International Journal of Industrial Ergonomics 110 (2025) 103847

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Nonverbal communication between cars: Influence of taillight expressions on message delivery effectiveness

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ARTICLE INFO

Keywords:
Event-related potentials
Information processing
Nonverbal communication
Taillight shapes

ABSTRACT

Failed information exchanges between vehicles and their surroundings can lead to traffic accidents. Drivers often rely on taillights to communicate with following vehicles, but traditional taillights provide limited information and are insufficient in complex traffic situations. Facial expressions, as a universal form of nonverbal communication, offer rich and efficient channels for message delivery. This offers potential to expand current vehicle-to-vehicle interaction methods and enhance driving safety. Therefore, this study conducted an exploratory experiment to enhance inter-vehicle communication through taillight expressions. Using a within-subjects experiment with a 2 (tail light shape) × 3 (tail light expression) design, this study examined the efficacy of taillights in conveying messages. Specifically, we investigated whether rear-end drivers can accurately interpret positive or negative messages conveyed by taillights through different expressions. The process of processing driving-related information involves both perception and analysis stages. In order to capture the neural processes underlying participants' information processing, this study recorded their Event-Related Potentials (ERPs) at these stages separately. The results revealed that negative expression taillights effectively conveyed negative messages through the information processing, and participants responded more swiftly to these messages. However, taillights with positive expressions only effectively conveyed messages during the perception stage. Additionally, linear taillights with negative expressions conveyed the most potent negative messages. The study highlights the potential of taillights to convey information through nonverbal communication, thereby expanding vehicle-to-vehicle interaction. These findings provide a reference for designers and manufacturers seeking to enhance driver–environment communication.

1. Introduction

Traffic accidents occur daily because of failed information interactions. For example, a driver may fail to perceive and understand the braking signals from the vehicle ahead, which can cause a rear-end collision (McIntyre et al., 2012). Accidents can also occur when a driver interacts improperly with a pedestrian, resulting in misjudgments by both parties (Nie et al., 2015). Such accidents, caused by ineffective message transmission, are steadily increasing (WHO, 2023). For instance, pedestrian fatalities in the U.S. rose by 13 % in 2021 compared with the previous year (Stewart, 2023). Therefore, vehicles must communicate information effectively to their surroundings.

Drivers can convey information through headlights or taillights, depending on the driving conditions. Taillights are typically used to increase the conspicuity of the lead vehicle and provide positional information to prevent rear-end collisions (Luo et al., 2021). In addition, drivers use taillights to provide information to following vehicles to enhance safety. Messages such as deceleration and emergencies are communicated to following vehicles through taillights (Lee et al., 2020; Nguyen-Phuoc et al., 2020). The use of flashing headlights also helps reduce the risk of nighttime collisions. Thus, headlights and taillights are essential channels for delivering messages to drivers.

Establishing effective communication between cars helps improve driving safety. Ambiguity arises when taillights convey information: if the lead vehicle slows down, the following driver must infer whether it is due to a hazard ahead or preparation to pull over, and this ambiguity can cause critical delays in driver response (Hsieh et al., 2022). Moreover, real-world traffic is more complex, and drivers often need to convey richer information to ensure safety. For example, when a following car yields, a positive message should be delivered to the vehicle as a sign of

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https://doi.org/10.1016/j.ergon.2025.103847
Received 14 June 2025; Received in revised form 15 November 2025; Accepted 22 November 2025

appreciation, reinforcing cooperative driving norms and potentially reducing aggressive maneuvers (Yang et al., 2020; Papakostopoulos et al., 2015). Conversely, negative messages should be conveyed to rear vehicles when they are following too closely (McIntyre et al., 2012). However, due to their plain design, traditional taillights provide limited and imprecise information, making it difficult for drivers to effectively convey positive or negative messages and to address the complexity of real-world traffic conditions. Consequently, it is necessary to explore how to design headlights and taillights to convey richer and more accurate messages and to adapt to complex traffic situations.

Recent innovations in automotive lighting have transformed the design of both headlights and taillights to convey richer information more effectively. The High-Resolution Pixel Headlight uses an array of LEDs to create pixelated illumination, projecting distinct patterns onto the road ahead (Wang et al., 2021). These headlights can project positive messages, such as signals for pedestrian yielding, and negative messages, such as hazard warnings, thereby enhancing driving safety (Rosenhahn, 2018; Kleinkes et al., 2019). In parallel, research on taillights has focused on improving information communication to following vehicles. As shown in Fig. 1A, Matrix taillights represent an innovative design that incorporates an internal matrix. This matrix can convey diverse information to following vehicles, such as warnings and speed indicators (Kurtulus, 2021). Similarly, pixel-projected taillights, illustrated in Fig. 1B, project text or images to deliver more precise information, for example, to signal braking (Kurtulus, 2021). Interaction with this new taillight information involves self-display and projection. Both enable vehicles to convey additional information, such as warnings, speed indicators, or braking intentions, thereby enriching driver-to-driver communication. However, despite their promise, these systems face significant limitations. Matrix displays are often discernible only at short distances, while ground projections may distract drivers from focusing on the vehicle ahead. Moreover, although textual signals provide richer and more accurate information, they usually take longer to interpret and are influenced by cultural background, limiting their universality (Goolkasian, 1996; Lin et al., 2023). These limitations underscore the need for signaling solutions that are universally interpretable, cognitively efficient, and reliable in safety-critical conditions.

Affective taillight expressions represent a promising approach to addressing this gap. Prior studies show that drivers often perceive the rear of cars as faces, and anthropomorphic cues can effectively communicate emotions (Tobitani et al., 2020; Chen and Park, 2021). Facial expressions are a universal form of nonverbal communication. They can convey positive, neutral, and negative messages, often carrying more meaning than verbal communication (Guerrero and Floyd, 2006; Giri, 2009). Basic expressions, such as smiles and anger, are also considered to be rapidly recognized across cultures and to require minimal cognitive effort (Ekman and Friesen, 1971; Guerrero and Floyd, 2006; Puffet and Rigoulot, 2025). These features suggest that if taillight expressions can convey information through nonverbal communication, they hold great potential for vehicle-to-vehicle interaction. Specifically, they could supplement current taillight systems with an efficient, informative, and universal means of communication. This would improve the effectiveness of vehicle-to-vehicle interaction and thereby enhance driving safety. Yet little research has examined the effectiveness of such affective designs in driving contexts. To address this gap, the present study investigates how taillight expressions influence message delivery, aiming to assess their potential as a complementary mechanism to existing signaling technologies.

