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

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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 chose a preferred light hues between blue and orange 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 electroencephalogram (EEG) and subjective assessments about style judgments 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 on seven adjectives towards an evidence-based proposal to search for user-centered light scenarios in automobiles.

key words: Ambient lighting, Dynamic light, Emotional experience, EEG, Self-Assessment

1 Introduction

The automotive industry is pushing state-of-art driving technology, and autonomous driving is one of the examples of its technical innovations. One of the essential concerns of advancements in such driving technology is how to enhance the emotional experience in a vehicle [34, 41]. Automobile industry has paid attention to the in-car affective computing solutions, expecting to identify and satisfy users' emotions and style tastes [47]. As light delivers the information and the emotional values intuitively and unobtrusively [18], car manufacturers have recently tried to facilitate ambient lights in vehicles [3, 8, 32, 17]. Additionally, the diverse range of light concepts is more easily implementable with the advancement of LEDs and automotive technologies [7]. Light plays a more prominent role in taking active care of users' physiological desires and emotional anticipation in the vehicle space with much fewer restrictions. As a result, users have a more significant physical and psychological space in an autonomous driving context. Hence, ambient lighting functions as the mood modulator in vehicles, and global car manufacturers demonstrate their light solutions, as shown in the Figure 1.

Figure 1: Examples of vehicular ambient light: A) Ambient lighting in Mercedes Benz S class 2021 [6]; B) Ambient light in Audi A5 Sportback 2021 [3]; C) Sky lounge in BMW 7 Series 2022 [8]; D) Ambient lighting in KIA K8 [32], E) Interior Ambient Lighting in Genesis G80 [17]

Previous studies have discovered the effect of light on cognitive behavior [29, 40, 46], the human body [12, 37, 43], or emotional state [42, 19, 11] combined with diverse light contexts. Studies have manipulated the optimal matches between user activity types and ambient light [26, 41, 39], namely, the user scenarios. For example, Locken et al. proposed 23 kinds of different lighting behavior signatures of bulb-shaped lights to connect with user scenarios in the automobile [27]. In a study by Meschtscherjakov et al., authors positioned a light stripe on the windshield. They proposed nine-light behaviors and matched them into five information types [31]. Mercedes Benz S class introduced dynamic light behaviors to visualize the voice assistant, speeding alarm, or lane departure warning, confirming that light functions as a multi-modal solution among the currently manufactured vehicles [6].

The empirical evidence has validated the affective effect, thereby expanding the human-centered light to a space that furnishes users' physical and mental states. Kim et al. have suggested a guideline about emotional modulation through the speed and characteristics of lighting behaviors [42]. Thus, a more holistic approach in evaluating lighting and its significance is required by utilizing diverse aspects, such as bio-feedback, cognitive performance, and self-reports.

However, only a few have attempted the investigation in the context of vehicle interior lighting. For example, precedent studies have varied the color hue of the ambient light to observe passengers' responses by comparing electroencephalography (EEG), and self-assessment results [35, 19]. Alternatively, some studies have examined bright blue light's therapeutic effect and collected EEG with subjective responses [12, 37]. When integrating the physiological and psychological reactions, the effect of light persuades industrial applications, including car interior light. However, there is limited evidence for lighting behavior and its effect on participants' subjective judgments. In these circumstances, this study focuses on brain activities and subjective assessments during passengers' exposure to the interior light varied in color hue, placements, and behaviors. This study expected to find evidence to enrich automobiles' affective experience through the optimal ambient lighting design based on the empirical data.

2 Related Work

2.1 The potential of lighting behaviors in vehicle design

The emotional effect of the illuminant adds value to its role in the space when it is in harmony with the user scenarios [2, 26]. For example, previous studies have incorporated light to manipulate driver emotions such as anxiety [16, 14] or stress [45, 4] by manipulating lighting attributes. Similar sensations of the space are applicable in the vehicle context, researchers have explicitly explored by controlling attributes of in-vehicle ambient light such as animations [30], brightness [12], color [10], and distributions [11]. Regarding the influence of color and brightness of the illuminants, orangish-white lighting, often labeled warm white, created a luxurious atmosphere in the vehicle [11]. In contrast, bluish-white lighting, cool white, effectively influences drivers' awakening state [10]. Another study have indicated that variation of brightness of the bluish-white light controlled humans' well-being, including alertness [12].

Often, ambient light's dynamic behaviors aimed to warn or alert the driver by presenting immediate responses in the form of fatigue. Technologies related to individual lighting control have evolved in a current vehicle on the market compared to the past, where vehicle lighting control is limited to the full LEDs in the vehicle [21, 41]. Therefore user-experience side of the ambient lighting control also improved by offering individual control of light colors and brightness accordingly. Accordingly, the time-sequence based dynamics of light behaviors result variations of light design exponentially [7].

Recent studies on dynamic behaviors distinguished the lighting signatures by varying their speed [42, 30, 31] and characteristics [28, 44, 9]. For example, the study examined whether the light installed across A-pillar and B-pilar enables users to perceive the car's speed by varying its lighting speed [30]. Alternatively, Troster et al. proposed seven LED characteristics by installing the LEDs on the windshield. The study surveyed a user experience questionnaire on installed LED characteristics [44]. In another study, Kim et al. observed how drivers' emotions change with light behaviors from the front panel and cluster. The responses were assessed in terms of pleasure, arousal, and uniqueness [42].

