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The effect of taillight shapes and vehicle distance on rearward drivers' hazard perception

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ABSTRACT

Rear-end collisions are prevalent during night driving. Taillights are vital in conveying hazards between leading and following vehicles at night. Taillights highlight a vehicle's presence, particularly for vehicles following from behind. Therefore, it is essential to design taillights that maximize the perception of hazards for drivers behind them. This study explored how different taillight shapes affect rear drivers' hazard perceptions during nighttime driving. Two experiments were conducted using ERP measurements to study the effects of taillight shapes (three square types in Experiment 1: solid, array, and contour; two linear types in Experiment 2: through type and non-through type) and the distance to the leading vehicle on participants' hazard perceptions. Participants responded to images of nighttime driving scenarios during the experiments while their ERP and behavioral data were recorded. The stimulus images showed the view from a driver looking at the vehicle ahead on a clear night. The neural process of hazard perception consists of two stages: automatic detection (early) and evaluation (later). In this study, P2 indicated attention bias to the stimulus during the detection stage, and LPP indicated the negative emotion triggered by the stimulus during the evaluation stage. Experiment 1 showed that solid-shaped taillights were perceived as more hazardous and processed faster than other square taillight shapes. Experiment 2 found that non-through-type and through-type linear taillights were perceived as more hazardous during the automatic detection and subjective evaluation stages, respectively. However, the behavioral data showed that through-type taillights were considered more hazardous and were associated with shorter response times. Thus, solid square taillights and through-type linear taillights can be optimal ergonomic solutions. These findings can serve as a reference for taillight designers, manufacturers, and potential car buyers regarding safety considerations.

1. Introduction

Human error is the primary cause of accidents, accounting for 94 %–96 % of all auto accidents (National Highway Traffic Safety Administration [NHTSA], 2016). Rear-end collisions, a type of accident due to human error, comprise about 40 % of all car accidents (NHTSA, 2016). Research indicated a strong connection between hazard perception and the likelihood of collisions. Hazard perception can be regarded as situation awareness for hazardous situations in the traffic environment (Horswill & McKenna, 2004). Enhanced

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hazard perception in drivers can significantly reduce risky driving behaviors, thereby decreasing the number of collisions (Curry et al., 2011; Cao et al., 2022). Therefore, studying hazard perception is beneficial for improving driving safety.

Hazards are effectively conveyed through various means; for example, signals, icons, and texts can convey hazards through their shapes, colors, and other attributes. Hazards like the direction of oncoming traffic (Li et al., 2022), sudden appearance of pedestrians (Castro et al., 2020), and adverse weather warnings (Senkbeil et al., 2020) guide driving behavior only if drivers can perceive them. According to the American National Standards Institute (ANSI) Z535.4 standard (2011), hazards are categorized into three levels: danger, warning, and caution. The perception of these hazards is influenced by the characteristics of the signals, icons, and texts used to convey them. For instance, red warning symbols indicate more severe hazards than yellow ones (Pravossoudovitch et al., 2014); similarly, triangular warning signs suggest stronger hazards than circular ones (Ma et al., 2018). Generally, drivers respond according to the warnings presented by hazards (Zavareh et al., 2017); thus, hazards play a significant role in regulating driving behavior.

Over the past two decades, several studies have explored the relationship between light shape and its conspicuity (Tsutsumi et al., 2008; Luo et al., 2021). For instance, Rensink (2011) observed that elongated objects are eye-catching, and elongated lighting systems can make vehicles more visible (Tsutsumi et al., 2008). Weaver and DeLucia (2022) claimed that drivers from greater distances notice larger headlight configurations sooner. Additionally, Luo et al. (2021) showed that long line-shaped taillights are more appealing and noticeable to drivers than other taillight shapes. However, few studies have assessed how highly visible light shapes affect the conveyance of hazards and subsequent hazard perception. To address this research gap, this study examined how the shape of taillights influences hazard delivery and subsequent hazard perception. Specifically, this study investigated the impact of different taillight shapes and vehicle distances on drivers' hazard perception, aiming to provide scientific guidance for taillight design.

Vehicle taillights convey critical hazards to other drivers, such as sudden braking, deceleration, and emergencies (Lee et al., 2020; Bullough et al., 2019; Nguyen-Phuoc et al., 2020). Research indicated that hazards signaled by triangular warning signs elicit stronger hazard perceptions than circular signs (Ma et al., 2018). Moreover, hazards indicated by rectangular shapes tend to produce relatively weak perceptions of hazard levels (Yu et al., 2004). In contrast, hazards communicated by octagonal shapes intensify perceptions of hazard levels (Grummon et al., 2019). Based on these findings, this study hypothesized that different taillight shapes can convey varied hazards, thereby influencing hazard perceptions.

The distance between vehicles affects the following driver's attention and, consequently, their hazard perception. Studies indicated that the distance between a leading and following vehicle affects the latter's visual attention towards the former (Gershon & Shinar, 2012; Wertheim, 2010); for example, a vehicle at a closer distance draws more attention than one further away (Luo et al., 2021). Objects or targets that attract more attention tend to compete for the driver's cognitive resources and working memory (Knudsen, 2007). Therefore, the distance between vehicles influences the rearward driver's attention resources directed at the vehicle ahead, subsequently affecting the cognitive resources allocated to it. According to previous studies, a driver's judgment of environmental hazard depends on the cognitive resources allocated (Groeger, 2000); a reduction in these resources directed towards the vehicle in front has a negative impact on their perception of hazard (Wood et al., 2016). Consequently, when the distance between vehicles is large, the following driver's decreased attention towards the vehicle ahead results in insufficient cognitive resources to manage the current driving scenario, adversely affecting their perception of hazard.

Drivers process hazards through hazard perception. According to the hazard response model by Grayson et al. (2003), hazard response is divided into two phases: hazard perception and response. The hazard perception phase includes detecting and evaluating hazards (Ma et al., 2014), while the response phase involves selecting and implementing behaviors. Studies have identified behavior selection and implementation as critical indicators of hazard perception due to their observability and efficiency (Wang et al., 2022; Castro et al., 2019). However, behavior selection and implementation are delayed reactions to hazard perception and may not be ideal for guiding taillight design.

As noted, hazard perception detection and evaluation processes involve cognitive mechanisms that are difficult to measure with conventional tools. Hazard perception studies have mainly used self-report questionnaires (Machin & Sankey, 2008; Rhodes & Pivik, 2011) and eye-tracking systems (Kübler et al., 2014; Li et al., 2022) for data collection. However, these methods are limited in directly uncovering the underlying cognitive processes. To overcome this limitation, this study employed event-related potentials (ERPs), which offer high temporal resolution and insights into neural processing mechanisms. Specifically, this research investigated the impact of taillight shapes on hazard perception using ERPs and behavioral data. The behavioral data consisted of participants' keystroke data and response times, serving as behavior selection and implementation indicators.

Several studies have used ERPs to measure hazard perception directly. For example, Li et al. (2022) examined how the severity and location of traffic hazards affect drivers' perceptions using ERPs. Their findings indicated that higher hazard levels elicited stronger P200 responses. Ma et al. (2014) also used ERPs to study the perception and evaluation of environmental hazards. Their results indicated that images depicting higher hazard levels prompted enhanced P2 and LPP responses. These findings emphasized the appropriateness of ERPs for analyzing neural processing mechanisms.

Detection is an early-stage attentional neural process, and ERPs' N1 and P2 components are indicators of this process (Nelson et al., 2015). N1 is a negative ERP component, typically occurring approximately 100 ms after the onset of a stimulus. By contrast, P2 is a positive ERP component with a peak latency of 150–275 ms (Dunn et al., 1998). P2 is associated with attention to and detection of objects. P2 is associated with selective attention, feature detection (color, orientation, and shape), and other early-stage mechanisms. When individuals are tasked with locating a target object that differs in color, orientation, or shape from the surrounding objects, their P2 component tends to be activated (Luck & Hillyard, 1994). Therefore, P2 reflects selective attention and detection based on feature information (Philips & Takeda, 2009).