Nonverbal communication involves conveying messages or signals without words (Giri, 2009). Prior research shows that it is highly efficient, accounting for 65 % or more of communicative meaning (Guerrero and Floyd, 2006). Thus, it can transmit substantial information without words. Facial expressions, as a form of nonverbal communication, allow individuals to convey negative (anger) and positive (friendly) messages (Giri, 2009). Adjusting the angle of taillights can create different facial-like expressions on the rear of cars (Tobitani et al., 2020). Therefore, drivers may use taillight expressions to send positive or negative messages to following vehicles. In real traffic, verbal communication between drivers is difficult, highlighting the importance of studying taillight expressions as a medium of nonverbal vehicle communication.

Nonverbal messages consist of three components: the underlying signal, the intended communication, and its interpretation (Mandal, 2014). The message sent by the encoder (sender) may not be interpreted by the decoder (receiver) in a way that accurately reflects the sender's intent (Hall et al., 2019). Any uncertainty or confusion on the part of the decoder can negatively affect communication (Hargie, 2021). As noted, taillights can convey positive or negative messages through their expressions. However, if these messages are not effectively perceived and decoded, the rear driver may fail to interpret them as intended by the front driver. Therefore, this study examined the effectiveness of messages conveyed by taillight expressions. Specifically, it investigated whether drivers can perceive and understand the messages conveyed by the vehicle ahead.

Driving information processing is typically described as a sequence of perception, analysis, and decision-making (Li et al., 2023). In the perception stage, visual information plays a critical role in safe driving. Drivers must filter out irrelevant information and focus their visual attention on driving-related cues (Wolfe et al., 2022; Pammer et al., 2018). Next, drivers interpret and analyze the perceived information and ultimately make behavioral decisions accordingly (Li et al., 2023). This study investigated the effectiveness of taillight messaging by examining participants' cognitive processing, specifically the stages of perception, analysis, and interpretation.

Fig. 1. (a): an example of matrix taillights; (b): an example of pixel-projected taillights (KURTULUS, 2021).

2. Related works

2.1. Studies on the interaction between automobiles and the external environment

The External Human-Machine Interface (eHMI) has been proposed to enhance communication between vehicles and their surroundings (Man et al., 2025). eHMI employs visual, auditory, or other cues to facilitate interaction. Building on this, researchers have developed text-based, anthropomorphic, icon-based, auditory, and projection-based eHMI designs to improve vehicle-to-environment communication, achieving notable progress (Eisma et al., 2023; Joisten et al., 2021; Rouchitsas and Alm, 2023; Bindschädel et al., 2023; Mok et al., 2022). However, existing studies have mainly focused on interactions between autonomous vehicles and pedestrians to improve pedestrian safety, rather than vehicle-to-vehicle communication. Moreover, few studies have examined the feasibility of conveying information via taillight expressions.

Some studies have employed image stimuli to investigate vehicle–environment interactions. For example, Luo et al. (2021) used nighttime driving images to examine the impact of taillight shapes on conspicuity. Similarly, Hou et al. (2024) examined how taillight shapes affect hazard perception using a comparable approach. This established experimental paradigm, in which participants respond to image stimuli, has been widely applied in studies of driving scene perception (Ma et al., 2014; Li et al., 2022). These studies have produced valuable insights and advanced the field. Therefore, this study adopts this method to examine how taillight expressions influence the effectiveness of information transmission.

2.2. How humans perceive emotions of anthropomorphic vehicles

In daily life, anthropomorphic products convey emotional messages to the outside world. Anthropomorphism refers to attributing human characteristics to non-human entities, making inanimate products appear more lifelike (Aggarwal and McGill, 2007). Humans are naturally inclined to recognize human characteristics in products (Epley et al., 2007) and perceive the emotions they convey (Chen and Park, 2021). Similar to human faces, the “faces” of anthropomorphic products can express negative, neutral, and positive emotions (Chen and Park, 2021), influencing others’ perceptions and behaviors (Delbaere et al., 2011; Surguladze et al., 2004).

Car fronts, as typical anthropomorphic products with strong symmetry, are easily perceived as human faces (Delbaere et al., 2011). The headlights are perceived as “eyes” and the sunken grille as a “mouth” (Maeng and Aggarwal, 2018), enabling car fronts to convey expressions. Recent studies suggest that taillights resemble a pair of eyes, allowing the rear of a car to be perceived as a face and enabling taillights to convey emotional information (Tobitani et al., 2020). Unlike car fronts, the rear lacks a grille, leaving only the taillights as “eyes.” Thus, it is crucial to explore whether information can be conveyed solely through taillight expressions, enabling rapid and efficient nonverbal communication between vehicles.

Different anthropomorphic expressions can convey distinct messages. Negative facial expressions, such as anger, convey adverse signals like hazards and threats, shaping recipients’ behavior (Reed et al., 2014; Pichon et al., 2009). In contrast, friendly expressions convey positive messages such as affinity (Feldmann-Wüstefeld et al., 2011; Aggarwal and McGill, 2007). Products with friendly expressions can elicit more positive attitudes from consumers (Delbaere et al., 2011). Thus, negative expressions (e.g., anger, fear) transmit negative messages, while positive expressions (e.g., happiness, friendliness) convey positive messages. Based on these arguments, this study proposed that people can perceive and understand positive and negative messages through taillight expressions. Formally stated:

H1. Taillights could convey negative messages effectively

H2. Taillights could convey positive messages effectively

People generally react more quickly to negative messages. Evolutionary psychology suggests that threatening stimuli are closely tied to human survival (Öhman, 1993). In cognitive processing, individuals prioritize hazardous stimuli with strong survival relevance, activating the avoidance system (Rozin et al., 2009). Therefore, people may respond faster to taillights conveying negative messages, such as hazards. This rapid, pre-attentive perception of threat is a critical survival mechanism (Li and Keil, 2023; Plate et al., 2024). It suggests that anthropomorphic cues could enable effective, intuitive safety warnings. Accordingly, this study proposed that taillights with negative expressions would be processed faster than other expressions. Formally stated:

H3. Taillights with negative expressions could be processed faster.