As reviewed, both car manufacturers and users are increasingly interested in new and novel light signatures. Hence, unique ambient light features are critical in offering the optimal solutions to strengthen the influence of the ambient light in the vehicle.

2.2 Measuring human responses to vehicular ambient light

Studies discovered how the light properties trigger the psycho-physical influence on humans. Studies have utilized diverse apparatus and metrics to investigate the human responses by measuring them within the space with various illuminants. Previous studies facilitated bio-feedback to measure users' alertness and relaxation under ambient lighting. The bio-feedbacks are the electroencephalogram (EEG) [12, 20], electrocardiogram (ECG) [13], Galvanic skin response (GSR) [5], or melatonin secretion [14]. A measurement type selection is deliberately made as each method has particular constraints or tolerance during the collection of brain responses [22, 15]. Additionally, the violating results between the measurements address how people perceive different from how their bodies have reacted. Such a comprehensive perspective nurtures the understanding of the empirical results.

In order to record the users' physiological responses to the vehicular ambient light, previous studies have adopted the EEG. For example, Kerstedt et al. engaged self-report and alpha wavelength of EEG to measure the subjects' alertness to light installation in a car simulation set in a laboratory [1]. Canazei et al. have conveyed the experiment in an actual driving situation and revealed the effect of the bright light in the vehicle helped subjects more awaken while driving [12]. The study utilized the alpha spindle of EEG in detecting alertness under the target ambient light condition.

This study intended participant's exposure to a series of ambient lights for no longer than an hour in total. Participants' reaction was regarded as an immediately evoked response after viewing the ambient light. For this reason, the EEG was suitable for observing participants' bio-feedback of their attention. Also, both self-report with the EEG responses were employed toward a coherence between bodily responses and subjective judgments.

3 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. Furthermore, it pursues a comprehensive understanding of the light condition's impact on participants by involving the EEG responses and self-assessments. It was expected to provide empirical evidence in designing user-centered light for the car interior with the study setup.

4 Plan for Experiment

Lighting components were installed in a passenger car (Sonata DN8, Hyundai Motor Company) to simulate an actual driving condition. The experimental setup was designed to produce the same lighting impact as the actual vehicle.The optical fiber to diffuse the LED light uniformly and its array. The vehicle's engine was idle throughout the experiment to resemble the actual lighting scenario within the driving context. The following sections cover lighting design, EEG setup, and survey construction.

4.1 Lighting Design: Placement, Behavior and Color Hue

The SK6811 RGB-White LEDs (Neopixel, Adafruit) were used as the light source. The single LED unit contains the four channels, such as R (red), G (green), B (blue), and W (white), which were unit-wise as well as channel-wise configurable between 0 and 255. The LED units were eligible for an ease installation on irregular surfaces. The optic fiber (5 mm in diameter) was covered along with the LED units' array to diffuse the light uniformly—the total number of 554 LED units used in total. In addition, an achromatic exterior and interior were deliberately selected to minimize the chromatic interaction between the interior surface and light. The representative color in the exterior were yellowish white, and the interior was grayish beige, and their colorimetry values measured with a Spectrophotometer (CM2600d, Konica Minolta) was L: 91.48, a: -0.98, b: 0.51 and L: 24.5, a: -0.69, b: -0.13, respectively. The attributes, such as lighting placements, lighting behaviors, and color hue were varied resulting in different light signatures.

4.1.1 Lighting Placements

In experiment the front instrument panel was mainly focused as the driver's field of view during driving. Initially, 15 regions were defined as presented in Figure 2), and then, to manipulate each region independently, a web-based serial control software was developed. The control software was build with P5.js and Node.js to control the light attributes. Finally, the regions were numbered to be linked to the graphical interfaces in the software's control panel. Then, the light regions were eligible for a quick manipulation through the corresponding numbers. In fact, the total number of light distribution reached to 32,768 variations, resulting from 2 (on or off)$\hat{1}5$ (15 regions). The scope of the experiment was taken into consideration, and hence, two best light placements were agreed by three designers who majored in industrial design or transportation design and have practiced vehicle design for at least three years. Using the control panel, designers have exploited various light distributions and proposed two types: 'Direct light placement' and 'Indirect light placement.' The suggested direct placement exposes the LED stripes directly to the eye, while the indirect placement reflects on the surface. Therefore, in determining the region where LED is installed, the first consideration was whether each region fits with direct or indirect light viewing. In addition, the aesthetic appeal was examined by providing stylish ambient light to the participants.

In addition, 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 pilar), 5 (Handle), 6 (Pocket), 11, 12, and 15 (Chair Mood).