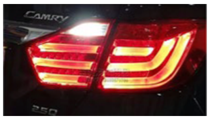
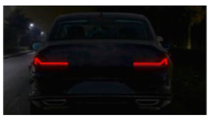
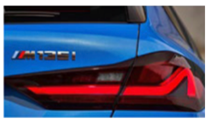
Additionally, P2 is sensitive to negative stimuli, reflecting an automatic attentional bias toward negative events (Huang & Luo, 2006) and contributing to the low-level processing of stimuli (Crowley & Colrain, 2004). Studies have demonstrated that P2 is associated with the early detection of threatening stimuli and can be elicited by stimuli such as frightful words or images (Carretié et al., 2001, 2006; Qin et al., 2009). An increased P2 amplitude indicates a higher allocation of attentional resources to threatening stimuli (Carretié et al., 2001). In a study involving hazard assessment within a flight simulator, P2 was used as an indicator of the detection stage of hazard perception; the study revealed that images depicting higher hazard levels attracted more attention and increased the amplitude of P2 (Ma et al., 2014). Therefore, employing P2 to reflect neural processes during the detection stage is appropriate in a hazard perception task. The amplitude of P2 is a valuable indicator of the level of attention drawn by a presented stimulus.

As mentioned, evaluation represents the latter stage of the cognitive processing of hazards, and the LPP component of ERPs is closely associated with this stage (Ma et al., 2014). LPP is a positive ERP component that typically emerges at 300 ms after the onset of a stimulus (Hajcak & Olvet, 2008). It reflects a later and more complex stage of semantic processing, encompassing evaluations of the content as well as reinterpretations of the stimulus content (Foti & Hajcak, 2008; MacNamara et al., 2009; Bublatzky & Schupp, 2012). Furthermore, LPP is strongly associated with emotion and reflects the selective processing of emotional stimuli (Schindler & Bublatzky, 2020). It responds to attentional bias toward emotional stimuli (Hajcak et al., 2010). Hajcak and Olvet (2008) reported that emotional stimuli triggered enhanced LPP responses compared to neutral stimuli and that unpleasant stimuli elicited increased attention compared to pleasant ones. Persistent attention to unpleasant information is associated with negative emotions (Compton, 2000). Therefore, more negative emotional stimuli may attract attention and increase LPP amplitude. Moreover, Olofsson et al. (2008) revealed that high-arousal stimuli elicited stronger LPP than low-arousal ones. High-hazard stimuli may induce stronger negative emotions (Ma et al., 2014). Therefore, high-hazard stimuli could elicit stronger negative emotions and receive sustained attention, as indicated by enhanced LPP. Accordingly, the present study used images depicting driving situations and conveying hazards that could evoke negative emotions. The study hypothesized that LPP could be an indicator of the evaluation stage of hazard perception and that the amplitude of LPP could represent an indicator of the intensity of negative emotional arousal in response to hazardous stimuli.

The present study investigated the effect of taillight shapes and distance on hazard perception. Taillight shapes and vehicle distance were used as independent variables, with hazard perception as the dependent variable. The study aimed to address the following research questions:

1. How does the shape of taillights influence the perception of hazards?
2. Can ERP indicators reflect the neural processing of hazards?

Table 1
Stimuli details of experiments.

Taillight shapes		Stimulus	Taillights in reality
Type A: Square shape (Experiment1 stimuli)	Solid shape		 Murcielago 2010
	Array shape		 Toyota Camry
	Contour shape		 Audi Q5
Type B: Linear shape (Experiment2 stimuli)	Non-through-type shape		 BMW 1 series
	Through-type shape		 Audi Tron

2. Taillight selection

The taillight stimuli in this study were taken from real-world market examples. Luo et al. (2021) categorize taillight designs into three shapes: square (e.g., Murcielago 2010), linear (e.g., Audi Tron), and array (e.g., Lamborghini Aventador). Considering the current landscape of the automotive market, square (e.g., Lavida 300TSI, Sagitar 280TSI, Audi A4L) and linear-shaped (e.g., Leading Ideal L9, Xiaopeng P5, Porsche Panamera) taillights are the predominant taillight designs in the market. Selecting square and linear taillamps as experimental materials can make the results more generalizable. As mentioned, this study aimed to examine how taillight shapes affect hazard perception and offer valuable insights for car manufacturers on designing taillights. Therefore, this study used square and linear-shaped taillights as the experimental stimuli.

Square taillights feature enclosed square designs, while linear-shaped taillights have slim lines. Square taillights have a larger area compared to linear-shaped taillights. Square taillights are classified into three types based on the size of the color-filled area: solid (completely filled with red), array (composed of an array of red lines), and contour (outlined in red; see Table 1). Solid taillights have the most extensive red-filled areas, followed by array and contour taillights. Solid taillights have the largest red-filled areas, followed by array and contour taillights. Additionally, linear-shaped taillights are categorized into through type and non-through type. Through-type taillights visually appear longer than non-through-type ones.

Night driving is dangerous, and taillights are essential for driving safety at night (Pillai & Radhakrishnan, 2016). As mentioned, to enhance the generalizability of the results, this study selected square and linear taillights, which dominate the market, as experimental materials. Square shapes are typically perceived as stable, conveying robust and effective information (Norman, 2007). Solid shape taillights have a large red area, offering apparent visual effects; array shape taillights have repetitive patterns; contour-shaped taillights are aesthetic, energy-efficient, and outline-displaying. Influenced by LED technology, many automobile taillights adopt linear designs to convey information. Non-through-type linear taillights abstractly represent traditional taillights, easily understood and accepted by drivers; through-type lights have a strong sense of technology and high conspicuity and are easily noticed by following vehicles (Luo et al., 2021). However, how solid, array, and contour shapes in square taillights and through type and non-through type shapes in linear taillights affect hazard communication is unknown. Hence, this study investigated the impact of taillight shape on drivers' hazard perception.

This study made two research hypotheses for square and linear shape taillights. Given that solid square taillights have the largest red-filled area, and red is associated with warnings (Pravossoudovitch et al., 2014; Braun & Silver, 1995), this study hypothesized that these taillights could effectively convey higher-level hazards, thus enhancing drivers' hazard perception. Moreover, longer shapes attract more attention than shorter ones (Rensink, 2011). Elements that draw more attention consume more working memory (Knudsen, 2007), and greater working memory allocation for leading vehicles is associated with increased hazard perception (Groeger, 2000; Wood et al., 2016). Consequently, this study hypothesized that through-type linear taillights would be perceived as more hazardous.

Square and linear taillight designs are the predominant taillight shapes produced by vehicle manufacturers. Therefore, this study evaluated design considerations for square and linear taillights through two separate experiments. The first experiment assessed the impact of square shape taillights on drivers' hazard perceptions, while the second experiment explored the impact of linear shape taillights on drivers' hazard perceptions. The schematic diagram of the experimental design is shown in Fig. 1.

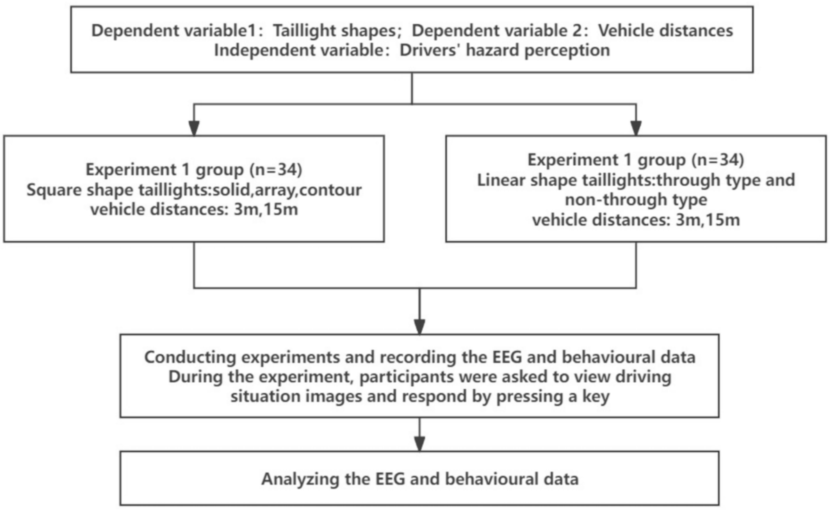


Fig. 1. Schematic diagram of the experimental design.

3. Experiment 1

3.1. Methods

3.1.1. Participants

For Experiment 1, 34 participants with a valid driver's license were recruited from a university campus. However, data from three participants were excluded from the analysis because of the excessive recording of artifacts and movement during the experiment. Therefore, the final sample for Experiment 1 comprised 31 participants with either normal or corrected-to-normal visual acuity (16 men; average age, 22–30 ± 1.59 years; mean age, 23.72 years). All participants were right-handed and reported no history of mental illness. The participants were recruited through online channels and provided written informed consent to participate in the experiment. In appreciation of their participation, the participants were compensated with 50 RMB. This study received approval from the Internal Review Board of the Inclusive User Experience Research Centre.