2.3. ERPs reflect emotional information

Several studies have employed Event-Related Potentials (ERPs) to investigate facial expressions in anthropomorphic products. For example, Liu et al. (2022) used ERPs to examine neural processing differences in facial emotions between humans and vehicles, revealing that human faces share partly similar neural processing mechanisms within a 100–300 ms latency window. Additionally, Cao et al. (2022) employed ERPs to test whether anthropomorphic app icons are perceived as more attractive than non-anthropomorphic ones. Their results showed that anthropomorphic app icons were rated as more attractive and elicited enhanced P2, P3, and LPP components. Li et al. (2022) demonstrated that fixation-related P1 amplitude varied across humanoid robot appearances, conveying positive, neutral, or negative impressions. Collectively, these findings underscore the suitability of ERPs for examining the neural processing of emotional information in anthropomorphic products.

As noted earlier, this study assesses messaging effectiveness from both perception and analysis perspectives, with P2 associated with perception. P2 is an early exogenous ERP component that typically peaks between 150 and 275 ms (Dunn et al., 1998). It is linked to selective attention and early-stage feature detection, such as color, orientation, and shape. Thus, P2 reflects attention directed by specific visual features (Philips and Takeda, 2009). Moreover, emotional stimuli elicit larger P2 amplitudes than neutral stimuli. Prior work demonstrated that attention can be oriented toward emotional stimuli, reflected in enhanced P2 (Kanske et al., 2011). Compared to neutral faces, emotional faces (angry and happy) elicited greater P2 amplitudes (Carretié et al., 2013; Conty et al., 2012). Therefore, in facial expression tasks, P2 reflects attentional bias toward emotion conveyed by stimuli. P2 amplitude is a valuable indicator of attention captured by emotional stimuli and was used here to reflect perceptual information processing.

The Late Positive Potential (LPP) is a later-stage ERP component that typically peaks 300–800 ms after stimulus onset (Ma et al., 2014). It is strongly associated with emotional processing and reflects selective attention to emotional stimuli (Schindler and Bublatzky, 2020; Hajcak et al., 2010). Prior studies found that emotional stimuli elicit larger LPP amplitudes than neutral stimuli (Hajcak and Olvet, 2008). Thus, LPP amplitudes increase when participants perceive positive or negative emotional information. In addition, LPP reflects more elaborate processing of hazard-related information. It is thought to represent later, more complex semantic processing of stimuli, including subjective evaluations and reinterpretations of emotional content (Foti and Hajcak, 2008; MacNamara et al., 2009; Bublatzky and Schupp, 2012). As noted earlier, analytical processing corresponds to the later stage of drivers’ information interpretation, when emotional content is evaluated. Accordingly, this study used LPP as an index of analytical emotional processing.

In this study, the independent variables were taillight shapes and expressions, and the dependent variable was message effectiveness. This study examined how taillight shapes and expressions affect message delivery effectiveness and aimed to address the following questions:

1. Could taillights convey negative messages effectively?
2. Could taillights convey positive messages effectively?

3. Methods

3.1. Participants

Before the experiment, G*Power 3.1.9 was used to estimate the required sample size. Assuming an effect size f = 0.25, α = 0.05, and power = 0.80, the required sample size was at least 19. A total of 31 licensed participants were recruited from a university campus. Data from three participants were excluded due to excessive artifacts and movement during recording, leaving 28 participants for the final analysis. All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of mental disorders (15 men; mean age = 20–26 ± 1.12 years). Participants were recruited online and provided informed consent prior to the experiment. Upon completion, they received 50 RMB as compensation. The study was approved by the Internal Review Board of the Inclusive User Experience Research Centre.

3.2. Experimental design

This study used a within-subjects 3 (taillight expressions) × 2 (taillight shapes) factorial design to examine their impact on message delivery effectiveness. Taillight expressions were manipulated at three levels: negative (angry), neutral, and positive (friendly), with neutral stimuli serving as the reference. Taillight shapes were manipulated at two levels: square and linear.

3.3. Stimulus materials

According to Luo et al. (2021), square-shaped taillights (e.g., Lavida 300TSI, Sagitar 280TSI, Audi A4L) and linear shape taillights (e.g., Leading Ideal L9, Xiaopeng P5, Porsche Panamera) are two dominant and commonly used types of taillights. Square taillights feature enclosed designs and cover a larger area, while linear taillights are defined by slim lines. Using both types enhances the generalizability of findings, and because they consist of two distinct units, they can be readily perceived as eyes. Therefore, this study used square and linear taillights as experimental materials.

Stimuli were adapted from Luo et al. (2021) and depicted a male driver observing the preceding vehicle under clear nighttime conditions (Fig. 2). Taillight expressions were manipulated using Photoshop: downturned taillights conveyed negative expressions (Ekman, 1993), upward-curved taillights conveyed positive expressions (Tobitani et al., 2020), and horizontally aligned taillights conveyed neutral expressions. Before the main experiment, a validation study was conducted to confirm that the synthesized taillight stimuli effectively conveyed the intended emotional expressions. Five automotive design experts (each with at least five years of product design experience) and five non-expert participants rated all 60 stimuli on a 5-point Likert scale (1 = very angry, 5 = very friendly). The ratings were analyzed using a mixed-design ANOVA. Results confirmed a successful emotional manipulation: stimuli designed as positive, neutral, and negative were rated in the intended order with significant differences between conditions. No significant differences were found between experts and non-experts in their perception patterns, confirming the stimuli's validity and suitability for the subsequent ERP study. Vehicle taillights are required to be red (NHTSA, 2010), and the stimulus color was controlled following Luo et al. (2021) (RGB ≈ 254, 0, 0; HSB ≈ 0, 100 %, 99 %). Taillight shapes were set at two levels: square and linear. Ten images were prepared for each condition, yielding 60 experimental stimuli in total (Table 1).

Fig. 2. Example of stimulus.

