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RESEARCH ARTICLE

User Responses to Dynamic Light in Automobiles With EEG and Self-Assessments

TAESU KIM [1], GYUNPYO LEE [1], MINJUNG PARK [1], HONG MIN LEE [2], JI-WOO PARK [3], AND HYEON-JEONG SUK [1], (Member, IEEE)

[1]Department of Industrial Design, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea
[2]Automotive Research and Development Division, Hyundai Motor Group, Hwaseong-si, Gyeonggi-do 18280, Republic of Korea
[3]HMI Advanced Development Team, LS Automotive, Anyang-si, Gyeonggi-do 14067, Republic of Korea

Corresponding author: Hyeon-Jeong Suk (color@kaist.ac.kr)

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ABSTRACT This study investigates the emotional responses to vehicle interior lighting by measuring physiological reactions and psychological judgments. Individually controllable LEDs are installed in the front area of the passenger car (Sonata DN8, Hyundai Motor Company) and generate light stimuli by varying the attributes of the LEDs for the user experiment. Forty participants volunteered in the experiment and opted to evaluate either blue (468 nm) and orange (589 nm) light prior to the main session. Each participant was presented with twelve lighting signatures made with six lighting behaviors applied to two types of placements. During the experiment, we collected the alpha and beta waves using an electroencephalography (EEG) and subjective assessments of the lighting with seven questions. The ratio of the beta waves was the highest in the Blink mode, followed by the Fade and Collide modes. We combined the EEG responses with subjective assessments of seven adjective pairs toward evidence-based guidance for designing user-centered light in automobiles.

INDEX TERMS Ambient light, dynamic light, electroencephalography, emotion, self-assessment.

I. INTRODUCTION

The automotive industry is pushing state-of-art driving technology, and autonomous driving is one technological innovation. An essential concern of advancements in driving technology is how to enhance the emotional experience in a vehicle [40], [47]. The automobile industry has paid attention to in-car affective computing solutions to identify and satisfy users' emotions and style tastes [53]. As light can deliver information and emotional values intuitively and unobtrusively [21], car manufacturers have recently focused on ambient lighting in vehicles [3], [10], [20], [38]. Additionally, the diverse range of light concepts is more easily implementable with the advancement of LEDs and automotive technologies [9]. Light plays a prominent role in taking active care of users' physiological desires and emotional anticipation in the vehicle space with few restrictions. Hence, ambient lighting functions as a mood modulator in vehicles, and global car manufacturers demonstrate their light solutions, as shown in Figure 1.

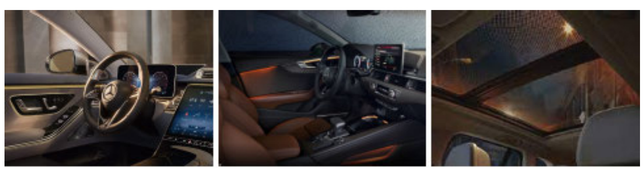
(a) Benz S 2021 (b) AUDI A5 2020 (c) BMW 7 2022

FIGURE 1. Examples of vehicular ambient light: A) Ambient lighting in Mercedes Benz S class 2021 [8]; B) Ambient light in Audi A5 Sportback 2021 [3]; C) Sky lounge in BMW 7 Series 2022 [10].

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Previous studies have explored the effect of diverse light contexts on cognitive behavior [34], [46], [52], the human body [14], [43], [49], or emotional state [13], [22], [48]. Studies have manipulated matches between user activity types and ambient light [31], [45], [47], namely, the user scenarios. For example, Locken et al. proposed 23 different lighting behavior signatures with bulb-shaped lights to connect user scenarios within the automobile [32]. Similarly, Meschtscherjakov et al. positioned a light strip on the windshield to explore light behaviors and user interaction. They proposed nine light behaviors with five matching information types [37]. Mercedes Benz recently introduced a dynamic light behavior system in the S class to visualize the voice assistant, speeding alarm, or lane departure warning. Such a lighting application confirms that light functions as a visual feedback solution for its users [8].

Empirical evidence has validated the affective effect, thereby expanding the human-centered light to spaces to accommodate users' physical and mental states. Kim et al. suggested a guideline about emotional modulation through the speed and characteristics of lighting behaviors [48]. Thus, a more holistic approach to evaluating lighting and its significance is required that utilizes aspects such as bio-feedback, cognitive performance, and self-reports. However, there are limited attempts to observe within the context of vehicle interior lighting. For example, precedent studies have varied the color hue of the ambient light and followed passengers' responses by comparing electroencephalogram (EEG) and self-assessment results [22], [41]. Studies have also examined bright blue light's therapeutic effect and collected EEG with subjective responses [14], [43]. The effect of light influences industrial applications, including car interior light, when integrating the physiological and psychological responses. However, there is limited evidence for lighting behavior and its effect on participants' subjective judgments. This study focuses on passengers' brain activities and subjective assessments while the color hue, placement, and behavior of the vehicle's interior light are varied. This study expected to find evidence to enhance automobiles' affective experience through the optimal ambient lighting design based on empirical data.

II. RELATED WORK

A. THE POTENTIAL OF LIGHTING BEHAVIORS IN VEHICLE DESIGN

The emotional effect of the illuminant introduces new value to its role in a space when it is in harmony with the user scenarios [2], [31]. For example, previous studies have incorporated light to manipulate user emotions such as anxiety [17], [19] or stress [6], [51] by changing lighting attributes by controlling its brightness [4], [5], colors [15], placements [26], and behaviors [16]. Sensations generated from the living space are similarly applicable in the vehicle context. Researchers have explicitly explored controlling attributes of in-vehicle ambient light such as animations [36], brightness [14], color [12], and distribution [13]. orange-enriched white lighting, often labeled as warm white light, created a luxurious atmosphere in the vehicle regarding the influence of color and brightness of the illuminants within the vehicle environment [13]. In contrast, blue-enriched white lighting, frequently labeled as cool white light, more effectively influences drivers' awakening state [12]. Another study indicated that variation of brightness of blue-enriched white light controlled humans' physiological status, including alertness [14].