3.1.2. Experimental design

A 3 (taillight shapes) × 2 (vehicle distance) within-group experimental design was employed to investigate the effect of square taillights and vehicle–observer distance on drivers' hazard perceptions during nighttime driving. The taillight shapes were categorized into three distinct categories (Table 1), and the vehicle–observer distance was divided into two conditions, namely, near (3 m) and far (15 m), according to the categorizations established by Luo et al. (2021).

3.1.3. Stimulus materials

In Experiment 1, the stimuli were modified by the methodology described by Luo et al. (2021). The stimulus images depicted a view from a driver's perspective, gazing at the vehicle in front of the driver on a clear night. The shapes of the taillights in these images were altered using Photoshop, with their color attributes controlled (RGB: ~254, 0, 0; HSB: ~0, 100 %, 99 %; Fig. 2). The selection of taillight shapes was based on popular vehicle brands and involved expert evaluations conducted by seven vehicle designers, each of whom had at least three years of design experience (Luo et al., 2021). For Experiment 1, the three categories of square taillights, solid, array, and contour, were used; 10 images were prepared for each. Additionally, the two distance conditions (3 vs. 15 m) were incorporated into each image. Additionally, this study prepared an image of only the environment without any vehicles as a background stimulus for subsequent processing. Thus, a total of 61 images were prepared for Experiment 1. As listed in Table 1, the taillight shapes in each experimental image were derived or modified from real-life taillights. All taillight stimuli used in Experiments 1 and 2 are shown in Fig. 3.

3.1.4. Procedure

During the experiment, the participants were asked to sit comfortably in an ergonomic laboratory and face a 24-inch monitor at a distance of 60 cm. The visual angle was maintained at 28.16° × 28.16°, and the monitor had a resolution of 1920 × 1080 pixels. The light conditions and temperature in the laboratory were maintained constant throughout the experiment, and the participants were given ample time to relax before the experiment. None of the participants had seen the experimental material before the experiment. Each session of the experiment commenced with a practice session.

The experiment began with the presentation of a fixation cross for 2000 ms, followed by stimuli for 2000 ms (Fig. 4). Before the commencement of the experiment, the participants received instructions that stated the following: "Thank you for coming to the experiment. Next, you will see many images of driving scenarios. When you feel a hazard is present, press '1'; otherwise, press '2'." Subsequently, the participants were asked to imagine that they were driving a car; they were instructed to treat each image stimulus as if it were an actual driving situation and to respond to the stimuli based on their immediate feelings. If the image conveyed a sense of hazard, the participants were asked to press the "1" key on the keyboard; otherwise, they were required to press "2." Before each image

Fig. 2. Stimulus examples.

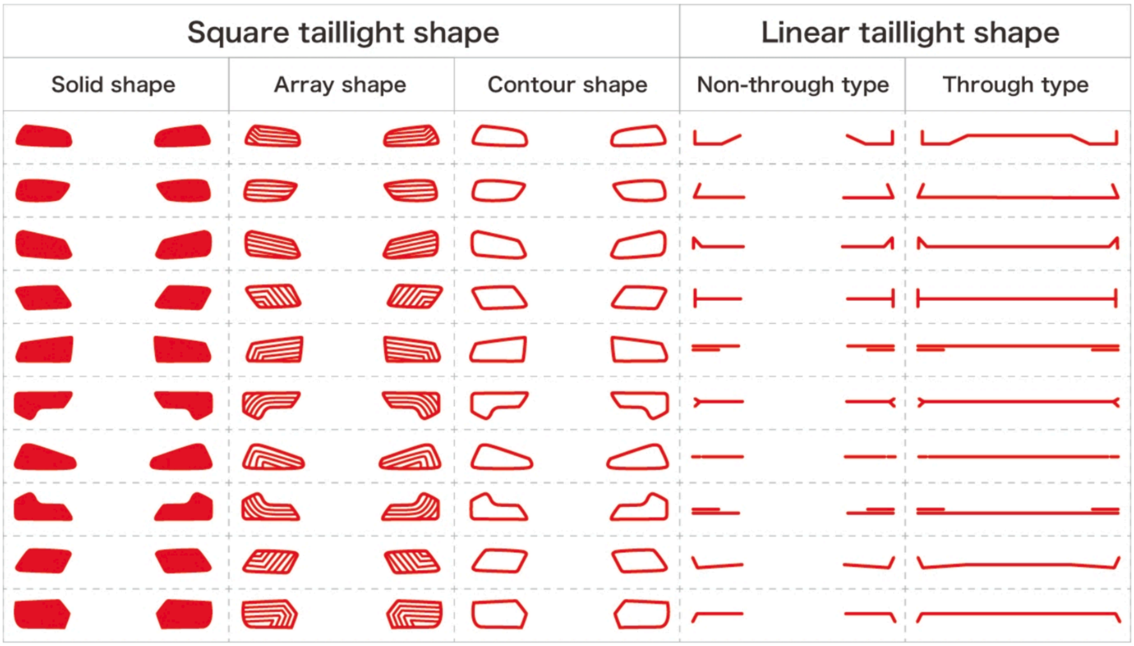


Fig. 3. All taillight stimuli used in Experiments 1 and 2.

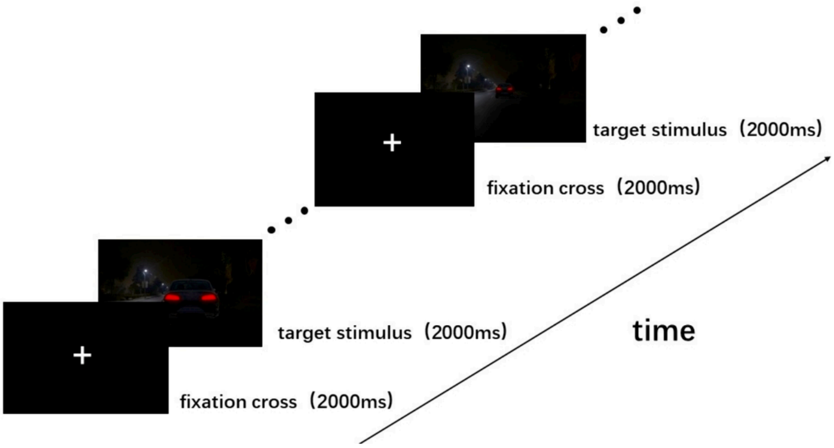


Fig. 4. Procedure for Experiment 1.

disappeared, the participants were required to perceive the hazard level of the current driving scenario and respond by pressing a button. All stimuli were presented in a random order.ERP data were averaged across all waveforms elicited for the same condition. For each of the six conditions, the 10 driving environment images were presented six times, resulting in a total of 60 trials per condition and a grand total of 360 trials across all conditions. Additionally, the background stimulus image was presented 60 times, resulting in a total of 420 trials for Experiment 1.The images were presented in a random order by using E-prime 3.0 software. The participants completed the experiment in approximately 28 min.

3.1.5. Data acquisition and analysis

Electroencephalogram (EEG) signals were recorded using the Neuroscan Synamp2 Amplifier (Scan 4.3.1, Neurosoft Labs, Inc. Sterling, USA). 64 Ag/AgCI electrodes were placed on the scalp per the international 10–20 system for EEG electrode placement. The EEG signals were recorded at a sampling rate of 1000 Hz, and the electrode impedance level was maintained at <5 kΩ. Two specific time windows were selected for ERP analysis: one from 220 to 280 ms after stimulus onset for P2 and the other from 500 to 700 ms after stimulus onset for LPP. For the measurement of the P2 component, electrodes located at F3, FZ, F4, FC3, FCZ, FC4, C3, CZ, and C4 were used for the frontal–central area. For the measurement of the LPP component, electrodes located at C3, CZ, C4, CP3, CPZ, CP4, P3, PZ, and P4 were used for the central–parietal area. The ERP data were processed offline using MATLAB 18b and the EEGLAB toolbox