3.4. Procedure

EEG and behavioral data were collected to capture participants' information processing and decision-making outcomes. Following the paradigm of Luo et al. (2021) and Hou et al. (2024), participants evaluated nighttime driving scenes while ERP data were recorded during repeated stimulus presentations. A button-response task was used to collect subjective judgments and elicit P2 responses, since passive viewing of emotional faces rarely evokes P2 (Li et al., 2022; Peschard et al., 2013). This active task ensured participants' cognitive engagement with the stimuli.

Given the inherent demands of hazard perception in nighttime driving, participants were instructed to assess whether each scene was hazardous (pressing '1' or '2'), rather than labeling the expression as negative, neutral, or positive. This task was chosen because drivers in real traffic often evaluate hazards to guide behavior (Horswill and McKenna, 2004), rather than explicitly classifying emotions.

In this study, negative expressions were expected to make participants perceive the driving scene as more hazardous (e.g., when the lead vehicle warns of an accident ahead, prompting more cautious driving; Zhang et al., 2025), whereas positive expressions were expected to make the scene appear less hazardous (e.g., when the lead vehicle expresses gratitude, reducing aggressive driving; Shen et al., 2018). The process of hazard judgment is inherently affective, as perceiving a situation as more hazardous typically induces stronger emotional responses. These affective responses are reliably indexed by P2 and LPP (Ma et al., 2014; Hou et al., 2024).

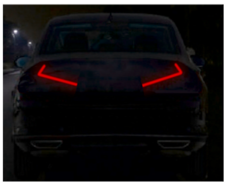
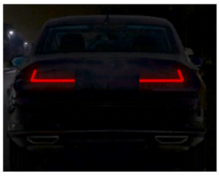
Thus, our design captures whether expressive taillights successfully transmit positive or negative information by testing their impact on hazard judgments and the associated neural responses. The neutral condition served as a baseline for comparison. This approach enhances ecological validity by simulating real driving decisions while linking message transmission to both behavioral and neural indicators.

Participants were seated comfortably in ergonomic laboratory chairs facing a 24-inch monitor positioned 60 cm away (1920 × 1080 resolution; visual angle = 28.16° × 28.16°). Lighting and temperature were strictly controlled, and participants received sufficient rest before completing a practice session to familiarize themselves with the tasks and stimuli.

In the formal experiment, each trial began with a fixation cross displayed for 2000 ms, followed by an image stimulus presented for 2000 ms (Fig. 3). The stimuli depicted nighttime driving scenarios. Participants were instructed to imagine themselves driving and to respond quickly: pressing "1" if the scene appeared hazardous and "2" otherwise. They were required to evaluate each image and respond before it disappeared. All stimuli were presented in random order.

Each of the 10 driving images was presented six times, yielding 60 trials per condition and 360 trials across six conditions. ERP data were

Table 1
Examples of all conditions.

		Taillight expressions		
		Negative	Neutral	Positive
Taillight shapes	Square			
	Linear			

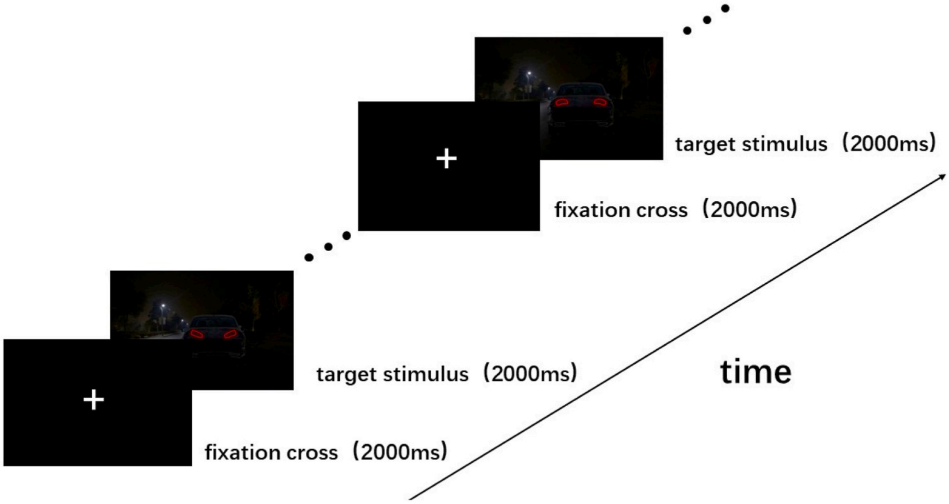


Fig. 3. Experimental1 procedure.

computed by averaging waveforms elicited within each condition. To reduce fatigue, participants were allowed breaks after every 180 trials. Stimulus presentation was randomized using E-prime 3.0 software, and the experiment lasted approximately 24 min.

3.5. Data acquisition and analysis

EEG data were recorded with a Neuroscan Synamp2 Amplifier (Scan 4.3.1, Neurosoft Labs, Inc., Sterling, USA) using a 64-channel Ag/AgCl cap arranged according to the international 10–20 system. Signals were sampled at 1000 Hz, with electrode impedances maintained below 5 kΩ. For the P2 component, analysis focused on the 190–260 ms window post-stimulus using data from frontal-central sites (F3, FZ, F4, FC3, FCZ, FC4, C3, CZ, C4). For the LPP component, analysis was conducted over the 400–750 ms window using data from central-parietal sites (C3, CZ, C4, CP3, CPZ, CP4, P3, PZ, P4). In addition, to ensure that the facial expression effect originated from emotional processing rather than shape differences between positive and negative taillights, the mean N1 amplitude was calculated within the 110–140 ms time window. The N1 component is generally considered to reflect low-level visual information processing, such as shape features and curvature (Vogel and Luck, 2000; Luck, 2014). The mean N1 amplitudes were calculated from occipital regions (Oz、PO3、PO4、O1、O2) for subsequent analyses.

Offline EEG data were processed using MATLAB 18b and the EEGLAB toolbox (Delorme and Makeig, 2004). A 0.5–30 Hz bandpass filter was applied, and data were segmented from −200 to 1000 ms relative to stimulus onset. Segments with poor signal-to-noise ratios or amplitudes beyond ±80 μV were excluded, and participants with >30 % rejected data were removed. Independent component analysis (ICA) was used to eliminate artifacts such as eye blinks and noise (Anemüller et al., 2003). Components identified as ocular or channel noise were removed after visual inspection (Hu and Zhang, 2019). ERP waveforms were averaged for six conditions, and P2 and LPP amplitudes were extracted within defined time windows. Data were analyzed using SPSS 19 (IBM, USA).