Frequently, ambient light's dynamic behaviors are designed to warn or alert the driver by presenting immediate responses and preventing fatigue. Technologies that allow individual lighting control within the vehicle have evolved and are offered in the recent vehicles on the market. Such improvement sets the current system apart from the past, when controlling the light modules was limited to control LEDs at once [24], [47]. Hence, the user experience of the ambient lighting control also improved by presenting individual control of light colors and brightness. Furthermore, the time-sequence-based dynamics of light behaviors result in dramatic variations in light design [9].

Recent studies on dynamic light behaviors distinguished the lighting signatures by varying their speed [36], [37], [48] and characteristics [11], [33], [50]. In addition, studies focused on visual feedback when light is provided and the transferred effects of the lighting. For example, one study examined whether varying the lighting speed of the light installed across the A-pillar and B-pillar areas affects users' perception of the car's speed [36]. Alternatively, Troster et al. examined seven characteristics of LEDs by installing LEDs on the windshield. The study collected data with a user experience questionnaire that asked about usability of installed LED characteristics [50]. Kim et al. observed how drivers' emotions change with light behaviors from the front panel and cluster. The responses were then assessed for pleasure, arousal, and uniqueness [48].

Both car manufacturers and users have increased interest in new and novel light signatures and light behaviors. However, the current research on vehicle ambient light focuses on evaluating visual feedback when light is presented. Evaluating emotional feedback to vehicle ambient light is also required when an emotional lighting solution is presented within vehicles. Furthermore, unique ambient light features are critical in offering optimal solutions to strengthen the influence of the ambient light in the vehicle.

B. MEASURING HUMAN RESPONSES TO VEHICULAR AMBIENT LIGHT

Previous studies discovered how the light properties trigger a psycho-physical influence on humans. Studies have also utilized diverse apparatus and metrics to investigate human responses by measuring those responses within a space lit by various illuminants. The variables assessed by physiological measures are usually not under participants' voluntary control and cannot be easily edited, as can self-reports

FIGURE 2. **Manipulating LED stripes mounted in a passenger car (Sonata DN8, Hyundai Motor Company) using light control software. (left) A control panel contained 15 buttons to switch the light components on or off in 15 regions. (mid) Press button number 3 and turn on the right side of cluster part lighting. (right) Press buttons number 3, 9, 10, 12, and 14 and turn on the lighting of cluster right, bent, mood, and pocket.**

and behaviors. Previous studies facilitated physiological measurements to measure users' alertness and relaxation under ambient lighting. The physiological measurements involve the following: the electroencephalogram [14], [23], electrocardiogram (ECG) [16], galvanic skin response (GSR) [7], or melatonin secretion [17]. A measurement type selection is made regarding the research objectives as each method has particular constraints or tolerances [18], [27]. Additionally, participants' comprehensive perspectives are collected through self-reports to identify any violating results by comparing responses obtained from the body with survey responses. Comparing the responses provides a more profound understanding of the empirical results.

Previous studies have adopted the EEG to record the users' physiological responses to a vehicle's ambient light. For example, Kerstedt et al. engaged self-report and ratio of alpha wavelengths from EEG to measure the subjects' alertness to a light installation in a simulated car in a laboratory setting [1]. Canazei et al. conducted an experiment in an actual driving situation and revealed the effect of the bright light in the vehicle helped subjects more awake while driving [14]. The study utilized the alpha spindle of an EEG to detect alertness under the target ambient light condition.

This study exposed participants to a series of ambient light variations for no longer than an hour. The participants' immediately evoked response to the lighting scenario should evaluate. For this reason, the EEG was suitable for observing participants' bio-feedback on their attention. Self-reports were employed to coordinate bodily responses from the EEG and subjective judgments.

III. STUDY OBJECTIVES

This study aims to identify the human responses to the ambient light in automobiles while changing behaviors, placements, and the color hue of the ambient light. The study pursues a comprehensive understanding of the light condition's impact on participants by examining the EEG responses and self-assessments. Therefore, the study investigates the following hypothesis:

- Which lighting induces users to be alert or relaxed?
- What sensitivity can be provided to users by the attributes of the lighting?

The study setup is expected to provide further ambient lighting design guidelines for designing user-centered light for the car interior based on empirical evidence.

IV. PLAN FOR THE EXPERIMENT

Lighting components were installed in a passenger car (Sonata DN8, Hyundai Motor Company) to imitate an actual driving condition. The experimental setup was designed to provide the same lighting impact as the actual vehicle. Optical fiber was installed to diffuse the LED light uniformly. The vehicle idled throughout the experiment to resemble the actual lighting scenario of the driving context. The following sections cover lighting design, EEG setup, and survey construction.

A. LIGHTING DESIGN: PLACEMENT, BEHAVIOR AND COLOR HUE

The SK6811 RGB-White LEDs (Neopixel, Adafruit) were used as the light source. The study utilized the LED units mounted on flexible printed circuit boards (PCBs) to easily install them on the curved surface of the vehicle's interior.

The single LED unit contains the four light sources: R (red), G (green), B (blue), and W (white). It supports unit-wise control and source-wise configurations within 0 and 255. The optic fiber (5 mm in diameter) was installed on top of the LED units' array to diffuse the light uniformly. A total of 554 LED units were used. This study incorporates an achromatic exterior and interior color and trim to minimize the external chromatic effect from observed objects and surroundings. The representative color on the exterior was yellowish-white. The interior was grayish beige, and their colorimetry values measured with a spectrophotometer (CM2600d, Konica Minolta) were L: 91.48, a: −0.98, b: 0.51 and L: 24.5, a: −0.69, b: −0.13, respectively. The attributes of lighting placements, lighting behaviors, and color hue were varied, resulting in different light signatures.