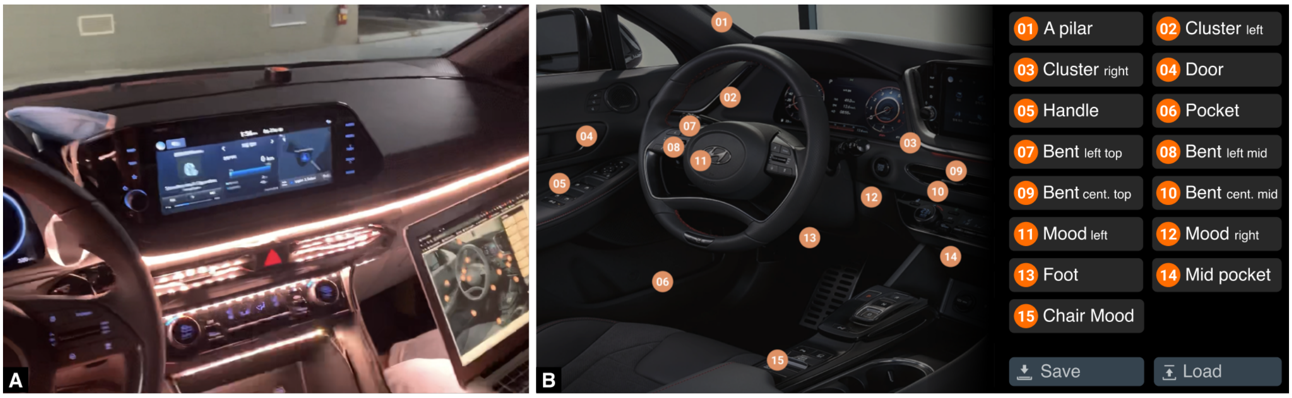

Figure 2: (left) LED stripes were mounted in passenger car (Sonata DN8, Hyundai Motor Company). (right) A control panel contained 15 buttons to switch on/off the light components in 15 regions.

4.1.2 Light Behaviors

The lighting behaviors have been increasingly investigated recently, and studies have demonstrated the different effects on visual styles [44] and users' effective judgments [30, 42]. Six distinctive types were organized for the experiment, including a constant mode ('On'). They were labeled with 'Blink', 'Fade', 'Collide', 'Spread', 'Move', and 'On'. We configured the looping sequences using a microprocessor (Mega 2560, Arduino). The Figure 3 illustrates the behavioral patterns every 500 milliseconds.

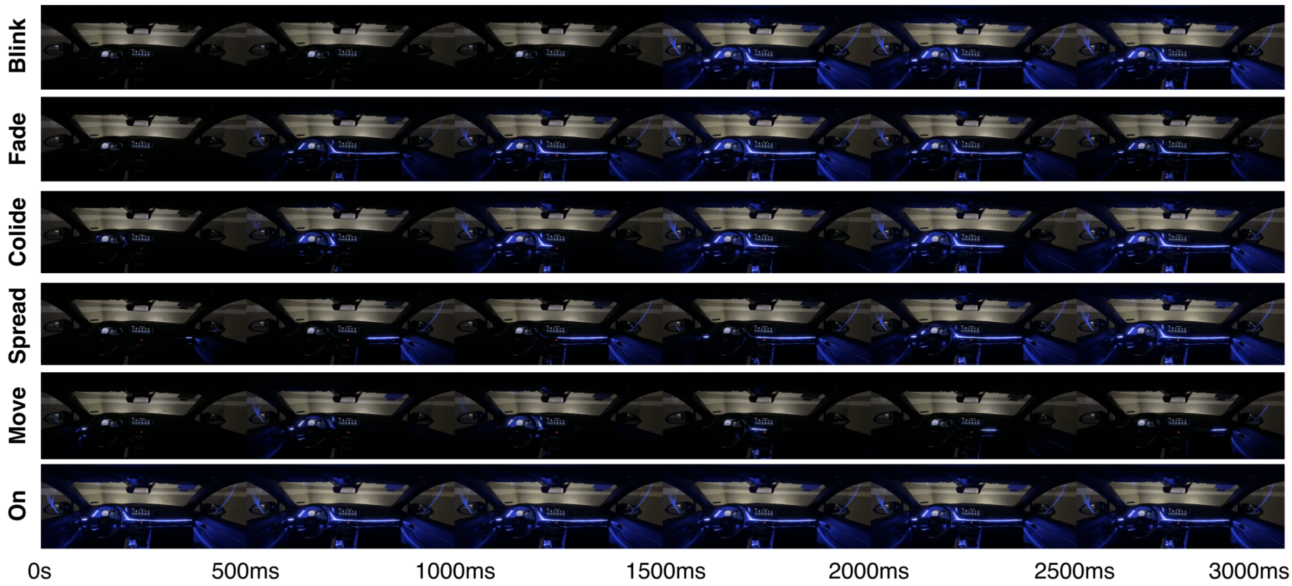

Figure 3: Six types of lighting behaviors during 3,000 milliseconds

4.1.3 Light Hue: Blue or Orange

Previous lighting studies mainly compared the emotional effects of bluish-white and orangish-white. Therefore, Caberletti et al. systematically suggested that lighting guidelines with manipulating drivers' emotions with two representative colors, blue and orange, used as two contrasting light colors [11]. Their chromatic characteristics are profiled within the CIE xyY 1931 color space [blue = (x: 0.1902, y: 0.1342, Y: 1017.25); orange = (x: 0.5872, y: 0.3766, Y: 931.64)] and long the visible spectrum in Figure 3. The relative spectral power placement of both light sources between 400 nm and 700 nm measured with a spectroradiometer (CS-2000, Konica Minolta). Furthermore, Figure 5 shows the lighting conditions altered with placement and colors with spectral power distributions after the lighting installation.

