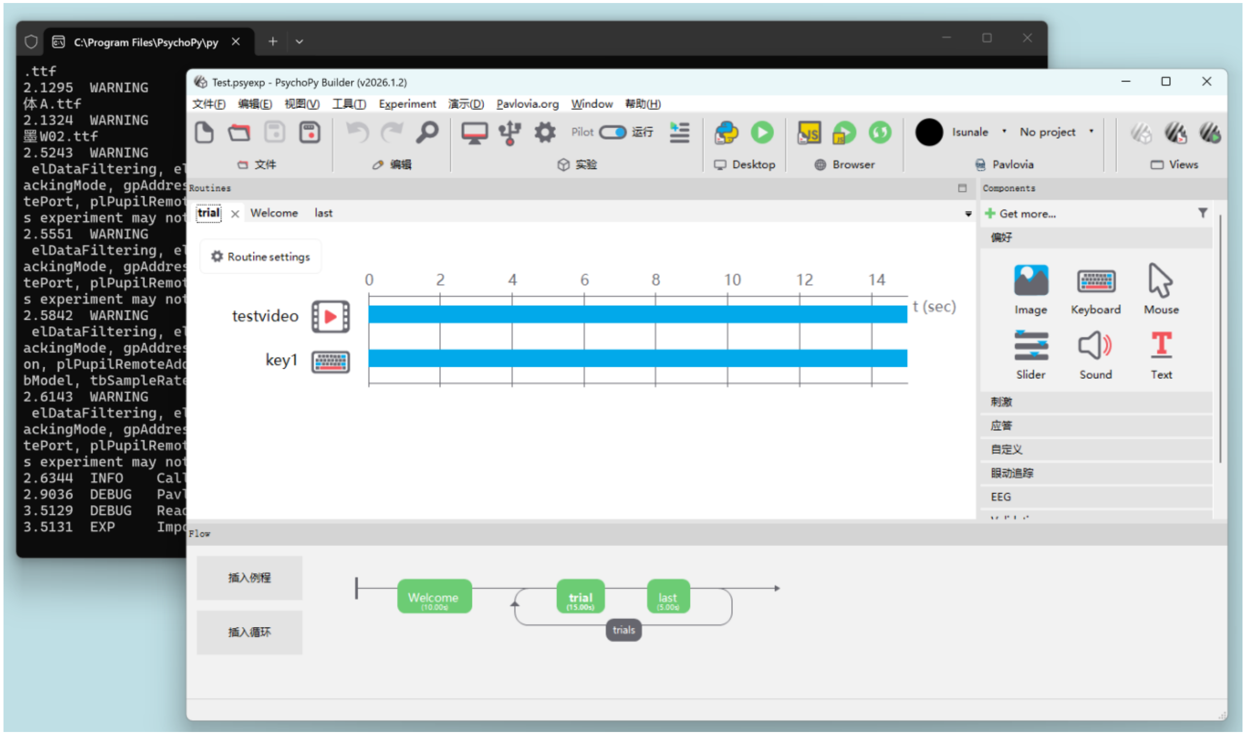
APPENDIX

Using Psychopy
Test 1

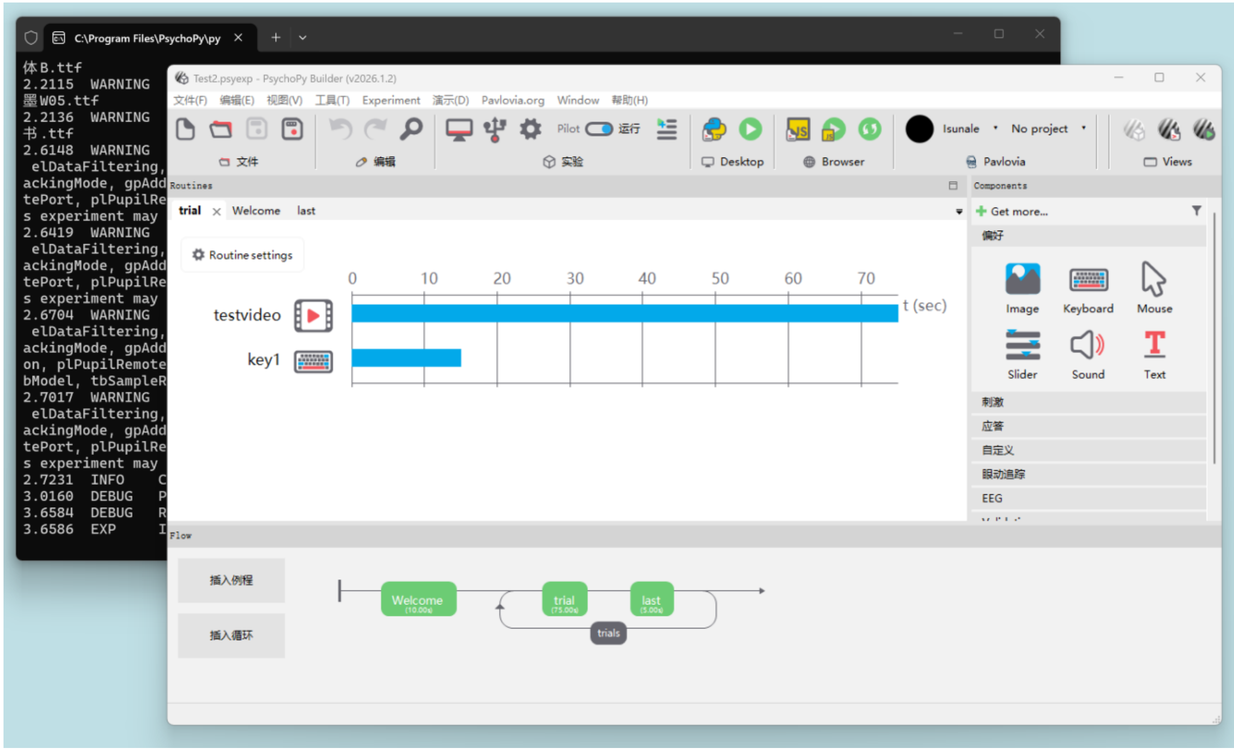


Welcome to test!

You are about to watch a few videos. Please keep your eyes focusing on the frame ahead or your phone. Which one you should do will be shown in front of each video. Please do not turn your head.

When you notice someone approaching the car or see the lights from inside, please press the button.

Test 2



Welcome to the test!

You are about to watch a few videos. Please keep your eyes focused on the mobile interface on the screen and read the story. You will observe the videos out of the corner of your eye.

When you notice someone approaching the car, or see a light come on inside the car, please press the button. The test will record the time you press the button.

Interview questions

What about the user experience and feel?

What about the colours?

What about the animation options (flashing, flowing light effects, gradients)?

What do you think is lacking?

UEQ

1. Please select how you feel about the **Experience** (the higher score means the most) *

	1	2	3	4	5
annoying	◯	◯	◯	◯	◯
not understandable	◯	◯	◯	◯	◯
creative	◯	◯	◯	◯	◯
easy to learn	◯	◯	◯	◯	◯
valuable	◯	◯	◯	◯	◯
boring	◯	◯	◯	◯	◯
not interesting	◯	◯	◯	◯	◯
fast	◯	◯	◯	◯	◯
good	◯	◯	◯	◯	◯
complicated	◯	◯	◯	◯	◯
usual	◯	◯	◯	◯	◯
unpleasant	◯	◯	◯	◯	◯
secure	◯	◯	◯	◯	◯
clear	◯	◯	◯	◯	◯
attractive	◯	◯	◯	◯	◯
friendly	◯	◯	◯	◯	◯
inefficient	◯	◯	◯	◯	◯

Information sheet for research project "Exploring the effectiveness of colour and dynamic patterns in vehicle interior lighting for conveying information"

1. Introduction

You have been invited to take part in research project Exploring the effectiveness of colour and dynamic patterns in vehicle interior lighting for conveying information, 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 the of colour and dynamic patterns in vehicle interior lighting will help to convey information.

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 to take the test. We will record the time you press the button.
- Interviewing you about experience after test and recording your answers via video. We will make a transcript of the interview. We will replace your name with a placeholder.
- Asking you to complete the UEQ form.
- 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 13-4-2026 by the ethical review committee of Eindhoven University of Technology.

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

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:

Fast Track approval for ERB-1087 | Exploring the effectiveness of colour and dynamic patterns in vehicle interior lighting for conveying information

JA

Jira automation<automation@tue.atlassian.net>

收件人: ⊗ Liu, Xinyue

周一 2026/4/13 11:23

已标记

这是原始消息

翻译至 中文 (简体)

You don't often get email from automation@tue.atlassian.net. Learn why this is important

Dear Xinyue Liu,

Your application ERB-1087 | Exploring the effectiveness of colour and dynamic patterns in vehicle interior lighting for conveying information has been automatically 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 (informed consent forms, surveys/interview questions, description of experiment/prototype etc.) available for at least 6 months.

Good luck with your research and have a nice day!