1) LIGHTING PLACEMENTS

The front instrument panel, in the lower part of the driver's field of view while driving, was the primary focus area of the experiment. First, 15 regions within the cluster area were defined as presented in Figure 2. Next, light modules were installed in these areas. Then, a web-based serial control program was developed and used to manipulate each region independently.

The control software was built with P5.js and Node.js and could control the light attributes instantaneously. Finally, each light module region was numbered and associated with the graphical interfaces in the software's control panel to manipulate the lighting module by clicking the numbered buttons.

The total number of lighting scenarios was 32,768 variations, resulting from 2 (on or off) to the fifteenth power (15 regions). The light placements were assessed by three professional industrial and transportation designers who have at least three years of design experience to confirm their placements. Using the control panel, designers manipulated various light distributions and proposed two types: "Direct light placement" and "Indirect light placement." The suggested direct light placement exposes the LED stripes directly to the eye, while light from the indirect placement is observed when reflected on the surface. The two best light placements were selected based on the scope of the experiment. The first consideration was whether each region fits with direct or indirect light viewing. Then, the final design of ambient light looks aesthetic appealing to the participants.

Both placements commonly included two regions, 11 (Mood left) and 12 (Mood right), to reserve the minimum illuminance level for both directional placements following the suggested region selection. The direct placement consisted of 2 (Cluster left), 3 (Cluster right), 11, and 12. The indirect placement was made up of 1 (A-pillar), 5 (Handle), 6 (Pocket), 11, 12, and 15 (Chair Mood).

2) LIGHT BEHAVIORS

Lighting behaviors have been increasingly investigated, and studies have demonstrated the different effects on visual styles [50] and users' effective judgments [36], [48]. Six distinctive types were organized for the experiment, including a constant mode (On). They were labeled as Blink, Fade, Collide, Spread, Move, and On. We configured the looping sequences using a microprocessor (Mega 2560, Arduino). Figure 3 illustrates the behavioral patterns every 500 milliseconds.

3) LIGHT HUE: BLUE (468nm) OR ORANGE (589nm)

Previous lighting studies mainly compared the emotional effects of blue-enriched white and orange-enriched white light. Thus, the main lighting in the current vehicle interior

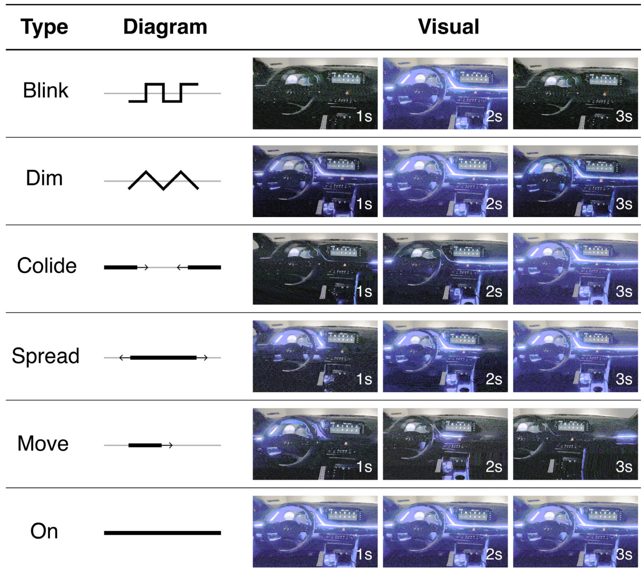

FIGURE 3. Six types of lighting behaviors during 3,000 milliseconds.

TABLE 1. The colorimetric value measured with a light meter (IM-1000, Topcon).

Light	x	y	Y
Direct blue	0.223	0.200	7.39 lx
Indirect blue	0.264	0.262	5.97 lx
Direct orange	0.423	0.390	8.65 lx
Indirect orange	0.385	0.383	6.50 lx
Off	0.337	0.379	4.88 lx

utilizes high chromaticity color with low illumination to enhance styling aspects, as shown in Figure 1. Caberletti et al. suggested lighting guidelines that manipulated drivers' emotions with blue and orange used as contrasting light colors [13]. The current study incorporated blue and orange light as the representative lighting color for the experiment. The chromatic characteristics of this light are profiled within the CIE xyY 1931 color space [blue = (x: 0.1902, y: 0.1342, Y: 1017.25, peak wavelength = 468nm); orange = (x: 0.5872, y: 0.3766, Y: 931.64, peak wavelength = 589nm)]. The relative spectral power placement of both light sources between 400 nm and 700 nm was measured with a spectroradiometer (CS-2000, Konica Minolta). Figure 4 shows the lighting conditions altered with placement with spectral power distributions, and Table 1 shows the colors after the lighting installation.

B. EEG SETUP

The prefrontal cortex was targeted with the EEG used in this light study. The prefrontal lobe controls emotion and attention and provides an immediate response to emotion and attention when exposed to lighting stimuli [16], [39]. We used two channels of EEG units (QEEG-32FX, LAXTHA). The two

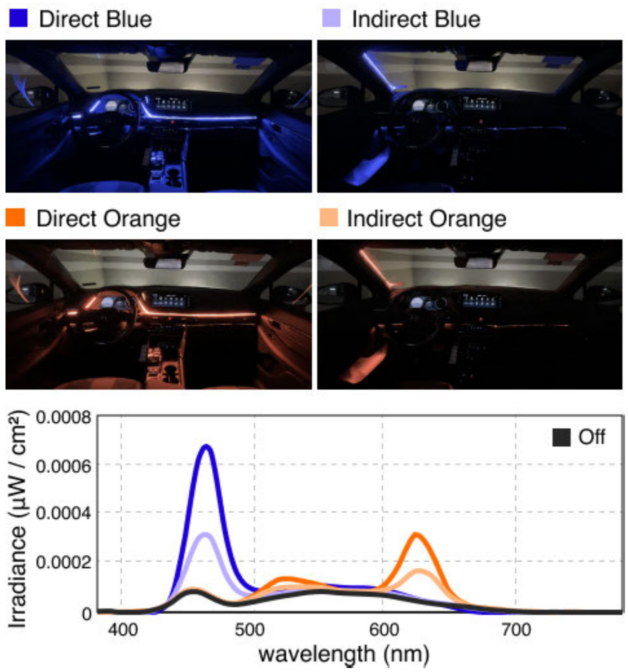

FIGURE 4. (Top) The four light conditions altered with placement and color. (Bottom) The spectral power distributions were measured with a light meter (IM-1000, Topcon).