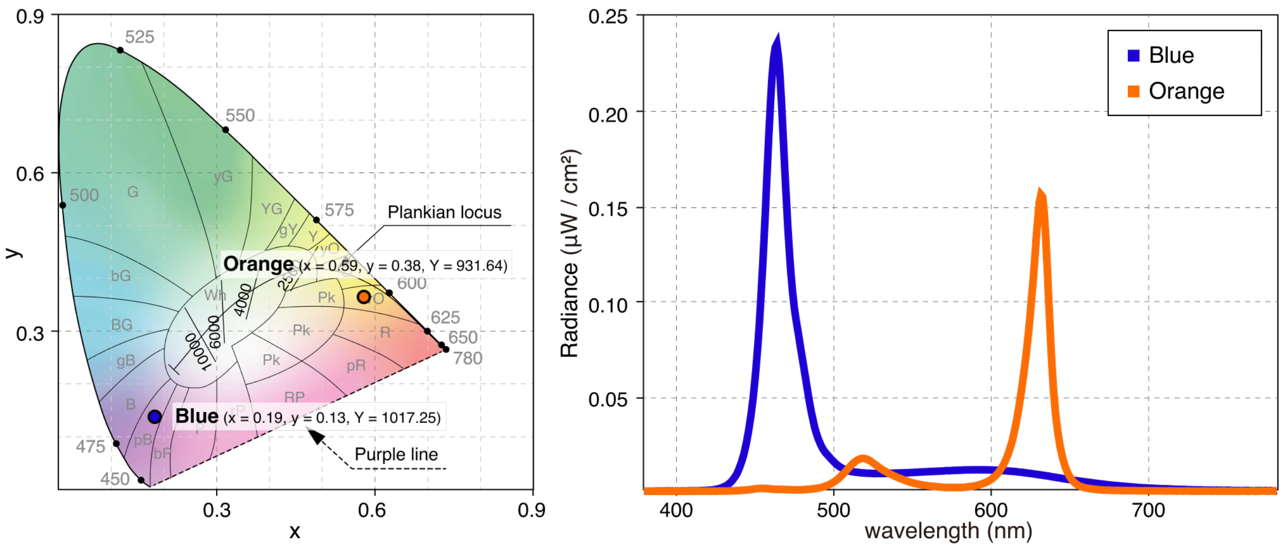

Figure 4: Left: Blue and orange light sources in CIE1931 Chromaticity diagram; Right: the relative spectral power placement of the light sources.

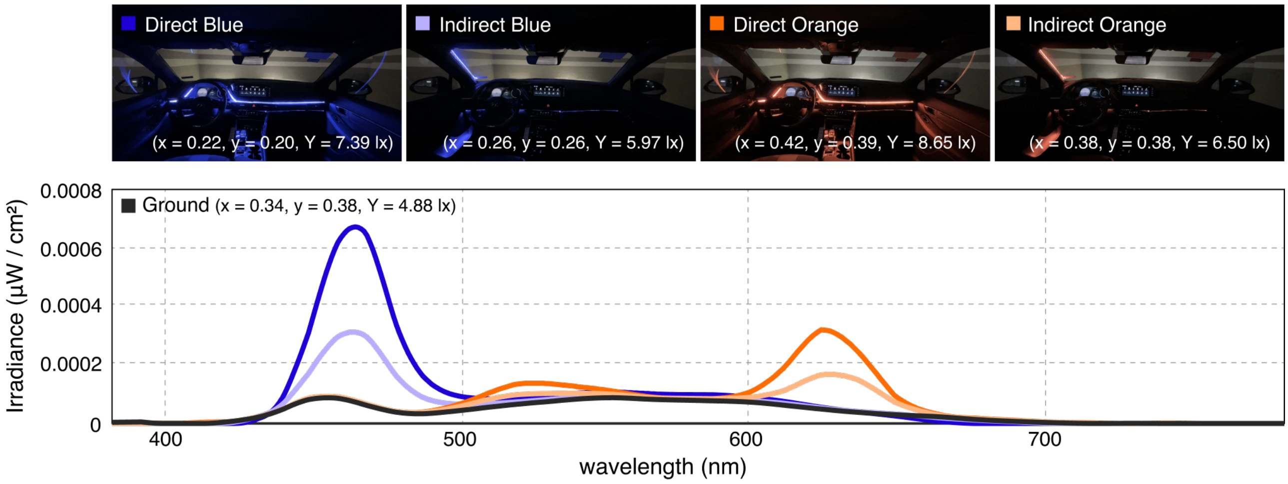

Figure 5: The four light conditions altered with placement and color. The spectral power distributions were measured with a light meter (IM-1000, Topcon).

4.2 EEG setup

When EEG was facilitated in light studies, frontal cortex was targeted [13, 33], and 5-channels of EEG units (QEEG-32FX, LAXTHA) were used. The five channels covered two frontal area channels, two reference channels, and one ground channel. During the experiment, the EEG signals were collected in 256 Hz from the two forehead positions corresponding to Fp1 and Fp2 following the 10-20 standard as illustrated in Figure 6. Supported by LAXTHA's TeleScan software, the raw EEG data were processed through the electrooculography (EOG) filter and the fast Fourier transform (FFT) analysis. Then the ratio of alpha and beta bands were analyzed, and their frequency ranges were 8-13Hz and 13-30 Hz, respectively [36]. During the EEG measurement, the participants were asked to keep silent while not moving.

Figure 6: While participants were exposed to the light stimuli, EEG responses were collected from their foreheads, Fp1 and Fp2. Participants were seated in the driver's seat.

The presented lighting looks like...