Behavioral data were averaged by condition and subject before analysis. Keystroke ratios were computed by dividing keystrokes per condition by total keystrokes. Specifically, the ratio of “1” keystrokes for negative versus neutral expressions, and “2” keystrokes for positive versus neutral expressions, were compared. Keystroke ratios assessed whether participants perceived negative taillights as more hazardous than neutral ones, and positive taillights as less hazardous. Mean response times were calculated per participant across all trials. Trials without responses within the allotted time were excluded. A two-way repeated-measures ANOVA examined both ERP and behavioral data. To control for false positives, the Bonferroni correction was applied. At $\alpha = 0.05$, P-values were adjusted by the number of tests (Chen et al., 2017). Taillight expressions (negative, neutral, positive) and shapes (square, linear) were within-group variables. Normality tests were conducted, and the Greenhouse–Geisser correction was applied when required.

4. Result

4.1. Behavioral data

4.1.1. Response time

Response times were analyzed using a repeated-measures ANOVA with three taillight expressions (negative, neutral, positive) and two taillight shapes (square, linear). A significant main effect of taillight expressions was found ($F = 6.092$, $p = 0.019$, $\eta_p^2 = 0.549$), indicating that expressions significantly influenced response times. Neither the main effect of taillight shapes ($F = 0.002$, $p = 0.968$, $\eta_p^2 = 0.001$) nor the interaction between expressions and shapes ($F = 1.642$, $p = 0.242$, $\eta_p^2 = 0.247$) was significant. These results suggest that participants responded faster to negative expression taillights.

4.1.2. The ratio of keystrokes

The ratio of "1" keystrokes in negative and neutral conditions was analyzed using a two-way repeated-measures ANOVA. The analysis showed a significant main effect of taillight expressions ($F = 22.412$, $p < 0.001$, $\eta_p^2 = 0.454$). However, neither the main effect of taillight shapes ($F = 1.294$, $p = 0.265$, $\eta_p^2 = 0.046$) nor the interaction effect ($F = 0.014$, $p = 0.905$, $\eta_p^2 = 0.001$) was significant. The findings suggest that negative-expression taillights conveyed a stronger negative message than neutral ones (0.702 ± 0.052 vs. 0.356 ± 0.055, $p < 0.05$). Consequently, participants perceived negative-expression taillights as more hazardous and pressed "1" more often.

The ratio of "2" keystrokes in positive and neutral conditions was analyzed using a two-way repeated-measures ANOVA. The analysis revealed a significant main effect of taillight expressions ($F = 10.313$, $p = 0.003$, $\eta_p^2 = 0.276$). However, neither the interaction effect ($F = 0.370$, $p = 0.548$, $\eta_p^2 = 0.014$) nor the main effect of taillight shapes ($F = 1.939$, $p = 0.175$, $\eta_p^2 = 0.067$) was significant. The findings showed that participants perceived taillights with positive expressions as less hazardous than neutral ones during the button task (0.807 ± 0.043 vs. 0.664 ± 0.055, $p < 0.05$). More participants pressed the "non-hazard" button when exposed to positive taillights.

4.2. ERP data

In this study, a larger P2 amplitude was interpreted as increased attentional bias toward emotional stimuli during the early perceptual stage of processing. In contrast, a larger LPP was associated with evaluative processing of emotional stimuli during later analytic stages. Fig. 4 displays the mean amplitudes and standard errors of these ERP components. For reference, Figs. 5 and 6 show the grand-average ERP waveforms and corresponding topographic maps.

4.2.1. N1 at 110–140 ms

At the occipital region, the N1 component was extracted and analyzed using ANOVA. The results showed that the main effects of shape ($F = 2.42$, $p = 0.132$, $\eta_p^2 = 0.082$) and expression ($F = 0.64$, $p = 0.538$, $\eta_p^2 = 0.047$) were not significant. In addition, the interaction effect was also not significant ($F = 0.39$, $p = 0.684$, $\eta_p^2 = 0.029$). These findings indicate that taillight expression conditions did not differ at the early visual stage indexed by N1, suggesting that later P2/LPP effects cannot be attributed to low-level visual confounds.

4.2.2. P2 at 190–260 ms

A two-way repeated-measures ANOVA was conducted to analyze the amplitudes of P2 extracted from electrodes in the frontal-central area. The results revealed a significant effect of taillight expressions on the amplitudes of P2 ($F = 5.408$, $p = 0.011$, $\eta_p^2 = 0.302$). However, the main effect of shapes ($F = 1.601$, $p = 0.217$, $\eta_p^2 = 0.058$) and the interaction effect ($F = 2.212$, $p = 0.131$, $\eta_p^2 = 0.150$) were not found to be significant. Further multiple comparisons indicated that both positive expression (1.987 ± 0.577 μV vs. 1.357 ± 0.550 μV, $p < 0.05$) and negative expression (1.990 ± 0.644 μV vs. 1.357 ± 0.550 μV, $p < 0.05$) elicited larger P2 amplitudes compared to neutral expression taillights. These findings suggested that, during the detection stage of information processing, driving situations with negative and positive expression taillights capture greater attentional resources compared to neutral expression taillights.

4.2.3. LPP at 400–750 ms

LPP amplitudes from the central-parietal region were analyzed using a repeated-measures ANOVA with three taillight expressions and two shapes as factors. The results showed a significant main effect of taillight expressions ($F = 5.391$, $p = 0.011$, $\eta_p^2 = 0.293$). However, the main effect of taillight shapes was not significant ($F = 0.002$, $p = 0.962$, $\eta_p^2 = 0.000$).