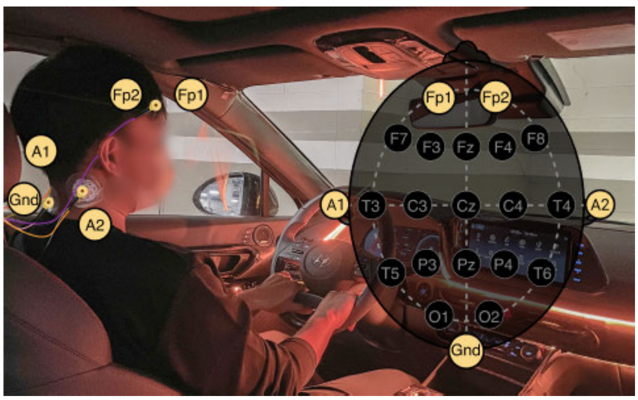

FIGURE 5. Two channels of EEG responses were collected from five electrodes attatched on participants' foreheads, Channel1 = Fp1-A1 and Channel2 = Fp2-A2 while participants were exposed to light stimuli. A1 and A2 were used as reference electrode, and Gnd was used as ground electrode. Participants were seated in the driver's seat.

channels covered: Channel1 = Fp1-A1 resect to ground and Channel2 = Fp2-A2. As shown in Figure 5, the EEG signals were collected at 256 Hz from the two forehead positions corresponding to Fp1 and Fp2 following the 10–20 standard. Supported by LAXTHA's TeleScan software, the raw EEG data were processed through the electrooculography (EOG) filter. The software adopts the method presented by Jung et al. in 1998. First, the method performs principal component analysis on neural signals to remove components of eye movements [25]. Then, the reformation of remaining neural signals is used in EOG artifact filtering. Filtered signals are further implemented in the fast Fourier transform (FFT) analysis. The ratio of alpha and beta bands was analyzed, and their frequency ranges were 8–13 Hz and 13–30 Hz, respectively [42]. The participants were asked to remain calm during the EEG measurement to eliminate signal noise.

C. SURVEY

Previous studies have made an effort to develop proper metrics for assessing the quality of ambient lighting. For example, Caberletti suggested 21 pairs of survey questions to describe ambient lighting effects on vehicle interior perceptions, including usability and affections. Schrepp et al. introduced seven modified user experience questionnaires [44] for measuring user experiences of the lighting visualizations [50]. Another study proposed emotional scales that differentiate the measurements of the uniqueness of the ambient lighting [48]. We aggregated a pool of adjective pairs from the initial review, grouped synonyms, and reduced the set to 17 pairs of words. Some inadequate adjectives were excluded as they were deemed inappropriate for describing the visual characteristics of a vehicle's ambient light.

A survey was finalized with seven questions using 7-point Likert scales. The ranges were labeled as Unobtrusive–Obtrusive, Simple–Complicated, Unhelpful–Assistive, Boring–Interesting, Old-fashioned–Cutting-edge, Relaxing–Energizing, Inappropriate–Satisfactory. Participants were asked to make subjective judgments after each lighting stimulus, and their EEG responses were not recorded while they responded to the survey.

V. EXPERIMENT

A. METHODS

1) SUBJECTS

Forty participants (20 men and 20 women) volunteered for the experiment. All participants were university students majoring in diverse subjects. Interestingly, ten men and ten women chose blue (468nm) light, and the rest chose orange light (589nm) as the color hue of choice for the light experiment. Their average age was 22.90 years, with a standard deviation of 3.22 years. Participants were instructed to avoid extreme physical activities, caffeine intake, and smoking at least 24 hours before joining the experiment. All experiment protocols were approved by the institutional review board (KH2021-230, KAIST).

2) PROCEDURE

Participants sat on the driver's side for the experiment and watched the twelve stimuli in random order: six lighting behaviors in two kinds of placements. Individually, each participant was exposed to every light stimulus for 1 minute, while their EEG was recorded. Then, a survey was offered immediately after each light stimulus. The survey required 1 minute to complete, and the EEG recording was stopped during the survey. The entire session was repeated again in another random order of stimuli exposure to prevent the interference of stimuli exposure orders. Additionally,