(Delorme & Makeig, 2004). The left and right mastoids were used as a reference for the EEGs, and the data were digitally filtered using a bandpass filter with a cutoff frequency of 0.5–30 Hz. The EEG recordings were segmented over a time window from 200 ms before stimulus onset to 1000 ms after stimulus onset, and segments with a low signal-to-noise ratio were excluded. Additionally, trials with amplitudes exceeding ±80 μV were excluded, and participants for whom more than 20 % of trials were eliminated were excluded from the dataset. Next, independent component analysis (ICA) addressed EEG artifacts such as blinking. ICA is a source separation technique used to identify independent sources of variance in EEG data (Anemüller et al., 2003). The EEG data were divided into independent components using ICA, and eye and single-channel noise components were identified through visual inspection of the components and data (Hu & Zhang, 2019). These components were labeled and removed before the next analysis step. Finally, data for each of the experimental conditions were independently averaged. To reduce interference from irrelevant factors in the image stimuli (such as streetlights), this study calculated the amplitude of the difference waves of ERPs induced by taillight stimulus images and the background stimulus image. The difference wave, created by subtracting one condition from the other, eliminates identical source waveforms in both conditions. This isolation allows for the identification of differing components. Take the voltage at each time point from one ERP waveform and subtract it from the voltage at the corresponding time point of another ERP waveform. The result is the voltage difference between the two waveforms at each time point (Luck, 2014). The process of generating a difference wave between a target waveform (x1) and a background waveform (x2) can be expressed as:

$$y = x_1 - x_2 \text{ (computed for each point in the waveform)}$$

The P2 and LPP components within the time window of the difference waves were averaged for subsequent calculations. Amplitude values for various conditions and regions were extracted, and differences were analyzed using SPSS 19 (IBM, USA).

For each condition, the number of “1” keystrokes was divided by the total number of keystrokes for that specific condition, and the response times for “1” were calculated. Behavioral data for all participants were averaged for each condition before calculation. Moreover, we averaged the response times of all participants in all trials for each condition. Participants who did not respond within the designated time were excluded from the analysis. The derived response times were used to determine which taillight shape was processed faster by the participants, and the keystroke ratios were used to determine which taillight shape received the highest number of “hazard” button presses. The ERP and keystroke data were analyzed using a two-way repeated-measures analysis of variance (ANOVA). To assess the significance of multiple comparisons, the Bonferroni method was used as needed. Specifically, at a significance level of 0.05, the P-value after multiple comparisons is multiplied by the number of tests to correct it (Chen et al., 2017). For example, in Experiment 1, there were three levels of square taillight shapes, and the p-value after multiple comparisons needed to be multiplied by 3 for correction. The distance values (near vs. far) and taillight shapes (solid vs. array vs. contour) were considered within-group variables. Furthermore, a normal distribution test was performed, and the Greenhouse–Geisser correction was conducted when appropriate.

3.2. Results

3.2.1. Behavioral data

The behavioral data in this study included keystroke response times and keystroke ratio. The keystroke ratio data provided insights

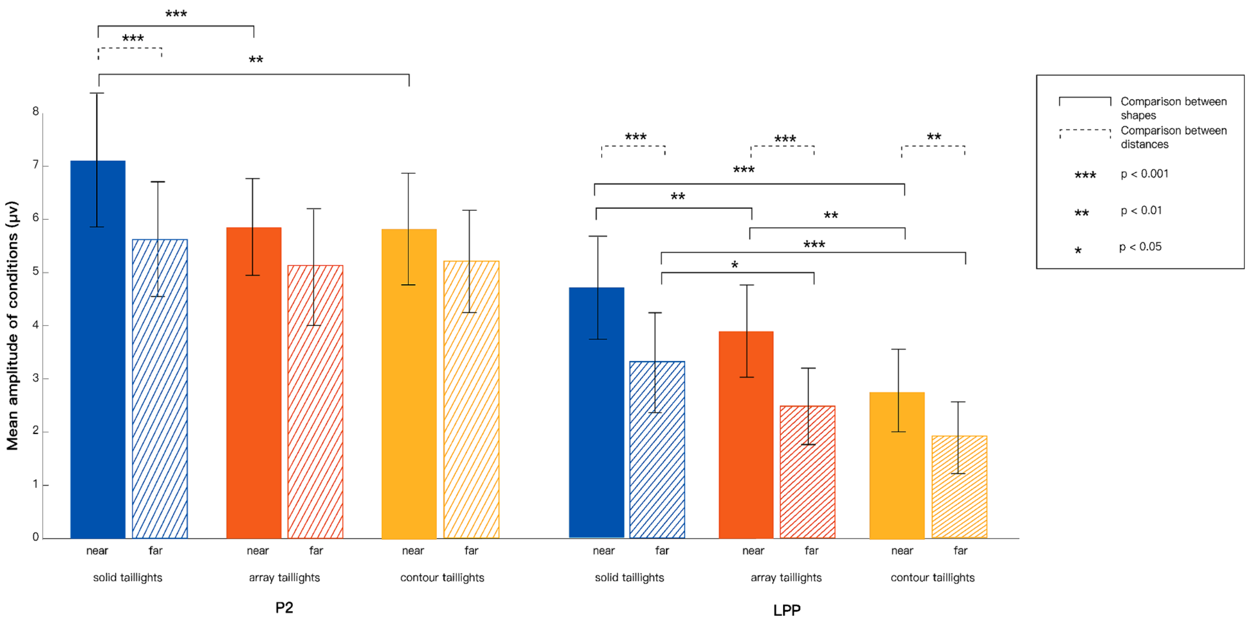


Fig. 5. Mean and standard errors of P2 and LPP amplitudes under both conditions. *statistical significance at 0.05.

into the participants' responses after perceiving potential hazards. The results revealed a nonsignificant interaction effect ($F = 0.983$, $p = 0.386$, $\eta_p^2 = 0.064$). However, the main effects of both distance ($F = 39.424$, $p < 0.001$, $\eta_p^2 = 0.568$) and taillight shapes ($F = 18.400$, $p < 0.001$, $\eta_p^2 = 0.559$) were significant. Multiple comparisons revealed that the solid square taillights were associated with a significantly higher keystroke ratio than did the array (0.773 ± 0.042 vs. 0.725 ± 0.042, $p < 0.01$, 95 % CI = 0.014–0.081) and contour (0.773 ± 0.042 vs. 0.404 ± 0.051, $p < 0.001$, 95 % CI = 0.247–0.491) taillight shapes. In addition, the near-distance condition received a higher keystroke ratio (0.817 ± 0.033 vs. 0.451 ± 0.057, $p < 0.001$, 95 % CI = 0.247–0.485). These results suggested that driving environments with solid square taillights were perceived as the most hazardous, as evidenced by the highest number of participants pressing the "1" button when encountering solid square taillights.

The recorded response times were analyzed through a repeated-measures ANOVA. The results revealed a nonsignificant interaction effect ($F = 1.131$, $p = 0.343$, $\eta_p^2 = 0.106$). However, the distance ($F = 17.302$, $p = 0.001$, $\eta_p^2 = 0.464$) and taillight shapes ($F = 8.739$, $p = 0.002$, $\eta_p^2 = 0.479$) significantly affected the participants' response times. Multiple comparisons revealed that the participants responded faster to the solid square taillights compared to array (744.856 ± 23.424 vs. 790.799 ± 27.782 ms, $p < 0.05$, 95 % CI = −86.667– −5.220) and contour (744.856 ± 23.424 vs. 839.707 ± 30.385 ms, $p < 0.01$, 95 % CI = −155.041– −34.660) shapes taillights. In addition, participants responded faster to the near-distance condition than the far-distance condition (739.763 ± 24.384 vs. 843.812 ± 30.708 ms, $p = 0.001$, 95 % CI = −156.227– −51.870).

3.2.2. ERP data

In this study, enhanced P2 was considered to indicate a greater attentional bias toward stimuli during the detection stage of hazard perception, whereas enhanced LPP was considered to indicate the presence of negative emotions elicited by stimuli during the evaluation stage of hazard perception. The mean and standard errors of the amplitudes of these ERP components are presented in Fig. 5. The grand-average ERP waveforms and topographic maps are presented in Figs. 6 and 7.

P2 at 220–280 ms

The average amplitudes of the P2 component extracted from the frontal–central region were analyzed using a repeated-measures ANOVA. The interaction effect ($F = 2.047$, $p = 0.147$, $\eta_p^2 = 0.124$) was not significant. The taillight shapes ($F = 3.640$, $p = 0.039$, $\eta_p^2 = 0.201$) and distance ($F = 6.741$, $p = 0.014$, $\eta_p^2 = 0.183$) significantly affected the P2 amplitudes. Multiple comparisons revealed that the solid square taillights elicited enhanced P2 compared to the array (6.469 ± 0.557 vs. 5.576 ± 0.443 μV, $p < 0.001$, 95 % CI = 0.028–1.759) taillights. Additionally, the near-distance condition elicited a larger P2 amplitude than the far-distance condition (6.367 ± 0.509 vs. 5.400 ± 0.437 μV, $p < 0.05$, 95 % CI = 0.026–1.729). These results indicated that the solid square taillights and near distance captured the greatest attentional resources during the detection stage (Huang & Luo, 2006; Philips & Takeda, 2009).