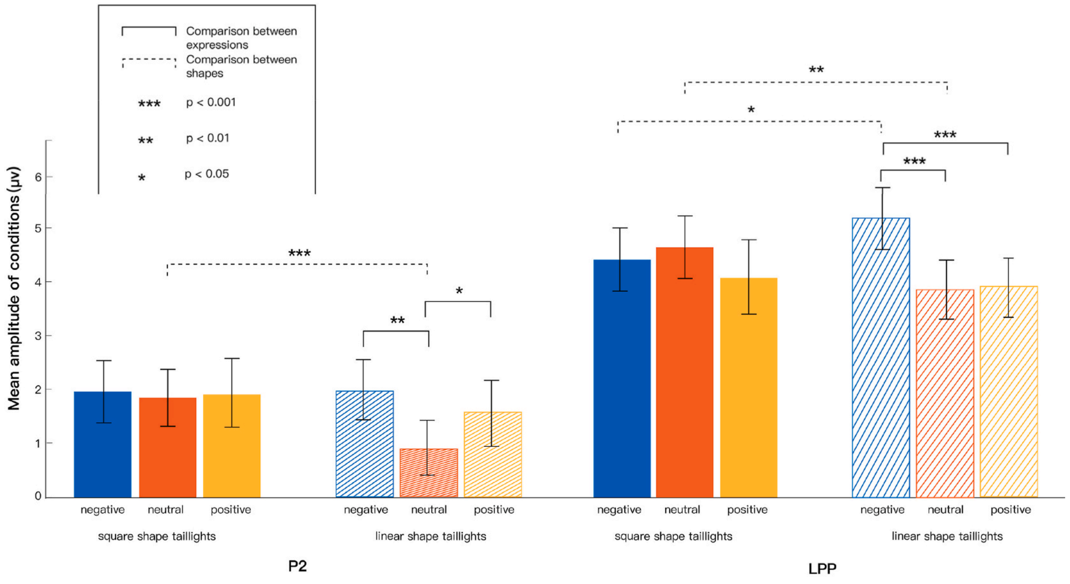


Fig. 4. Mean and standard errors of P2 and LPP amplitudes under both conditions. *statistical significance at 0.05.

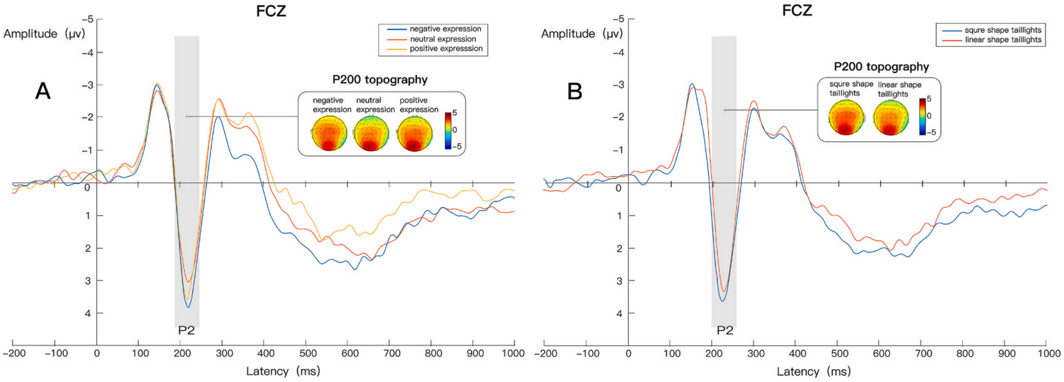


Fig. 5. (A) Grand-average ERPs from frontal–central electrodes in response to taillights with different expressions, accompanied by corresponding topographic maps. Blue, red, and yellow lines represent negative, neutral, and positive expressions, respectively. (B) Grand-average ERPs from the same electrode sites for taillights with varying shapes, along with topographic maps. Blue and red lines denote square and linear shapes, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

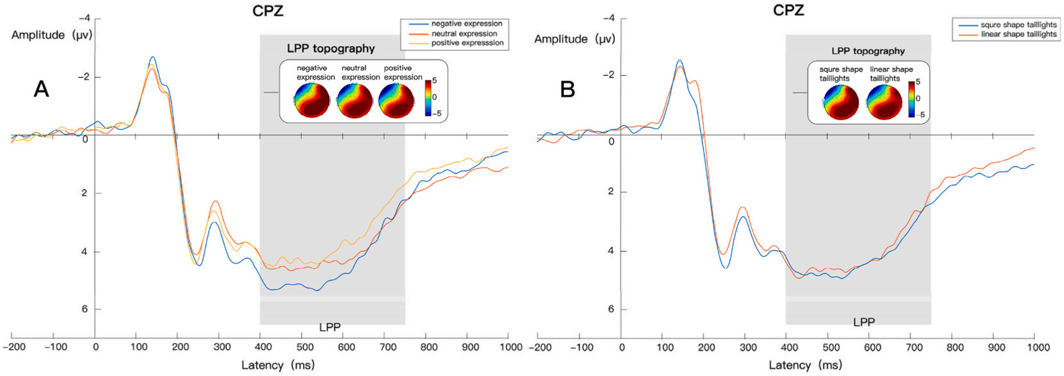


Fig. 6. (A) Grand-average ERPs recorded from central–parietal electrodes in response to taillights with different expressions, accompanied by corresponding topographic maps. Blue, red, and yellow lines represent negative, neutral, and positive expressions, respectively. (B) Grand-average ERPs from the same electrode sites for different taillight shapes, along with topographic maps. Blue and red lines indicate square and linear shapes, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

There was also a significant interaction between taillight shapes and expressions ($F = 5.786$, $p = 0.08$, $\eta_p^2 = 0.308$). Multiple comparisons showed that negative-expression taillights elicited a larger LPP than neutral ones (5.394 ± 0.626 μV vs. 4.794 ± 0.605 μV, $p < 0.05$). Under the negative condition, linear-shaped taillights elicited a larger LPP than square-shaped ones (5.773 ± 0.679 μV vs. 5.015 ± 0.627 μV, $p = 0.05$). These findings suggest that negative expression taillights evoke stronger emotional responses when participants evaluate the conveyed messages. In the negative expression condition, linear taillights conveyed the strongest negative information, eliciting the most intense negative emotions from participants.

5. Discussion

This study set out to examine expressive taillights as a novel approach for enriching vehicle-to-vehicle communication. This study explores the potential of using taillight expressions for nonverbal communication, aiming to enrich vehicle-to-vehicle interaction in an efficient, universal, and low–cognitive load manner to enhance road safety. This study examined the effects of taillight expression and shape on occipital N1 amplitudes. The absence of expression effects at N1 confirms that the later modulations of P2 and LPP were not driven by low-level visual differences. Instead, taillight expressions significantly affected P2 and LPP, with linear negative expressions eliciting the largest LPP. These findings highlight how individuals perceive and process emotional information conveyed by taillight displays. In addition, behavioral data showed that participants responded faster to negative taillight expressions.