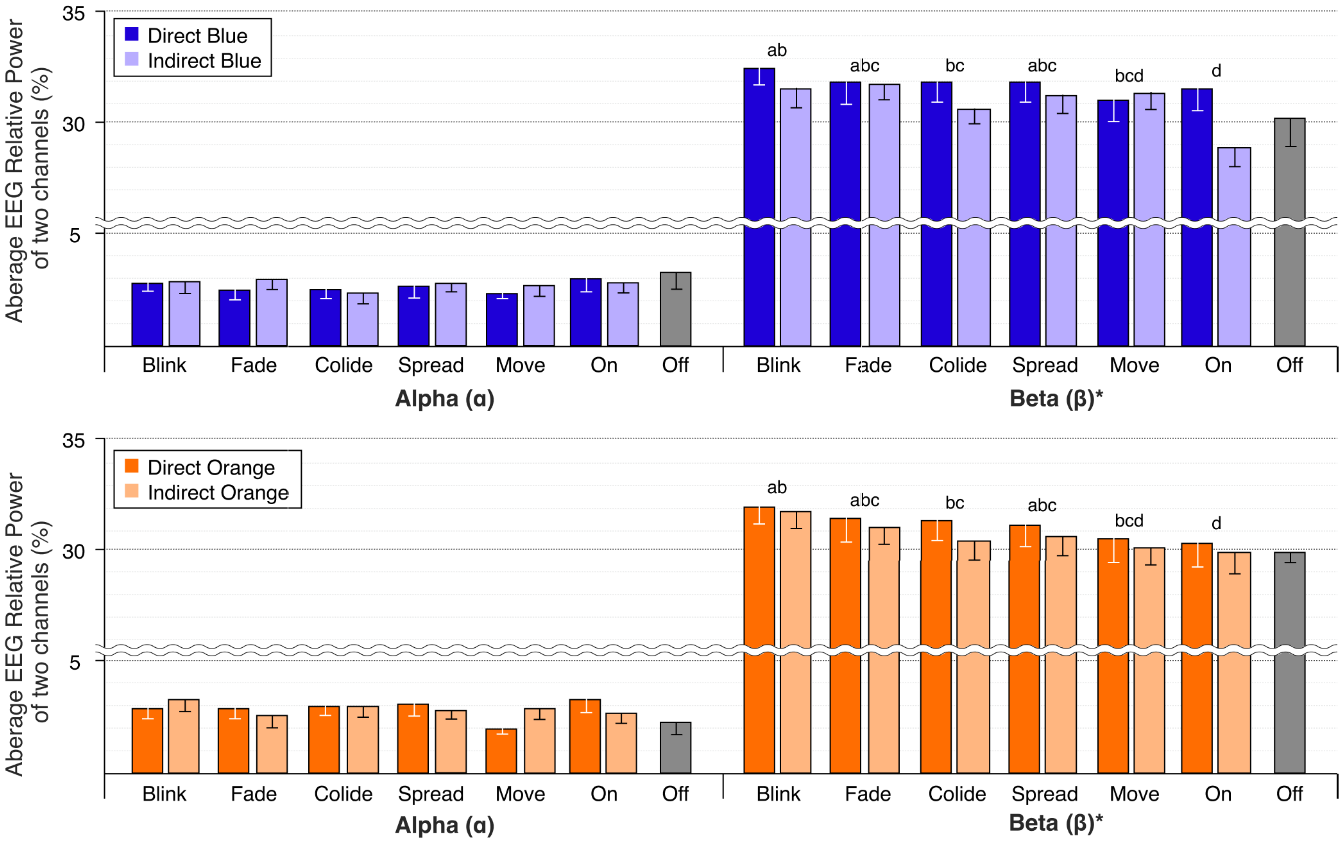

FIGURE 6. Ratios of alpha-wave (8–13 Hz) and beta-wave (13–30 Hz) to entire EEG signals (0.5–40 Hz) on averaging two channels (Channel1 = Fp1-A1, Channel2 = Fp2-A2) along the six lighting behaviors. Bars in deep and pale tones are the responses to the direct and indirect light placements, respectively. Subset groups with post hoc tests on behavior patterns show in the alphabet above the bar graph. The gray bars on the right indicate the averaged alpha and beta ratios in a dark condition. * p <.05.

the ground state, open participant's eye without closed was measured before and after the experiment to prevent the incompetent to reflect the real effects on EEG. The experiment lasted approximately 50 minutes on average.

VI. RESULTS

The analysis of the EEG responses and survey answers was intended to comprehend how lighting behaviors influenced subjects' stress levels and emotional perceptions of the lighting.

A. EEG RESPONSES

The ratios of alpha (8—13 Hz) and beta (13—30 Hz) waves were estimated from the whole range of brain waves between 0.5 and 40 Hz. Alpha waves should be noticeable when the subject is relaxed. Beta waves should be found when the subject is focused, alert, or concentrating, like solving a problem [42]. This study examined the average alpha and beta waves observed in response to the six types of light behaviors in two light placements. Figure 6 illustrates the average of EEG collected from two channels for alpha and beta wave ratios. Each gray bar in the figure (Off) indicates the average ratios of alpha or beta waves in a dark condition for 1 minute.

TABLE 2. Results of three-Way mixed ANOVA with repeated measures of EEG data from variations of light behavior and placement. Values of the degrees of freedom are included in parenthesis. * *p* <.05.

Independent Variables (df1, df2)	**Alpha** (α)	**Beta** (β)
behavior (5,190)	F = 2.18 p = .06, η_p^2 = .05	**F = 4.91*** p <.05, η_p^2 = .11
placement (1,38)	F = .00 p = .58, η_p^2 = .02	**F = 5.65*** p <.05, η_p^2 = .13
color (1,38)	F = .04 p = .85, η_p^2 = .00	F = .29 p = .59, η_p^2 = .01
behavior × **placement** (5, 190)	F = 1.72 p = .13, η_p^2 = .04	F = .85 p = .52, η_p^2 = .02
behavior × **color** (5, 190)	F = .94 p = .46, η_p^2 = .02	F = .32 p = .90, η_p^2 = .01
placement × **color** (1, 38)	F = .00 p = .61, η_p^2 = .01	F = .00 p = .42, η_p^2 = .02
behavior × **placement** × **color** (5, 190)	F = 1.02 p = .41, η_p^2 = .03	F = .74 p = .60, η_p^2 = .02

A dependent sample t-test was conducted to compare brainwaves and brainwaves of lighting scenarios to determine

TABLE 3. Results of three-way mixed ANOVA with repeated measures on the survey results. Values of the degrees of freedom are included in parentheses * p <.05.