	-3	-2	-1	0	1	2	3	
Unobtrusive								Obtrusive
Simple								Complicated
Unhelpful								Assistive
Boring								Enjoyable
Afterwards								Cutting-edge
Sleep								Awakening
Inappropriate								Satisfactory

Figure 7: After the exposure to each light stimulus, participants assessed the quality of the light experience on seven questionnaires using 7-point Likert scales.

4.3 Survey

Concerning the quality assessment of the ambient lighting, previous studies have made an effort to develop proper metrics. For example, Caberletti suggested 21 pairs of survey questions to describe ambient lighting effects on vehicle interior perceptions, including usability and affections. Sandra has introduced seven modified user experience questionnaires [38] for measuring user experiences of the lighting visualizations [44]. Another study has proposed emotional scales in that measuring uniqueness of the ambient lighting is differentiated [42]. A pool of adjective pairs from the initial review and then synonyms were grouped and reduced to 17 pairs. Also, some inadequate adjectives were excluded, when they were inappropriate for describing the visual characteristics of the car ambient light.

A survey was finalized with seven questionnaires using a 7-point Likert scales as presented in Figure 3. The questionnaires were labeled as "unobtrusive–obtrusive", "simple–complicated", "unhelpful–assistive", "boring–enjoyable", "afterwards–cutting-edge", "sleep–awakening", "inappropriate-satisfactory". Participants were asked to make subjective judgments after each lighting stimulus, and their EEG responses were not recorded during the survey.

5 Experiment

5.1 Methods

5.1.1 Subjects

Forty participants made up of 20 men and 20 women volunteered in experiment. All participants were university students majoring in diverse subjects. Interestingly, ten men and ten women chose blue light, and the rest chose orange light as the color hue of choice for the light experiment. Their average age was 22.90 years old, 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. (Approval number is blind for review)

5.1.2 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 one minute, while EEG was being recorded. Then, a survey was proceeded right after the each light stimulus. It took another one minute, and the EEG record was stopped during the survey. The entire session was repeated twice, and the experiment lasted around 50 minutes on average to complete.

6 Results

Based on the EEG responses and survey answers, analysis was proceeded to comprehend how lighting behaviors influenced subjects' stress levels and perceptual quality.

6.1 EEG responses

Based on the brain waves, the ratios of alpha (8–13 Hz) and beta (13–30 Hz) waves were estimated from the whole range, 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 problem-solving [36]. In this study, the average alpha and beta waves observed from the experiment were compared among the six types of light behaviors in two light placements. The Figure 8 illustrates the average ratios of alpha and beta waves, and tone alternatives, deep or pale tones, direct or indirect light placements. Each grey bar, "Off", in the Figure indicates the average ratios of alpha or beta waves in a dark condition for 1 min.

A Three-Way Mixed ANOVA was performed and examined the effect of light behaviors, placements, and color hue, while dependent variables were the brain waves and the subject assessments of questionnaires. The repeated measures were on light behaviors and placements. The Table 1 and Table 2 display the F and significance values of the ANOVA results. In general, the light behaviors and placements significantly influenced the ratios of beta waves and subjective assessments at an alpha level of 0.05. The direct blinking light ("Blink" in deep tone) resulted in the highest ratio of beta waves, whereas the constant indirect light ("On" in pale tone) resulted in the lowest. Furthermore, the ratios of the beta waves of the constant indirect light resulted much lower than the "Off" mode of both color hues. The beta ratio during the constant indirect light was 28.02% (blue light) and 29.85% (orange light), which is lower than the "Off" by 30.72% (blue light) and 29.91% (orange light). In addition, most of the interaction effects were not statistically significant.