5.1. Taillights could convey negative messages effectively

Behavioral data showed that taillights with negative expressions conveyed stronger negative messages than neutral ones. Keystroke data revealed more "1" keystrokes for negative expressions than for neutral ones, with more participants pressing the "hazard" key under negative conditions. This indicates that participants perceived negative-expression taillights as conveying stronger negative messages, making the driving scene appear more hazardous.

ERP results were consistent with the behavioral findings. Specifically, the P2 and LPP components showed the largest amplitudes in response to negative expression taillights. The P2 component reflects automatic attention bias (Philips and Takeda, 2009). Previous studies have shown that emotional stimuli increase P2 amplitude (Carretié et al., 2013; Conty et al., 2012). In this study, the P2 component reflected perception of taillight expressions during the early stage of information processing. The LPP component is a late ERP marker associated with emotion (Schindler and Bublatzky, 2020; Hajcak et al., 2010). The LPP reflects detailed processing of emotional content, and prior studies show that emotional stimuli increase LPP amplitude (Foti and Hajcak, 2008; MacNamara et al., 2009; Bublatzky and Schupp, 2012). In this study, the LPP was used to represent the analytic stage of information processing. These findings suggest that emotional stimuli elicit larger P2 and LPP amplitudes than neutral stimuli. Recognition of taillight expressions is reflected in significantly larger P2 and LPP amplitudes compared to neutral expressions. The ERP results indicated that, compared to neutral conditions, negative expression taillights engaged more attentional resources during perception and elicited stronger emotional responses during analysis. Taken together, these ERP effects indicate that, in our task, negative taillight expressions were perceived and evaluated more strongly than neutral expressions, consistent with successful decoding of negative messages.

Chen and Park (2021) noted that anthropomorphic products can communicate emotions through facial expressions. Facial expressions, as nonverbal communication, can convey negative messages without words (Giri, 2009). For example, anger can transmit negative messages that affect recipients' emotions and influence subsequent actions (Reed et al., 2014; Pichon et al., 2009). Therefore, when drivers decode negative messages from taillight expressions, they adjust their driving behavior accordingly. Behavioral and ERP results showed that participants perceived and analyzed negative messages from leading vehicles during processing and made keystroke choices accordingly. These results suggest that drivers are able to decode the negative messages conveyed by taillight expressions in a rapid and intuitive manner, without relying on language or symbolic conventions. Thus, in line with Hypothesis 1, taillights with negative expressions can effectively convey negative messages.

Taillights with negative expressions were processed more quickly. In this study, participants' response times were measured using keystroke analysis. The findings showed that negative expression taillights significantly reduced participants' response times. This may be explained by cognitive processing: individuals prioritize survival-related stimuli, activating the avoidance system (Rozin et al., 2009). People respond more rapidly to negative or potentially hazardous events (Wentura et al., 2000). Consequently, negative taillights conveying negative messages were detected more quickly. These results align with Tobitani et al. (2020) and support Hypothesis 3.

5.2. Taillights could convey positive messages effectively during the perception stage of information processing

Response times and keystroke ratios were calculated for participants in this study. Behavioral analysis showed no significant response time differences for positive expression taillights compared to other conditions. However, the keystroke ratio was significantly higher for the neutral condition. The ratio of "no hazard" button presses was computed, revealing a significantly higher rate for positive expression taillights compared to neutral ones. This suggests that more participants perceived positive taillights as less hazardous than neutral ones.

P2 findings indicated that participants perceived positive messages conveyed by the taillights. Results showed that positive expression taillights elicited larger P2 amplitudes than neutral ones. The P2 component reflects attentional resource allocation, and prior studies show emotional stimuli enhance P2 responses (Carretié et al., 2013; Conty et al., 2012). This study aimed to test whether taillights could effectively convey positive messages through expressions. P2 results suggested that during early bottom-up processing, participants perceived positive taillight messages and allocated more attentional resources to them. This finding partially supports Hypothesis 2, showing that positive taillights can capture early perceptual attention.

LPP results differed from P2. Specifically, LPP results showed no significant amplitude differences between positive and neutral taillights. The LPP reflects later, more refined neural processes in information processing (Schindler and Bublatzky, 2020; Hajcak et al., 2010). Previous studies consistently show that emotional stimuli evoke larger LPP amplitudes than neutral ones (Foti and Hajcak, 2008; MacNamara et al., 2009; Bublatzky and Schupp, 2012). Based on the LPP results, participants seemed unable to distinguish between messages from neutral and positive taillights during later analytic processing. This suggests no significant difference in messages conveyed by positive and neutral taillights during the later stage. This suggests that, while positive expressions can be perceived initially, they may lack the strength to sustain deeper evaluative processing compared to negative expressions.

Specific facial regions influence how individuals recognize emotions. Eye-tracking studies show that when viewing a fearful face, people focus more on the eyes. Conversely, when viewing a happy face, attention shifts toward the mouth region (Scheller et al., 2012). Studies also show that people fixate longer on the mouth in happy expressions. In contrast, for sad and angry expressions, people attend more to the eyes than the mouth (Kestenbaum, 1992). Thus, negative expressions are mainly recognized through the eyes, while positive expressions are primarily recognized through the mouth. As noted above, the rear of a vehicle lacks a "mouth" but conveys expressions through the "eyes." Therefore, the rear of a vehicle may convey negative messages more effectively and positive messages less effectively. This structural limitation helps explain why positive taillights did not yield significant LPP differences. It may also pose a design challenge for the communication of positive intent. Thus, positive taillights failed to convey positive messages during the later stage of processing, partially supporting Hypothesis 2. Positive taillights drew more attention during early processing but failed to deliver valid positive messages during later analysis. From a nonverbal communication perspective, positive taillight messages were not successfully decoded, suggesting that future designs may need to incorporate additional expressive elements to strengthen the communication of cooperative or gratitude signals in driving contexts.