LPP at 500–700 ms

The average amplitudes of the LPP component extracted from the central–parietal region were analyzed using repeated-measures ANOVA. The interaction effect was insignificant ($F = 1.095$, $p = 0.348$, $\eta_p^2 = 0.070$). In addition, the results revealed that taillight shapes ($F = 17.595$, $p < 0.001$, $\eta_p^2 = 0.548$) and distance ($F = 24.603$, $p < 0.001$, $\eta_p^2 = 0.451$) significantly affected the LPP amplitudes. Multiple comparisons indicated that solid square taillights elicited greater LPP than did the array (3.986 ± 0.426 vs. 3.187 ± 0.334 μV, $p < 0.01$, 95 % CI = 0.250–1.34) and contour (3.986 ± 0.426 vs. 2.339 ± 0.316 μV, $p < 0.001$, 95 % CI = 0.945–2.350) taillights. Additionally, the near-distance condition elicited a larger LPP amplitude than the far-distance condition (3.786 ± 0.382 vs. 2.556 ± 0.334 μV, $p < 0.001$, 95 % CI = 0.724–1.737). These results indicated that during the subjective evaluation stage, the driving situations with solid taillights and near distance significantly evoked stronger negative emotions (Foti & Hajcak, 2008; Ma et al., 2014; Schindler & Bublatzky, 2020).

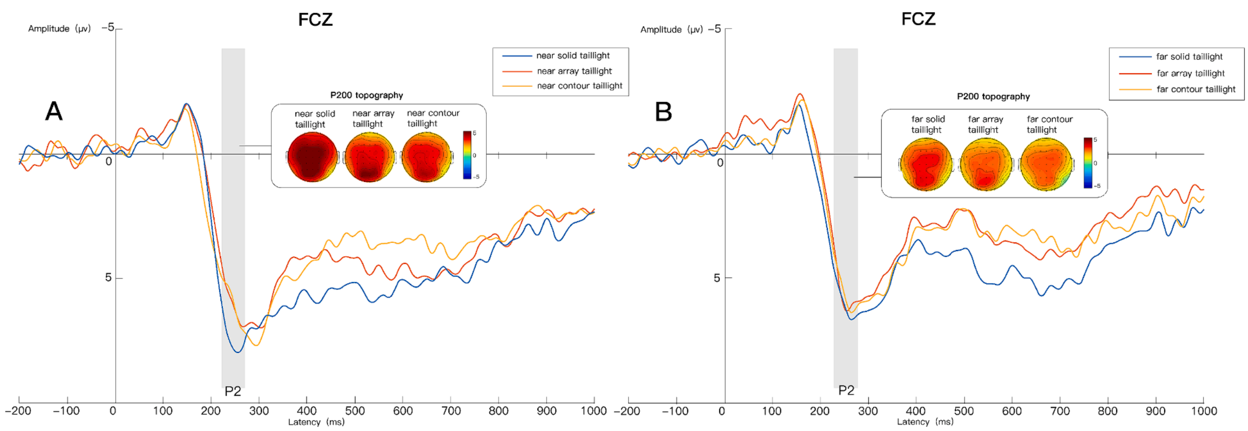


Fig. 6. (A) Grand-average ERPs obtained from electrodes in the frontal–central area for taillights under the near-distance condition; the corresponding topographic maps are also presented. The blue, red, and yellow lines indicate solid, array, and contour taillights, respectively. (B) Grand-average ERPs obtained from electrodes in the frontal–central area for taillights under the far-distance condition; the corresponding topographic maps are also presented. The blue, red, and yellow lines indicate solid, array, and contour taillights, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

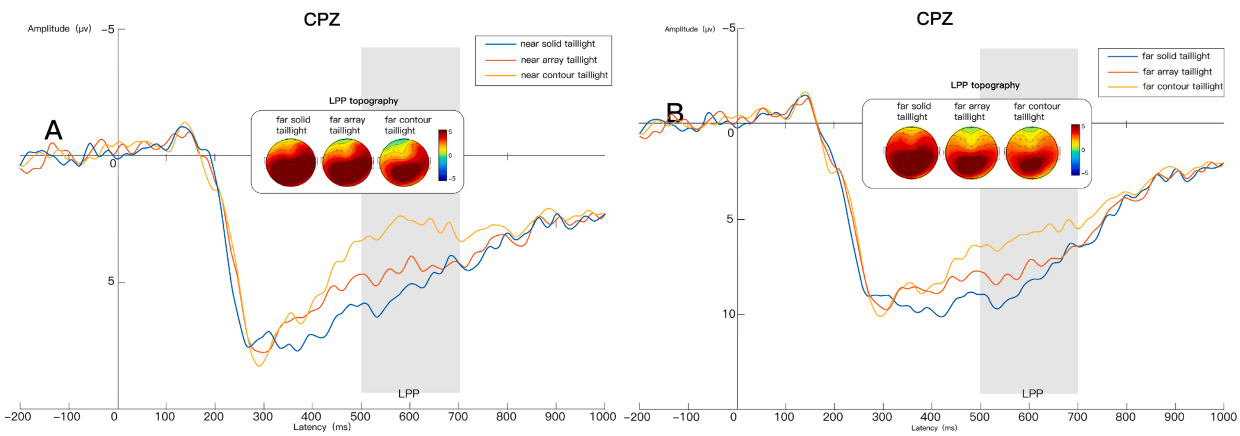


Fig. 7. (A) Grand-average ERPs obtained from electrodes in the central–parietal area for taillights under the near-distance condition; the corresponding topographic maps are also presented. The blue, red, and yellow lines indicate solid, array, and contour taillights, respectively. (B) Grand-average ERPs obtained from electrodes in the central–parietal area for taillights under the far-distance condition; the corresponding topographic maps are also presented. The blue, red, and yellow lines indicate solid, array, and contour taillights, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Experiment 2

4.1. Methods

4.1.1. Participants

In Experiment 2, 30 participants were recruited independently from Experiment 1. Four participants' data were excluded because of excessive recording artifacts and movement. Thus, the data of the remaining 26 participants (13 men; average age, 22–25 ± 1.14 years; mean age, 23.54 years) were retained. Other participant characteristics and recruitment methods were consistent with those in Experiment 1.

4.1.2. Experimental design

A 2 (taillight shapes) × 2 (vehicle distance) within-group experimental design was used to investigate the effect of linear-shaped taillights and vehicle–observer distance on drivers' hazard perceptions during nighttime driving. The linear-shaped taillights were divided into two categories (through type and non-through type; Table 1), and the vehicle–observer distance was divided into near and far conditions (3 vs. 15 m).

4.1.3. Stimulus materials

The stimulus presentation process in Experiment 2 was similar to that in Experiment 1. For Experiment 2, the two categories of linear-shaped taillights were used (i.e., through and non-through types), and ten images were prepared for each category. Similar to Experiment 1, the near and far distances (3 and 15 m, respectively) were incorporated into each image. Additionally, experiment 2 also

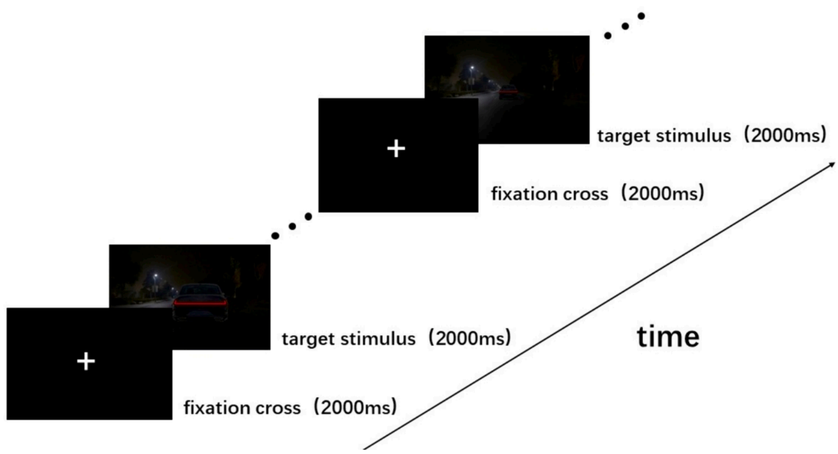


Fig. 8. Procedure for Experiment 2.

prepared the background stimulus for subsequent processing. Thus, 41 images were prepared for use in Experiment 2.