Independent Variables (df1, df2)	Unobtrusive - Obtrusive	Simple - Complicated	Unhelpful - Assistive	Boring - Interesting	Old-fashioned - Cutting-edge	Relaxing - Energizing	Inappropriate - Satisfactory
behavior (5, 190)	**F = 13.37*** p <.05, η_p^2 = .26	**F = 22.22*** p <.05, η_p^2 = .37	**F = 19.13*** p <.05, η_p^2 = .34	**F = 15.37*** p <.05, η_p^2 = .29	**F = 12.30*** p <.05, η_p^2 = .26	**F = 27.96*** p <.05, η_p^2 = .42	**F = 6.00*** p <.05, η_p^2 = .14
placement (1, 38)	F = 2.73 p = .11, η_p^2 = .07	**F = 11.76*** p <.05, η_p^2 = .24	**F = 5.85*** p <.05, η_p^2 = .13	F = .45 p = .51, η_p^2 = .01	F = .90 p = .35, η_p^2 = .02	**F = 13.42*** p <.05, η_p^2 = .26	F = .98 p = .33, η_p^2 = .03
color (1, 38)	F = .01 p = .92, η_p^2 = .00	F = .00 p = .99, η_p^2 = .00	F = .32 p = .57, η_p^2 = .01	F = 1.31 p = .26, η_p^2 = .03	**F = 4.88*** p <.05, η_p^2 = .11	F = .18 p = .67, η_p^2 = .01	F = 1.15 p = .29, η_p^2 = .03
behavior × **placement** (5, 190)	F = .74 p = .59, η_p^2 = .02	F = .94 p = .46, η_p^2 = .02	F = 1.33 p = .26, η_p^2 = .03	F = .81 p = .54, η_p^2 = .02	F = .90 p = .49, η_p^2 = .02	F = .14 p = .98, η_p^2 = .00	F = .47 p = .80, η_p^2 = .01
behavior × **color** (5, 190)	F = 1.16 p = .33, η_p^2 = .03	F = .67 p = .65, η_p^2 = .02	F = .26 p = .93, η_p^2 = .01	F = .36 p = .88, η_p^2 = .01	F = .69 p = .63, η_p^2 = .02	F = 1.21 p = .31, η_p^2 = .03	F = .60 p = .70, η_p^2 = .02
placement × **color** (1, 38)	F = 1.15 p = .29, η_p^2 = .03	F = .32 p = .57, η_p^2 = .01	F = .07 p = .80, η_p^2 = .00	F = .18 p = .67, η_p^2 = .01	F = .16 p = .69, η_p^2 = .00	F = .32 p = .57, η_p^2 = .01	F = .02 p = .90, η_p^2 = .00
behavior × **placement** × **color** (5, 190)	F = 2.06 p = .07, η_p^2 = .05	F = 2.05 p = .07, η_p^2 = .05	F = 1.83 p = .11, η_p^2 = .05	F = 0.94 p = .46, η_p^2 = .02	F = 2.21 p = .06, η_p^2 = .06	F = 0.88 p = .50, η_p^2 = .02	F = 2.00 p = .08, η_p^2 = .05

whether lighting can increase participants' alertness. The ratios of the beta waves in response to indirect blue light (468nm) were much lower than in the Off mode ($t_{beta}(19) = 2.77$, p <.05). Both ratio of alpha and beta wave were increased for direct lighting in Blink ($t_{alpha}(19) = 2.457$, p <.05, $t_{beta}(19) = 2.49$, p <.05). They were also increased for Collide animation ($t_{alpha}(19) = 2.51$, p <.05, $t_{beta}(19) = 2.16$, p <.05) for the orange lights. Additionally, indirect placement with Blink ($t_{beta}(19) = 2.18$, p <.05) and direct placement with Fade ($t_{beta}(19) = 2.42$, p <.05) increased ration of beta wave compared to the Off condition.

A three-way mixed ANOVA was performed to examine the effect of light behaviors, placements, and color hue. Dependent variables were the brain waves and the subjective assessments. The repeated measures were light behaviors and placements. Table 2 displays the F and significance values of the ANOVA results. In general, the light behaviors and placements significantly influenced the ratios of beta waves (p <.05). The direct blinking light (Blink in a deep tone) resulted in the highest ratio of beta waves, whereas the constant indirect light (On in a pale tone) resulted in the lowest.

B. SELF-ASSESSMENTS

The assessments were collected along with the entire light behaviors and placements across two color hues. Figure 7 presents the averaged assessments, and the style adjectives were rated between −3 (not agree at all) and +3 (absolutely agree).

As found in Table 3, there were differences in all adjectives for all light behaviors. For the arrangement, the direct light was found in light placements: Simple, Assistive, and Energizing. However, the main effect of color hues was not statistically significant, except for both colors' Cutting-edge styles.

However, the subjective assessments showed more drastic changes in the light behaviors than the EEG responses. Regarding the distribution, both direct and indirect lights showed similar trends. However, the results of the assessments on direct light varied more than those on indirect light.

C. AMBIENT LIGHT DESIGN GUIDELINES

Based on the EEG responses and subjective assessments, we determined that Blink, Fade, and On patterns with the entire lighting controlled at the same time showed a higher preference than individually controlled patterns, like Collide, Spread and Move. Therefore, we suggest five guidelines for optimizing the design of ambient lighting:

- Discrete blinking light (Blink behavior) caused the highest levels of "alert" among other behaviors. The ratio of beta waves was the highest in both blue (468 nm) and orange (589 nm) lights in the Blink behavior. The self-assessments correlated with the results of the ratio of beta wave increased in EEG. The participants evaluated this behavior as Assistive and Energizing. The finding supports that the luminous surface or interfaces with the Blink behavior should be used to alert the driver about an urgent notification.
- Even a smoothly blinking light alerted the participants. The Fade behavior was assessed as Unobtrusive and more Cutting-edge than the Blink behavior with the smooth blink. However, it feels less Assistive and Energizing than the Blink behavior, so a smooth blink should be appropriate to express a non-urgent notification.
- On behavior also scores high on Satisfactory. Participants evaluated the On behavior as Unobtrusive and