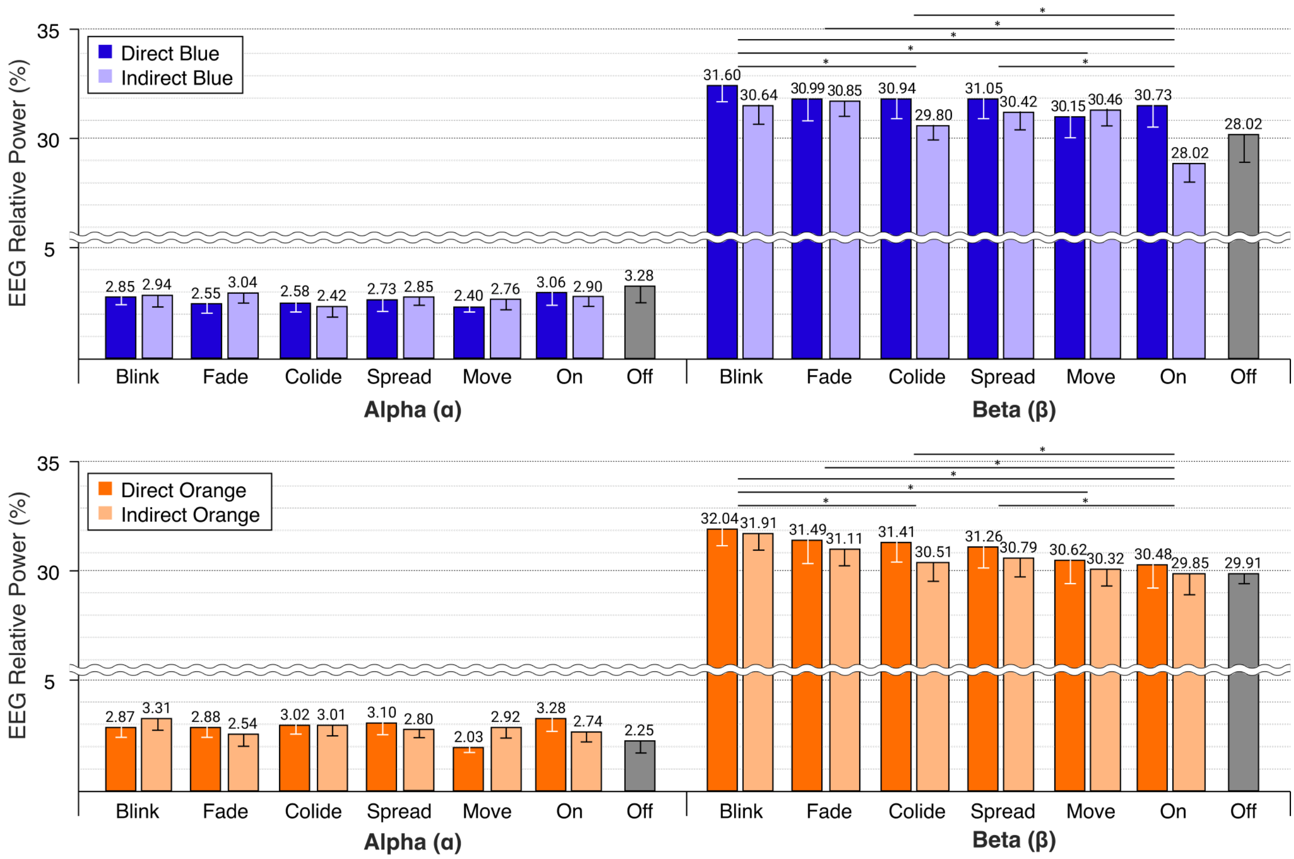

Figure 8: Ratios of alpha-wave (8–13 Hz) and beta-wave (13–30 Hz) to entire EEG signals (0.5–40 Hz) along the six lighting behaviors. Bars in deep and pale tones are the responses to the direct and indirect light placements, respectively. The grey bars on the right indicate the averaged alpha and beta ratios in a dark condition. * p <.05

	Alpha-ratio	**Beta-ratio**
behavior	F(5,190) = 2.18, p = .06, η_p^2 = .05	F(5,190) = 4.91, p <.05, η_p^2 = .11
placement	F(1,38) = .00, p = .58, η_p^2 = .02	F(1,38) = 5.65, p <.05, η_p^2 = .13
Color	F(1,38) = .04, p = .85, η_p^2 = .00	F(1,38) = .29, p = .59, η_p^2 = .01
behavior × placement	F(5,190) = 1.72, p = .13, η_p^2 = 0.04	F(5,190) = .85, p = .52, η_p^2 = 0.02
behavior × Color	F(5,190) = .94, p = .46, η_p^2 = 0.02	F(5,190) = .32, p = .90, η_p^2 = 0.01
placement × Color	F(1,38) = .00, p = .61, η_p^2 = 0.01	F(1,38) = .00, p = .42, η_p^2 = 0.02
behavior × placement × Color	F(5,190) = 1.02, p = .41, η_p^2 = 0.03	F(5,190) = .74 p = .60, η_p^2 =0.02

Table 1: Results of Three-Way Mixed ANOVA with repeated measures on light behavior and placement. * p <.05

6.2 Self-Assessments

The assessments were collected along with the entire light behaviors and placements across two color hues. The Figure 9 presents the averaged assessments, and the style adjectives were rated between -3 (not agree at all) and $+3$ (absolutely agree).

As found in Table 2, there were differences in all adjectives for all light behaviors. The direct light was found in light placements: "Obtrusive", "Simple", "Assistive", "Awakening". However, the main effect of color hues was not statistically significant, except for both colors' "cutting-edge" style. However, compared to the EEG responses, the subjective assessments showed more drastic changes in the light behaviors. Regarding the distribution, both direct and indirect lights have shown similar trends. However, the results of the assessments on direct light were varied more than those on indirect light. It indicates that participants found the style characteristics distinctive when the light was emitted directly to the participant's viewing angle. Similarly, based on the EEG responses and subjective assessments, we have figured out five directions towards optimizing the ambient light design:

- Discrete blinking light ("Blink" behavior) found the most awakening among other behaviors. The ratio of beta waves was the highest in both blue and orange lights. The self-assessments were found "simple", "assistive", and "awakening". The impact is more significant with direct placement than with indirect one. The finding supports that the luminous surface or interfaces with the "Blink" behavior should be appropriate to alert the driver for an urgent notification.

- Even with the light blinking smoothly, it alerted the participants. The "Fade" behavior was assessed as "unobtrusive" and more "cutting-edge" from the "Blink" behavior with the smooth blink. A smooth blink should be appropriate to express notification nicely. When the "Fade" behavior is installed indirectly, it will be more "satisfactory" and "cutting-edge".

- The "Spread" behavior was the most cutting-edge relevant when the light source was observed directly. It looks "obtrusive" and "enjoyable" while evoking "awakening" emotion. It can be an option to consider when an alert needs to be stylish.

- Participants responded "unobtrusive" and "simple" with the "On" behavior: a simple contact direct light. However, a luminous element is adequately presented to support the driver with immediate attention. The "On" behavior received the highest satisfaction score when the light source was luminous with direct placement.