4.1.4. Procedure

The procedure for Experiment 2 was similar to that for Experiment 1, illustrated in Fig. 8. ERP data were averaged across all waveforms elicited for the same condition. Each of the ten images was presented six times for each of the four conditions, resulting in 60 trials per condition and a total of 240 trials for all conditions. Additionally, the background stimulus image was presented 60 times, resulting in 300 trials for Experiment 1. Images were presented in random order by using E-prime 3.0 software. The participants completed Experiment 2 in approximately 25 min.

4.1.5. Data acquisition and analysis

The data acquisition and analysis methods were similar to those employed in Experiment 1. The time window was 220–280 ms after stimulus onset for P2 and 500–700 ms after stimulus onset for LPP2.

4.2. Results

4.2.1. Behavioral data

The ratio of subjective hazard keystrokes to the total number of keystrokes was calculated and analyzed using a repeated-measures ANOVA, and the results revealed a nonsignificant interaction effect ($F = 0.374$, $p = 0.546$, $\eta_p^2 = 0.015$). However, distance ($F = 26.159$, $p < 0.001$, $\eta_p^2 = 0.511$) and taillight shapes ($F = 6.880$, $p = 0.015$, $\eta_p^2 = 0.216$) had significant main effects. Through-type taillights were associated with a significantly higher keystroke ratio than the array non-through-type (0.375 ± 0.059 vs. 0.264 ± 0.053, $p < 0.05$, 95 % CI = 0.024 –0.198). In addition, the near-distance condition received a higher keystroke ratio (0.514 ± 0.079 vs. 0.124 ± 0.045, $p < 0.001$, 95 % CI = 0.233 –0.547). These results indicated that the participants were likelier to press the "hazard" key when presented with driving environments with through-type taillights and near-distance.

The recorded response times were analyzed using a repeated-measures ANOVA. The results revealed that the interaction effects ($F = 1.272$, $p = 0.302$, $\eta_p^2 = 0.175$) and the main effects of distance ($F = 0.961$, $p = 0.365$, $\eta_p^2 = 0.138$) were insignificant. However, taillight shapes ($F = 5.857p = 0.05$, $\eta_p^2 = 0.494$) significantly affected the participants' response time. These results indicated that the participants had shorter response times when they encountered through-type linear taillights (885.715 ± 63.933 vs. 1028.645 ± 109.095 ms, $p < 0.05$, 95 % CI = −286.636 –1.577).

4.2.2. ERP data

The mean and standard error of the amplitudes of the ERP components under the two conditions are presented in Fig. 9. The grand-average ERP waveforms and topographic maps obtained in Experiment 2 are presented in Figs. 10 and 11.

P2 at 220–280 ms

The average amplitudes of the P2 component extracted from the frontal–central area were analyzed using a 2 × 2 repeated-measures ANOVA. The results showed no significant interaction effect ($F = 0.166$, $p = 0.687$, $\eta_p^2 = 0.007$). In addition, taillight shapes ($F = 5.137$, $p = 0.032$, $\eta_p^2 = 0.170$) and distance ($F = 9.466$, $p < 0.01$, $\eta_p^2 = 0.275$) significantly influenced the P2 amplitudes. These results signify that the non-through-type taillights (5.143 ± 0.420 vs. 4.454 ± 0.479 μV, $p < 0.05$, 95 % CI = 0.063 –1.321) and near distance (5.328 ± 0.487 vs. 4.266 ± 0.426 μV, $p < 0.05$, 95 % CI = 0.351 –1.773) garnered more attentional resources during the automatic detection stage of hazard perception (Huang & Luo, 2006; Philips & Takeda, 2009). A possible explanation is that, according to the feature integration theory, visual processing during automatic hazard detection is parallel (Treisman & Gelade, 1980; Kristjánsson & Egeth, 2020). Since non-through type taillights add an additional object compared to through type taillights, this

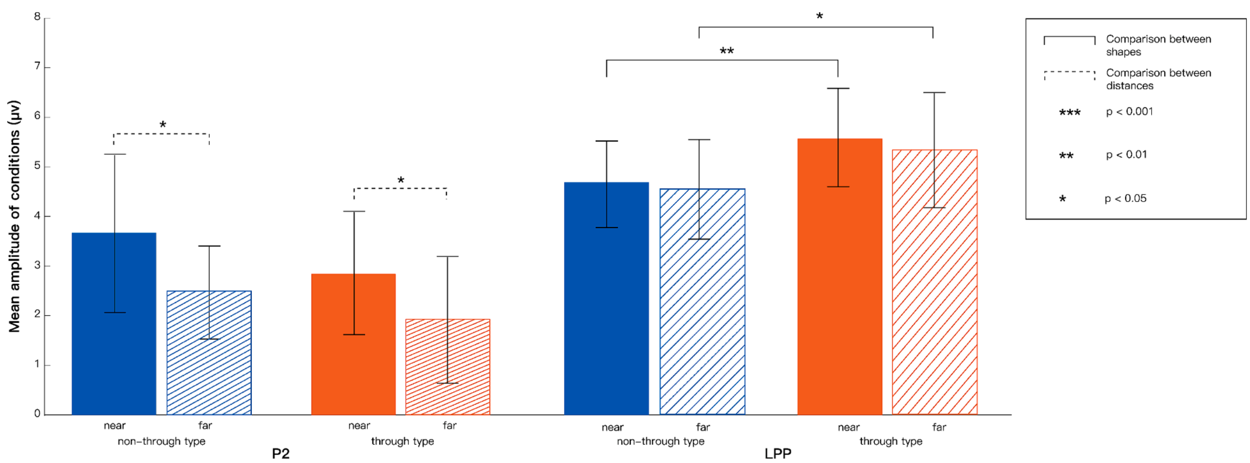


Fig. 9. Mean and standard errors of P2 and LPP amplitudes under all conditions. *statistical significance at 0.05.

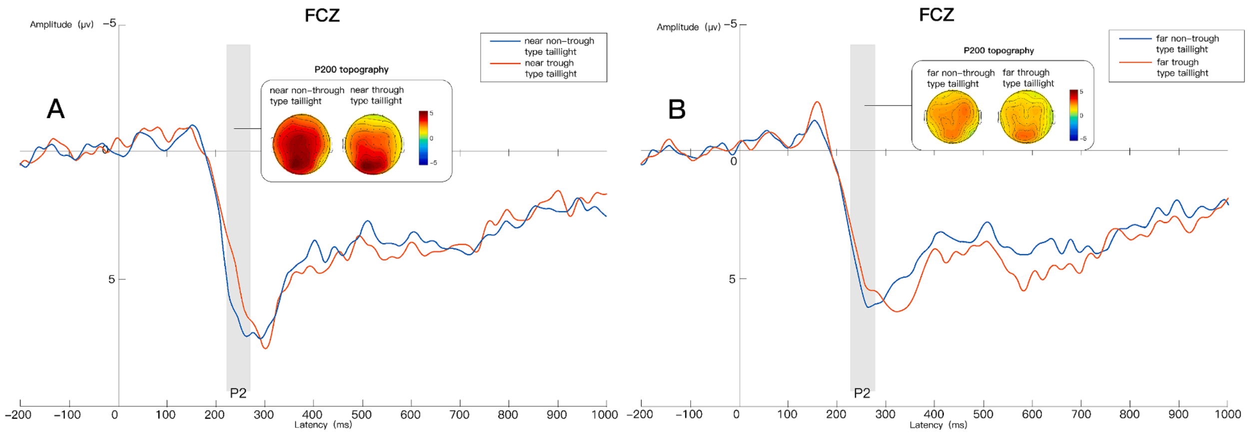


Fig. 10. (A) Grand-average ERPs obtained from electrodes in the frontal–central area for taillights under the near-distance condition; the corresponding topographic maps are also presented. The blue and red lines indicate non-through-type and through-type linear taillights, respectively. (B) Grand-average ERPs obtained from electrodes in the frontal–central area for taillights under the far-distance condition; the corresponding topographic maps are also presented. The blue and red lines indicate non-through-type and through-type linear taillights, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