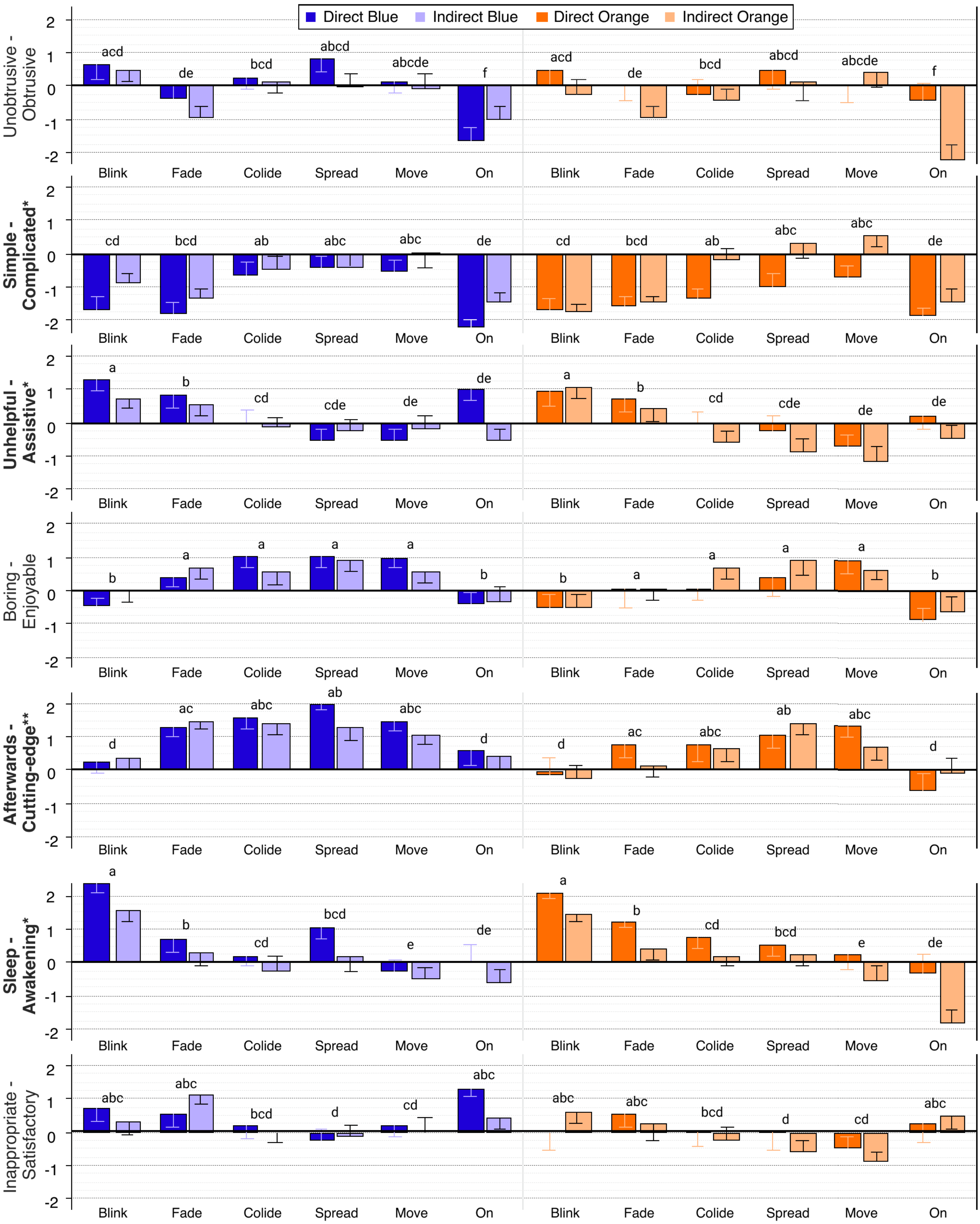

FIGURE 7. Responses to seven questions about the six lighting behaviors (−3: not agree at all, +3: absolutely agree). Bars in deep and pale tones are the responses to the direct and indirect light placements, respectively. Subset groups with post hoc tests on behavior patterns are shown in the alphabet above the bar graph. * p <.05 on placement factor ** p <.05 on color factor.

Simple. However, it was also evaluated as higher on Relaxing than the other behaviors.
- Collide, Spread, and Move behavior show lower Satisfactory scores, and they also show similar results on the self-assessment. Among them, the Spread behavior was seen as more Cutting-edge, Obtrusive, and Interesting and evoked more Energizing than the two other behaviors. Spread can be an option to consider when an alert needs to be cutting-edge.
- Lastly, the color hue did not show a different dominant effect from previous aesthetic approaches. Except for the subjective judgment on Cutting-edge, the responses for blue (468 nm) and orange (589 nm) light were not statistically different. Blue light received higher Cutting-edge scores than orange light. However, because the participants selectively experienced only one of the two color hues, no conclusions can be drawn from this finding.

VII. DISCUSSION

A. GENERAL DISCUSSION

Our study intended to observe the effect of ambient light on drivers within an actual vehicle. The ambient light design influences psychological and physiological effects. Therefore, we collected the participants' responses using the EEG as empirical evidence and survey questionnaires as the participants were exposed to various ambient light. The study intended to describe the user responses to vehicular ambient light comprehensively, physiologically, and psychologically through this setup.

The light conditions were varied in terms of dynamic behaviors and placement type. The participants were divided into two hue groups, blue (468 nm) and orange (589 nm), depending on individual preference. While the earlier studies focused on the effects of light behaviors on self-assessments [11], [33], [36], [37], [48], [50], our experiment demonstrated the drivers' physiological effect alongside self-assessments. The two hue groups showed similar tendencies in the EEG responses and the subjective assessments. Our results showed a similar trend as precedent studies that found the blinking behavior of car interior lighting alerts the driver [48], [50]. The ratios of beta waves have changed significantly depending on the lighting behaviors and placement types. The results from this study showed coherence with previous studies that revealed that indirect lighting is less obtrusive than direct lighting [13], [28].