- Lastly, the color hue did not show the dominant effect differently from previous aesthetic approaches. Except for the subjective judgment on "cutting-edge", the responses were not statistically different between blue and orange light. Concerning the "cutting-edge" aspect, blue light received higher scores than orange light. However, because the participants selectively experienced only one color hue between the two, it is not concluded whether it is unrelated to their responses.

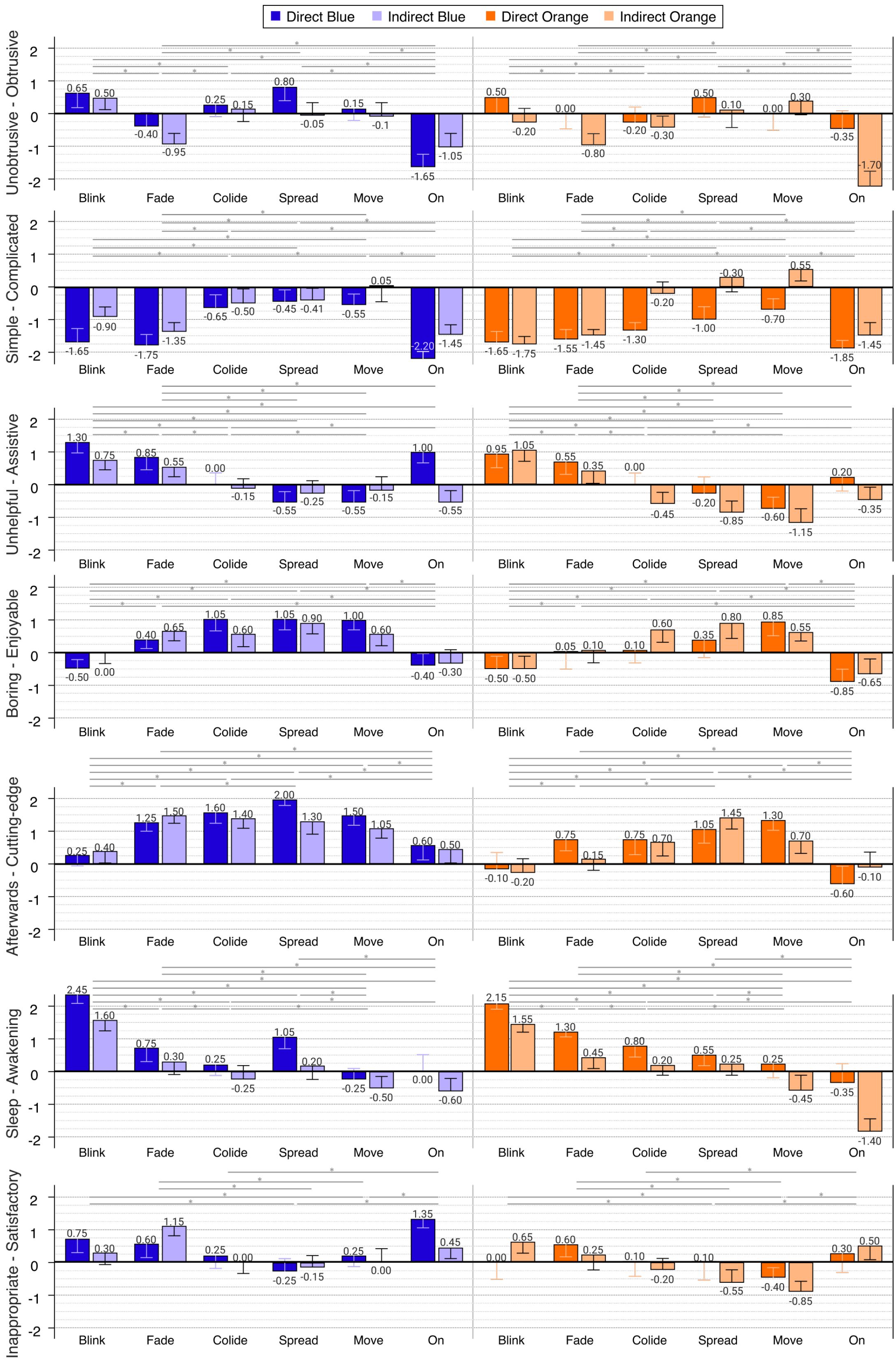

Figure 9: Responses of seven questions along the six lighting behaviors (−3: not agree at all, +3: absolutely agree). Bars in deep and pale tones are the responses to the direct and indirect light placements, respectively. The grey bars on the right indicate the averaged alpha and beta ratios in a dark condition. * p <.05