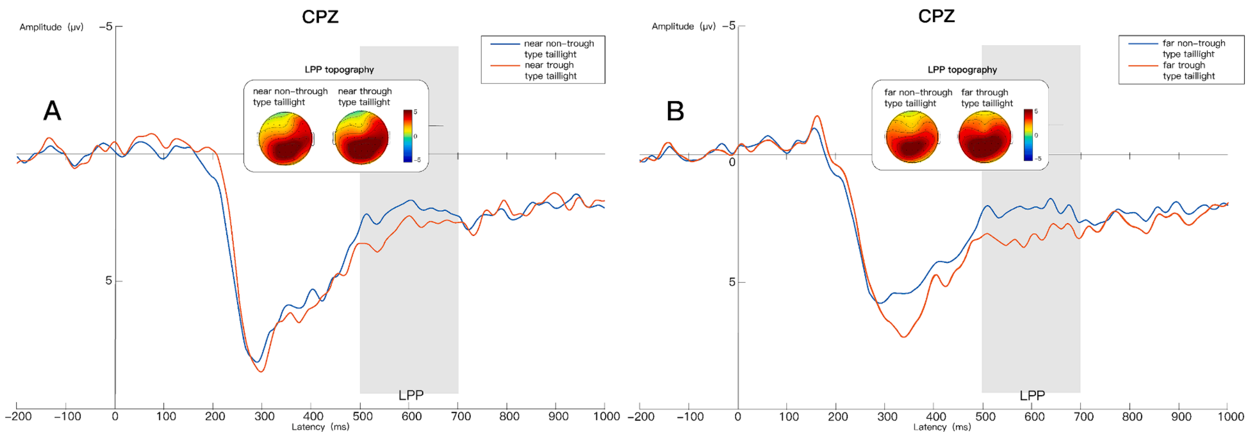


Fig. 11. (A) Grand-average ERPs obtained from electrodes in the central–parietal area for taillights under the near-distance condition; the corresponding topographic maps are also presented. The red and blue lines indicate through-type and non-through-type linear taillights, respectively. (B) Grand-average ERPs obtained from electrodes in the central–parietal area for taillights under the far-distance condition; the corresponding topographic maps are also presented. The red and blue lines indicate through-type and non-through-type linear taillights, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

increased visual complexity, and more attentional resources were allocated to processing stimuli with non-through type taillights (Wolfe, 1994; Kristjánsson & Egeth, 2020), leading to a larger P2 response.

LPP at 500–700 ms

The average amplitudes of the LPP component extracted from the central–parietal area were analyzed using repeated-measures ANOVA. The results revealed a nonsignificant interaction effect between distance and taillight shapes ($F = 0.087$, $p = 0.771$, $\eta_p^2 = 0.003$). Taillight shapes ($F = 14.853$, $p < 0.01$, $\eta_p^2 = 0.373$) significantly affected the LPP amplitudes, whereas distance ($F = 0.465$, $p = 0.501$, $\eta_p^2 = 0.018$) had no significant effect on the LPP amplitudes. These findings suggest that the driving situations with through-type taillights (2.840 ± 0.359 vs. 1.983 ± 0.303 μV, $p < 0.001$, 95 % CI = 0.339 –1.315) significantly increased the participants' negative emotions during the subjective evaluation stage of hazard perception (Foti & Hajcak, 2008; Ma et al., 2014; Schindler & Bublatzky, 2020).

5. Discussion

The results of Experiment 1 demonstrate that solid square shape taillights elicited larger amplitudes of P2 and LPP. However, Experiment 2 yielded different findings regarding the two stages of hazard perception. Specifically, the non-through-type taillights elicited greater P2 during the automatic detection stage, whereas the through-type taillights induced enhanced LPP during the subjective evaluation stage. This study recorded ERP and behavioral data of participants facing driving scenarios under different conditions. The ERP data reflected the neural processes of participants perceiving the hazards of different driving scenarios, revealing how taillight shapes influence the conveyance of hazards. The behavioral data reflected the outcomes of participants' decisions after perceiving hazards.

5.1. Solid square taillights significantly enhanced hazard perceptions

This study discussed the results using feature integration theory. According to this theory, perceiving stimuli can be divided into pre-attentive and focused attention. In the pre-attentive stage, the brain automatically and in parallel collects and stores independent features (such as color, shape, and movement) of objects; in the focused attention stage, the collected feature information is integrated into objects for perception in a top-down and serial manner (Treisman & Gelade, 1980; Kristjánsson & Egeth, 2020). This study recorded participants' neural processes of hazard perception from automatic detection and subjective evaluation perspectives. By applying feature integration theory, this study discussed the impact of taillight shapes on hazard detection from the perspective of feature information collection and hazard evaluation from the perspective of integrating features to perceive objects. This approach enhanced the understanding of how taillight shapes affect hazard perception.

Experiment 1 showed that solid square taillights generated a higher P2 amplitude than other shapes. The P2 component indicates the allocation of attentional resources to negative events (Huang & Luo, 2006) and the bottom-up detection of hazards (Qin & Han, 2009; Qin et al., 2009). Furthermore, negative stimuli generally produce larger P2 amplitudes (Carretié et al., 2001). Thus, the solid square taillights required more attentional resources, suggesting an increased perception of potential hazards. In the pre-attentive stage, different brain parts automatically gather basic features from the visual field. In this stage, distinctive features contrasting with the background can recruit more attention resources (Wolfe, 1994; Nothdurft, 2000). Compared to other square taillights, solid square taillights had a larger area of red, making the difference from the background more pronounced, thus attracting greater attention. This explained why square taillights, predominantly featuring completely red-filled areas, recruited more participants' attentional resources, as reflected by the increased P2 amplitude.

Solid square taillights significantly improved drivers' hazard perception during the subjective evaluation stage of hazard perception. Specifically, Experiment 1 showed that solid square taillights elicited higher LPP amplitudes. LPP is closely linked to emotional responses. Negative stimuli typically evoke negative emotions, which lead to increased LPP amplitudes (Olofsson et al., 2008; Ma et al., 2014). For instance, LPP amplitudes are significantly higher in individuals exposed to threatening stimuli than those exposed to nonthreatening stimuli. Additionally, LPP indicates detailed cognitive processing of content in hazardous environments and is associated with the subjective evaluation of hazards (Foti & Hajcak, 2008; MacNamara et al., 2009; Bublatzky & Schupp, 2012). Thus, within hazard evaluation tasks, LPP can indicate the extent of negative emotions elicited during participants' subjective evaluation of hazard levels. Our results indicated that solid square taillights triggered stronger negative emotions in participants, leading to an increased subjective evaluation of hazard levels. This finding aligns with the "1" keystroke ratio data analysis. In the top-down focused attention stage, feature information is processed into complete objects (Kristjánsson & Egeth, 2020), allowing participants to perceive the objects in the driving scene. The solid square taillights have the most significant red area compared to other square shape taillights. Red is typically associated with warnings, hazards, or importance (Pravossoudovitch et al., 2014; Braun & Silver, 1995). This connection has been strengthened through evolution, making red more attention-grabbing than other colors (Elliot & Maier, 2014). Therefore, the solid square taillights, with their distinct red-filled areas, conveyed the most intense negative message, attracting the most attention and subsequently triggering the highest levels of negative emotions during the subjective evaluation stage, resulting in receiving the highest number of "1" keystrokes. A study on warning signs yielded similar results: a larger red area within a square-type sign induced stronger hazard perceptions (Adams & Edworthy, 1995). These findings support Hypothesis 1. In addition, our findings showed that the presentation of images from driving scenarios elicited P2 and LPP responses, suggesting that these ERP components could serve as indicators of neural hazard processing.

Drivers could process solid square taillights more rapidly. Specifically, this study measured participants' "1" keystroke response times and found that solid taillights were associated with significantly shorter response times. According to the feature integration theory, salient and attention-grabbing stimuli accelerate the integration process (Treisman & Gelade, 1980; Lavie, 2005). As previously mentioned, images with solid square taillights are more salient and attract more attention than other square taillight stimuli. Therefore, when facing solid square taillights, participants can process the features of the stimulus scene more quickly, leading to faster completion of subsequent key-press tasks.

5.2. Through-type linear taillight enhanced drivers' hazard perception only during the subjective evaluation stage

This study showed that non-through-type linear taillights captured more attentional resources during the automatic detection stage, the initial stage of hazard perception. Specifically, ERP results revealed that non-through-type linear taillights were associated with significantly higher P2 amplitudes during the first stage of hazard perception. The P2 component is linked to selective attention and detection processes (Philips & Takeda, 2009), and stimuli inducing fear or distress, like alarming words or images, typically result in increased P2 amplitudes (Carretié et al., 2006; Qin & Han, 2009; Qin et al., 2009). Negative stimuli draw considerable attention, leading to increased P2 amplitudes (Carretié et al., 2001). Experiment 2 showed that non-through-type linear taillights consistently elicited higher P2 amplitudes, indicating they effectively communicated a stronger hazard and attracted more attention during the automatic detection stage.