5.3. Linear taillights with negative expression conveyed stronger negative messages

Negative linear taillights conveyed the strongest negative messages. P2 results showed that negative linear taillights did not elicit significantly larger amplitudes than other conditions. This suggests that negative linear taillights offered no advantage over other taillights during the bottom-up perception stage. However, LPP and keystroke ratio analyses indicated that negative linear taillights elicited the largest LPP amplitudes. This indicates that their impact was strongest in the later top-down analytic processing stage, when participants engaged in deeper evaluation of the conveyed messages.

The heightened negativity of negative linear taillights may be explained by their resemblance to facial structure. Facial expressions largely result from stereotyped facial muscle movements that alter the eyes' visual appearance (Rinn, 1984). For example, surprise and fear widen the eyes, while anger narrows them. Thus, wide-open eyes effectively convey fear, whereas narrowed eyes are associated with anger (Sacco and Hugenberg, 2009). In the context of taillights, linear designs that are slimmer and more elongated than square ones produce a narrowed "eye-like" appearance that enhances their capacity to convey anger and intensify negative expressions. Therefore, when conveying anger, the elongated appearance of linear taillights communicates negative messages more effectively than square taillights. Behavioral data showed that negative linear taillights received the most "1" keypresses. In summary, the slim, elongated shape of linear taillights amplifies angry expressions and conveys strong negative messages more effectively than other designs.

5.4. Design implications

The findings of this study indicate that taillights with negative expressions can effectively convey negative messages. In contrast, taillights with positive expressions were only effective during the early perception stage and did not sustain deeper evaluative processing.

For future in-vehicle interaction designs, it may be valuable to consider mechanisms that allow vehicles to actively display negative expressions in safety-critical situations. For instance, drivers could intentionally trigger taillight expressions to signal hazards to following vehicles, which provides a clearer and less ambiguous warning than conventional brake lights. Specifically, this study found that thin and narrow taillights (such as linear taillights) are particularly effective in conveying negative information, due to their resemblance to narrowed “eyes” associated with anger-like expressions. However, the potential side effects of negative signaling should be considered. Overly strong negative cues might irritate following drivers and lead to unintended consequences (Bjureberg and Gross, 2021).

For positive information, this study suggests that taillights alone cannot effectively convey positive messages because the vehicle’s rear lacks a "mouth," a key feature for recognizing human facial expressions. Designers may therefore consider adding expressive elements, such as shapes or dynamic light patterns resembling a “mouth,” to enhance the communication of positive intent.

In practice, affective signaling depends on the lead driver actively sending positive or negative messages. Requiring drivers to select or trigger specific expressions adds interaction steps and increases cognitive load, especially during time-critical situations. Interaction with in-vehicle information systems may cause distraction (Ma et al., 2022), and such messages do not always give clear guidance on how the following driver should respond. There is also a risk that unfamiliar expressive patterns could be misinterpreted by other road users, or that inappropriate activation (e.g., due to system malfunction or driver error) could undermine trust in the signals. Therefore, designers and manufacturers could explore integrated taillight systems that allow drivers to deliver messages more safely, efficiently, and with clearer meaning, for example by minimizing manual input and supporting context-aware or semi-automated activation.

Nevertheless, taillight design must balance communicative effectiveness with practical factors such as aesthetics, cost, regulatory constraints, and manufacturing feasibility. Achieving this balance remains challenging for designers and manufacturers, but the current findings highlight directions for advancing nonverbal vehicle-to-vehicle communication. Overall, expressive taillights should be seen as a complementary communication layer that enriches vehicle-to-vehicle information exchange and ultimately enhances driving safety.

6. Limitations and future works

This research examined how taillight expressions affect message delivery, aiming to explore new approaches for inter-vehicle interaction. The findings indicate that taillights can effectively convey negative messages, with linear taillights showing a clear advantage. However, this study has several limitations. First, participants were primarily undergraduate and graduate students, who represent the largest group of potential car buyers in China, where many purchase their first car after graduation. However, many participants were novice drivers. Driving experience strongly influences driving-related decision-making (Crundall et al., 2021; Horswill et al., 2020; Feng et al., 2023). Future studies should include a broader age range to account for differences in driving experience. Second, this study used repeated static images to satisfy the ERP paradigm and obtain overlayable ERP data. However, real driving scenarios are dynamic, and participants engage in more complex behaviors than simply pressing keys. Future research could use driving simulators to enhance the ecological validity of findings. Third, participants performed hazard judgments rather than direct emotion labeling. This improved ecological validity by reflecting real driving evaluations, but hazard judgment is not a pure measure of emotional perception and may be shaped by other factors (Cao et al., 2022). Future studies could combine it with complementary tasks to strengthen the interpretation of emotional message transmissions. Fourth, although the expressions used in this study (e.g., anger, happiness) are widely regarded as universal across cultures, their interpretation may still vary in specific cultural or situational contexts (Dailey et al., 2010). Fifth, although this study calculated N1 to help ensure that the ERP components were driven by emotional processing rather than low-level visual features (e.g., shape), we cannot fully exclude the possibility of residual confounding effects. Sixth, this study examined only three expressions. However, human facial expressions are diverse and convey rich information. Future studies should explore whether taillights can communicate other expressions effectively through nonverbal means. Seventh, the proposed affective taillight concept presents feasibility and safety concerns that this study did not directly assess. Although we note possible increases in driver workload, distraction, and misinterpretation in the design implications, we did not empirically test these risks. We also did not examine how system malfunctions, inappropriate activations, or regulatory rules may affect automotive lighting. Future studies should evaluate these issues carefully before expressive taillights are introduced in production vehicles.

7. Conclusion

This study examined the potential for inter-vehicle interaction through taillight expressions as a form of nonverbal communication. It investigated how different taillight expressions affected message delivery by analyzing participants’ ERP data and behavioral responses. Findings showed that participants perceived and analyzed negative taillight messages and processed them more quickly. During information processing, drivers also perceived positive messages from taillights. However, positive messages did not differ significantly from neutral ones during later stages of processing. The study also found that negative linear taillights conveyed the strongest negative messages. These findings highlight the potential of anthropomorphic car faces for nonverbal communication, broadening understanding of inter-vehicle interaction. The results offer valuable insights for manufacturers and designers aiming to improve the scope and effectiveness of inter-vehicle communication.

CRediT authorship contribution statement

Guanhua Hou: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Zixian Lei:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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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