	Unobtrusive - Obtrusive	**Simple - Complicated**	**Unhelpful - Assistive**	**Boring - Enjoyable**	**Afterwards - Cutting-edge**	**Sleep - Awakening**	**Inappropriate - Satisfactory**
behavior	F(5,190) = 14.10, p <.05, η_p^2 =	F(5,190) = 20.60, p <.05, η_p^2 = .35	F(5,190) = 20.50, p <.05, η_p^2 = .35	F(5,190) = 14.10, p <.05, η_p^2 = .27	F(5,190) = 11.58, p <.05, η_p^2 = .23	F(5,190) = 30.16, p <.05, η_p^2 = .44	F(5,190) = 6.17, p <.05, η_p^2 = .14
placement	F(1,38) = 17.63, p <.05, η_p^2 = .10	F(1,38) = 42.60, p <.05, η_p^2 = .26	F(1,38) = 14.70, p <.05, η_p^2 = .14	F(1,38) = .35, p = .70, η_p^2 = .00	F(1,38) = 2.70, p = .28, η_p^2 = .03	F(1,38) = 58.10, p <.05, η_p^2 = .35	F(1,38) = 3.17, p = .35, η_p^2 = .02
Color	F(1,38) = .39, p = 54, η_p^2 = .01	F(1,38) = .21, p = .65, η_p^2 = .01	F(1,38) = .78, p = .38, η_p^2 = .02	F(1,38) = .93, p = .34, η_p^2 = .02	F(1,38) = 5.58, p <.05, η_p^2 = .13	F(1,38) = .02, p = .88, η_p^2 = .00	F(1,38) = 1.63, p =.21, η_p^2 = .04
behavior × placement	F(5,190) = 2.04, p = .40, η_p^2 = .03	F(5,190) = 1.64, p = .40 , η_p^2 = .03	F(5,190) = 2.28, p =23, η_p^2 = .04	F(5,190) = .92, p = .60, η_p^2 = .02	F(5,190) = .77, p = .63, η_p^2 = .02	F(5,190) = .40, p = .96, η_p^2 = .01	F(5,190) = 1.52, p = .54, η_p^2 = .02
behavior × Color	F(5,190) = 1.36, p = .24, η_p^2 = .04	F(5,190) = .74, p = .02, η_p^2 = .02	F(5,190) = .30, p =. 92, η_p^2 = .00	F(5,190) = .47, p = .80, η_p^2 = .01	F(5,190) = .89, p = .49, η_p^2 = .02	F(5,190) = .13, p = .13 , η_p^2 = .04	F(5,190) = .75, p = .75 , η_p^2 = .01
placement × Color	F(1,38) = 1.88, p = .51, η_p^2 = .01	F(1,38) = .75, p = .24, η_p^2 = .01	F(1,38) = .13, p = .06, η_p^2 = .00	F(1,38) = 1.10, p = .49, η_p^2 = .01	F(1,38) = .68, p = .59, η_p^2 = .01	F(1,38) = .20, p = .94, η_p^2 = .00	F(1,38) = .20, p = .94, η_p^2 = .00
behavior × placement × Color	F(5,190) = 3.28, p = .15, η_p^2 = .04	F(5,190) = 2.86, p = .11, η_p^2 = .05	F(5,190) = 14.29, p = .15, η_p^2 = .04	F(5,190) = 1.36, p =. 37, η_p^2 = .03	F(5,190) = 2.74, p <.05, η_p^2 = .06	F(5,190) = 1.14, p = .70, η_p^2 = .02	F(5,190) = 3.61, p = .10, η_p^2 = .05

Table 2: Results of Three-Way Mixed ANOVA with repeated measures on self assessments. * p <.05

7 Discussion

The ambient light delivers aesthetic style on psychological and physiological influences. Our study intended to observe the effect of ambient light on drivers inside the actual vehicle. Therefore, we collected the participants' responses using the EEG as empirical evidence and survey questionnaires during the experiment as the participants were exposed to various ambient light. Study intended to describe the user responses to vehicular ambient light comprehensively, physiologically, and psychologically through the above setup.

The light conditions were varied in terms of dynamic behaviors and placement type. Hence,the participants were divided into two hue groups, blue and orange, depending on individual preference. While the earlier studies focused on the effects of light behaviors on self-assessments [42, 30, 31, 28, 44, 9], our experiment have demonstrated the drivers' physiological effect alongside self-assessments. The two hue groups showed similar tendencies from the EEG responses and subjective assessments. Our data and results showed a similar trend with precedent studies that the blinking behavior of car interior lighting assists the driver alert [42, 44]. The ratios of beta waves have changed significantly depending on behaviors and placement types. The results from this study showed coherence with previous studies that revealed that indirect lighting is less obtrusive compared to direct lighting in the vehicle [11, 23].

As a higher ratio of the beta waves indicates an increase of alertness, various target situations were associated with the light characteristics. The ratio of beta waves was the highest with the "blinking" light behavior and followed by the "fading" and "colliding" behaviors. It had reduced when the light placement was indirect and was observed lower than in the dark condition with the indirect light setting. These observations were compared with the scores of adjectives collected from the self-assessments better 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 on providing more user-centered ambient lighting.

The hue difference did not yield statistically significant responses than the initial anticipation of the study. The only exception was with the "cutting-edge" assessment. Previous studies have distinguished that the blue color of the car interior conveys a futuristic image to the consumers [24, 25]. The "cutting-edge" assessment yielded similarly by having a higher score on blue light than the orange. Though we observed compelling results from the study, we are aware of the limitations of this study. To minimize participants' attention loss, the number of experimental stimuli were inevitably reduced. In addition, prior to the experiment, participants' personal preference for blue or orange 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.

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 more profound empirical evidence by collecting the EEG from an actual situation within the vehicle with physical lighting modules. The findings based on the EEG responses and self-assessments can be utilized in providing evidence-based user scenarios. Thus, as autonomous driving will acquire more active light, more creative light designs are expected to enrich users' emotional experience in automobiles.

8 Conclusion

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

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