The findings of P2 were incongruent with Hypothesis 2, as it was observed that longer through-type taillights did not elicit increased attention during the detection stage. This can be explained by feature integration theory. According to feature integration theory, visual processing is divided into two stages: first, the pre-attentive stage, where visual features are processed automatically and in parallel; second, the focused attention stage, where an individual's attention is focused on specific parts of the visual scene, integrating these features to form a complete perception of the object (Treisman & Gelade, 1980; Kristjánsson & Egeth, 2020). In the pre-attentive stage, driving situations with non-through-type taillights contain more objects than those with through-type taillights. Both two taillights are processed as independent features in parallel, increasing the overall feature complexity and visual information of the image, thereby recruiting more of the participants' attentional resources (Wolfe, 1994; Kristjánsson & Egeth, 2020), reflected in a larger P2.

During the subjective evaluation stage (i.e., the second stage of hazard perception), the through-type linear taillights significantly increased the participants' hazard perceptions. In particular, these taillights elicited increased LPP amplitudes. LPP is strongly associated with emotion and responds to attentional bias toward emotional stimuli (Schindler & Bublatzky, 2020; Hajcak et al., 2010). In the context of hazard perception, the LPP component indicates drivers' subjective evaluation and comprehensive processing of hazard-related information (Foti & Hajcak, 2008; MacNamara et al., 2009). Enhanced LPP indicated that, during the evaluation stage, participants allocated more attentional resources to processing the driving scenario through-type taillights and experienced stronger negative emotions triggered by the image stimuli (Olofsson et al., 2008; Ma et al., 2014). As mentioned, in the subsequent subjective attentive stage, visual information processing is serial, with the brain allocating limited resources to the targets that require attention (Treisman, 1998). During this process, individuals perceive the overall scene. Due to their length, the longer through-type linear taillights may lead participants to allocate more attentional resources to evaluate the hazard level of images with these taillights (Rensink, 2011). This, in turn, could elicit stronger negative emotions in participants, as reflected in the LPP. This explains why participants perceived through-type linear taillights as more hazardous during the subjective evaluation stage, as evidenced by the "1" keystroke ratio data. However, participants perceived non-through-type linear taillights as more hazardous during the automatic detection stage, which was inconsistent with Hypothesis 2.

The behavioral data from this study show that participants processed through-type linear taillights quickly. Specifically, through-type linear taillights were associated with significantly faster response times compared to non-through-type linear taillights. Non-through-type taillights have two separate objects, which increased the overall visual complexity compared to through-type taillights, thereby increasing the time required for feature integration (Treisman & Sato, 1990; Kristjánsson & Egeth, 2020). Additionally, the integration of object features is related to experiential knowledge, with familiar object features being integrated more quickly (Chan & Hayward, 2009). In daily life, long bars are more common than two separate short bars, so individuals can more quickly collect the feature information of continuous taillights and integrate them into objects for perception. Therefore, participants could respond faster to driving scenes with through-type taillights.

This study used feature integration theory to explain the results from the feature information collection and integration perspective. Feature integration theory is a visual perception theory about attention, often effectively explaining results from attention-related experiments, such as visual search tasks (Treisman, 1990; Kristjánsson & Egeth, 2020). However, in tasks unrelated to visual attention, such as auditory experiments on alarms during driving, the effectiveness of feature integration theory is limited.

5.3. Design implications for taillights

Taillight design is a complex process that involves various factors such as materials, brand positioning, and aesthetic considerations. Thus, basing design solely on the distinction between linear and square shapes can be overly simplistic. The main goal of our study was to identify optimal ergonomic solutions for both square and linear-shaped taillights and offer recommendations to automobile manufacturers and designers.

With advancements in LED technology, square taillights have evolved from solid shapes to more diverse, aesthetically appealing forms such as arrays and contours. However, this study found that solid square taillights were more effective at conveying hazards and could be processed faster during nighttime driving. Notably, solid square taillights significantly improved participants' hazard perceptions during both the automatic detection and subjective evaluation stages. Enhancing hazard perceptions is crucial as it helps drivers effectively anticipate potential scenarios and ultimately reduce the incidence of vehicle collisions (Vlakveld, 2011; Curry et al., 2011). Therefore, solid square shapes should be prioritized in the design of square taillights. Solid square taillights represent an optimal ergonomic solution for enhancing nighttime driving safety. Nonetheless, car manufacturers should strive to balance aesthetics and safety in their design choices.

New energy vehicles, including electric vehicles, are becoming increasingly popular among consumers. These vehicles often feature linear-shaped lights as a standard design element to showcase their advanced technology. The study found that non-through-type linear taillights effectively conveyed significant hazards during the automatic detection stage. Conversely, through-type linear taillights conveyed more significant hazards that were effectively perceived during the subjective evaluation stage. However, behavioral data from this study showed that through-type linear taillights were associated with greater hazard perceptions and faster response times compared to non-through-type taillights. Therefore, through-type configurations are an optimal ergonomic solution for designing linear taillights.

6. Limitations

This study used ERP measurements to explore how taillight shapes and vehicle distance affect hazard perceptions. The results indicated that solid square shape and through-type linear taillights are optimal ergonomic solutions. However, this study has several limitations that should be noted. First, while ERPs provide excellent temporal resolution, they offer low spatial resolution. Using devices with higher spatial resolution could enable more accurate measurements of brain region activities. Second, this study selected young individuals as study participants because they constitute the largest population of potential consumers of cars. In China, young people typically purchase their first car after graduation from college. However, the young participants were predominantly novice drivers and may be outperformed by experienced drivers in different hazard perception tests (Crundall et al., 2021; Horswill et al., 2020). Consequently, the findings may not be generalizable to more experienced drivers. To enhance insights into taillight design, future studies could include participants of various ages. Third, this study did not include visually impaired individuals. Future studies could include visually impaired participants to understand how they perceive hazards, contributing to a more inclusive understanding of hazard perception. Fourth, to prevent participant fatigue and learning effects, each level of tail light shape included ten images, the slight differences among which were not well controlled. Future studies should better control the variations in experimental materials or eliminate the effects of these differences during data processing. Fifth, This study only selected two main types of taillight shapes; future studies should consider a wider variety of taillight designs. Finally, using static images in a lab setting may not fully replicate real-world driving conditions; real-world driving conditions are more complicated and require consideration of factors such as pedestrians, vehicle speed, and weather. Therefore, future studies should aim for greater ecological validity by using driving simulators or presenting stimuli through animation or real driving videos. Furthermore, this study used feature integration theory to discuss the results from the feature information collection and integration perspective. However, real-life driving scenarios typically contain increasingly complex feature information, affecting individuals' perception of driving scenes. Therefore, further research should determine whether feature integration theory can explain perception in real driving scenarios.

7. Conclusion

This study consisted of two experiments that explored how the distance and shape of leading vehicle taillights affect drivers' hazard perception. Experiment 1 found that solid square taillights improved participants' hazard perceptions during both the automatic detection and subjective evaluation stages. Consequently, participants processed these taillights more quickly. Experiment 2 showed that non-through-type linear taillights were perceived as more hazardous during the automatic detection stage. In contrast, through-type linear taillights were perceived as more hazardous during the evaluation stage. Notably, participants identified hazards more frequently and quickly when encountering through-type linear taillights. As a result, solid square taillights and through-type linear taillights are more effective at conveying hazards and influencing drivers' hazard perceptions compared to other taillight types. In addition, P2 and LPP could serve as indicators of neural hazard processing.

The findings of this study can help designers and automobile manufacturers better understand how the shape of taillights influences the conveyance of hazards and the rearward driver's perception of it. These insights also offer preference from a driving safety perspective for designers and potential consumers. Furthermore, the research methods employed in this study can also be applied in future studies of hazard perception, considering the transmission of hazards and an individual's hazard perception from a neural process perspective.

CRediT authorship contribution statement

Guanhua Hou: Writing – review & editing, Funding acquisition, Conceptualization. **Zixian Lei:** Writing – original draft, Project administration, Formal analysis, Data curation, Writing – review & editing. **Huiwen Wang:** Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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