As a higher ratio of beta waves indicates increased alertness, various target situations were associated with the light characteristics. The ratio of beta waves was the highest with the Blink light behavior, followed by the Fade and Collide behaviors. Alertness was reduced when the light placement was indirect and On behavior was observed to be lower than the dark condition. These observations were compared with the scores of adjectives collected from the self-assessments to describe the target situation in a more detailed manner. The self-assessments served as a tool for a thorough explanation of the EEG observations. Thus, combining these two observations enabled us to collect better insights into providing more user-centered ambient lighting.

The hue difference did not yield responses that were statistically significantly different from the initial anticipation of the study except for the Cutting-edge assessment, with a higher score for blue (468nm) light than orange (589nm). The result showed similarity with the result from Lu and Fu, which configured out blue light (481nm) evaluated for elegant light as vehicle ambient light [35]. Additionally, previous studies have established that the blue color of the car interior conveys a futuristic image to the consumers [29], [30].

The empirical result highlights the relevance of dynamic behaviors. As reviewed, previous studies on emotional responses to ambient light have mainly focused on the color characteristics of light placements. Only a few have demonstrated the impact of dynamic behaviors on human responses. This study tried to provide additional empirical evidence by collecting EEG responses from an actual situation within the vehicle with physical lighting modules. The findings based on the EEG responses and self-assessments can be utilized for evidence-based user scenarios. Thus, as autonomous driving vehicles will acquire more active light, more creative light designs are expected to enrich users' emotional experience in automobiles.

B. LIMITATIONS AND FUTURE WORK

Throughout the study, this study used gel-based disk electrodes to capture and measure minuscule changes in low-light illumination. Then, it was a challenge to recruit sufficient participants for the experiment due to the COVID-19 pandemic for putting gel base disk on their hair. To make it easier for the volunteers, we only set the gel-based disk electrode on the prefrontal lobe reduced hair irritation and inconvenience. However, the captured EEG was limited to the prefrontal lobe, whereas the responses from the frontal lobe for collecting EEG with less noises, occipital lobe should be essential for examining visual stimuli. Also, the records from the prefrontal area were inevitably influenced by eye movements, such as EOG and electromyography (EMG). Additionally if more channels were collected, network analysis could be performed to configure out steps for cognitive process according to light stimuli in the brain.

For stimuli design, the number of experimental stimuli were reduced to minimize participants' attention loss. In addition, prior to the experiment, participants' personal preference for blue (468nm) or orange (589nm) was surveyed, and then the preferred color hue was assigned individually. Beyond blue and orange variation, a wider color diversity is necessary, primarily when the ambient lighting pursues an aesthetic appeal or brand identity.

Moreover, as the study focuses on the effect of the space illuminants, participants were instructed to stay still during the experiment to reduce noise in their EEG data. Such restriction might have provided an unrealistic environment for experiencing vehicle interior and interior lighting conditions. Investigations on behavior measurements of the light scenarios are expected in a future study. Providing a simulation environment with actual road conditions with participants needs to be explored to properly understand the full effect of the lighting scenarios examined in this study.

VIII. CONCLUSION

This study used EEG responses and survey questionnaires to investigate human responses to ambient vehicle lighting. The lighting design of this study contains dynamic behaviors, placement types, and color hues in the experiment setup. Then, 516 RGBW LEDs were applied and installed in a Hyundai Sonata DN8. A customized GUI was developed to operate lighting variations. Based on the ratio of beta waves of the participants, it was found that discrete Blink behaviors elicited the most attentive response, followed by Fade and Collide behaviors. The survey answers elaborated on the participants' emotional experiences. In general, the participants' responses were consistent between two light hues: blue (468 nm) and orange (589 nm). The brain waves and self-assessments were influenced by how dynamic the light behaviors were and how they were installed from the participants' view angle. The empirical evidence of this study should provide fertile ground for further study in search of the optimal ambient lighting design for desired user scenarios in automobiles.

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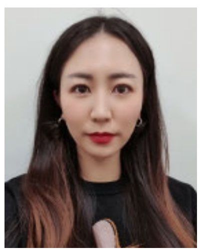
TAESU KIM received the B.S. degree in industrial design from the Korea Advanced Institute of Science and Technology (KAIST), South Korea, in 2018, where he is currently pursuing the Ph.D. degree. His current research interest includes assisting designers design emotional lighting in products, especially in an automobile context.

GYUNPYO LEE received the bachelor's degree in fine arts in transportation design from the College for Creative Studies, in 2015. He is currently pursuing the master's degree with the Color Laboratory, Industrial Design Department, Korea Advanced Institute of Science and Technology (KAIST), South Korea. He has experience as an Automotive Exterior Designer at the Changan European Design Center for about four years. His research interests include visual semantic evaluation of designers and users, aesthetic quality and cognitive evaluation of products, and emotional aspects of how people perceive forms as pleasurable.

MINJUNG PARK is currently pursuing the master's degree with the Color Laboratory, ID KAIST. She majored in industrial design and minored in business management and technology at KAIST. Her research interests include lighting interfaces and emotional conveyance.

HONG MIN LEE received the B.S. degree in mechanical engineering from Sungkyunkwan University. He is currently a Senior Research Engineer with the Research and Development Division, Hyundai Motor Group. Currently, he is working with the Interior Design Team in HMC research and development for developing new cars.



JI-WOO PARK received the B.S. degree in optoelectronics from Sejong University. She is currently a Senior Research Engineer with the Research and Development Division, LS Automotive Technologies. She is also an Optical Engineer in the interior and exterior lighting of vehicles and her main work is designing and analyzing optical components.

HYEON-JEONG SUK (Member, IEEE) received the B.S. and M.S. degrees in industrial design from KAIST and the Ph.D. degree in psychology from the University of Mannheim. She is currently a Professor with the Department of Industrial Design, KAIST. She is also leading with the Color Laboratory (color.kaist.ac.kr). Her research interests include color psychology and emotional design.