Proceedings

EXPERIENCING LIGHT 2009

International Conference on the Effects of Light on Wellbeing

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Keynotes and selected full papers
Eindhoven University of Technology,
Eindhoven, the Netherlands, 26-27 October 2009

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ISBN: 978-90-386-2053-4

Reference specification:
Name Author(s), "Title of the Article", In: Proceedings of EXPERIENCING LIGHT 2009 International Conference on the Effects of Light on Wellbeing (Eds. Y.A.W. de Kort, W.A. IJsselsteijn, I.M.L.C. Vogels, M.P.J. Aarts, A.D. Tenner, and K.C.H.J. Smolders), 2009, pp. X (startpage) – Y (endpage).

Influence of Ambient Lighting in Vehicle Interior on the Driver's Perception

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INTRODUCTION

Ambient interior lighting for vehicles is an issue of dramatically growing relevance in the automotive industry. In the last decade the number of light sources in the car interior providing this illumination has drastically increased. A steadily growing amount of cars in the high and middle class segments are equipped with such lighting.

Ambient lighting provides an indirect illumination of the passenger compartment in low light settings, such as during the night. Its importance lays in the fact that it provides a better orientation in the car, an improved sense of spaciousness, as well as an impression of safety, value and comfort. Furthermore it conveys an emotional and brand-oriented atmosphere to the otherwise dark car interior at night. Moreover, ambient lighting can harmonise the luminance level between the vehicle interior and the external environment, thus decreasing the driver's fatigue when driving at night [20]. Ambient lighting does not perform a pure functional role and therefore it can be designed in any colour, since it does not require a high colour rendering. Indeed, car makers use different colours also in order to give a branded image of the car interior.

It is important to notice that since ambient lighting is an indirect illumination, the materials upon which it reflects acquire new value and quality. Night design thus plays a central role, since the materials and the lines of the car interior are visible not only during daytime but at night too. On the other hand, disability and discomfort glare caused by ambient lighting should be avoided, in order not to impair vision and decrease safety during drives at night.

MOTIVATION

Previous studies by Grimm [7] proved that disability and discomfort glare originating from ambient lighting can be eliminated by keeping maximum luminance under $0.1 cd/m^2$. In this way, negative effects on the safety can be neglected.

Studies by Schellinger et al. [15] and Klinger and Lemmer [11] stated that the driver's contrast vision won't be negatively affected by ambient lighting, if the driver can control its brightness.

Other studies on vehicle interior lighting addressed the issue of possible glare caused by reading lamps or dome lights through veiling luminance and unwanted mirror effects [3] [14].

However, there are no guidelines which indicate how to correctly and consequently arrange ambient lighting in the car interior in order to maximise its positive effects. In fact, this procedure is based nowadays upon experts' personal judgement.

Many studies investigate the effects of lighting on mood [12] [13], emotions [6] and perceptions [8] [18], within the scope of lighting design in buildings and in office-environments. Of interest in this study is if such effects can be caused even in the relatively small environment of the vehicle and with such small luminance levels as in the case of ambient lighting.

Thus, in order to fully understand the advantages of ambient lighting in relationship to its characteristics and parameters, an experimental research study has been conducted and will be presented in this paper.

METHOD

In an immersive virtual test environment, 31 test persons had the task of "driving" a real stationary vehicle on a virtual highway. In the vehicle, a different ambient lighting scenario was displayed in each run. In total twelve different scenarios were tested, in which the following parameters were varied: light colour, luminance and position.

Experimental Setup

The test took place in a static driving simulator at the BMW Group research centre [9]. The choice of using a simulator environment rather than leading the test on real streets gave a complete control on the environmental variables, guaranteed the repeatability of the experiment, and thus increased the significance of the results.

A BMW 3 Series equipped with special interior light features was used for the experiment. It was connected to the simulator in a way that allowed the driver to steer the car but not to accelerate and brake (a collision with the preceding vehicle was impossible because of the control mechanisms in the driving simulation software). The driving simulation was projected on three screens placed in front and around the car, which covered a viewing angle of about 135°. In the simulator room, an ambient luminance between 0.01 cd/m² and 0.1 cd/m² was present, which caused a mesopic visual adaptation. The luminance level on the simulated street lane was between 0.1 cd/m² and 1.5 cd/m², a range of values which matches the measured street luminances in reality [1] [2] [16] [19].

Test subjects

The investigation took place with 31 participants, 8 women and 23 men, between 21 and 58 years-old (mean age 35 years). 18 of them had already experienced ambient lighting while driving. 14 of them wore glasses or contact lenses. For each participant the experiment lasted 1.5 to 2 hours.

Execution of the test

After the execution of the Ishihara Colour Vision Test [10] (all the participants had a good colour vision) the room was darkened. The test persons had 10 minutes for dark adaptation. During this time the investigator described the objectives and the methods of the research. Afterwards the participants drove the vehicle a few minutes on the simulator in order to become familiar with its steering feeling. After this period of adaptation the test started.

The investigator sat in a separated room and communicated with the test persons through a radio. After he started the simulation, the vehicle accelerated to 100 km/h and then remained at this speed. During the acceleration the appropriate lighting scene was activated and then maintained for 3 minutes. Meanwhile, the participants drove according to their main task, which was to follow a car on the right highway lane. Since the attention of the test persons was focused on the driving task, the ambient lighting was only perceived peripherally, as in reality.

Each minute the participants were asked to accomplish a secondary task. The aim of these tasks was to give the test persons the possibility to evaluate the functionality of the current lighting situation in enabling normal actions that take place while driving. For example, typical secondary tasks were the adjustment of the climate ventilation nozzles or the finding and operation of a specific control button. When the driver was unable to accomplish the secondary task, he was allowed to refuse it.

After 3 minutes, the ambient lighting was turned off and the vehicle was stopped by the investigator and brought on the side-strip. The participants then completed the questionnaire relating to the perceived lighting scenario. This process was repeated with all twelve lighting scenarios, which were presented in random order to each test person.

Ambient Lighting Scenarios

In the test vehicle twelve different ambient lighting scenarios were realised (Table 1). Three parameters were varied: colour, position of the lighting sources and luminance, as described in Table 2.

Table 1 Description of the tested lighting scenarios

Nr.	Lighting Scenario
1.	Everything on – bright level with accents
2.	Series (Centre console + Door trims)
3.	Doors – bright level
4.	Doors – low level
5.	Without lighting
6.	Everything on – bright level
7.	Everything on – low level
8.	Everything on – middle level
9.	Foot space – bright level
10.	Foot space – low level
11.	Centre console
12.	Everything on blue – low level

Table 2 Experimental parameters

Parameter	States
Colour	Orange (605 nm)
	Blue (471 nm)
Position	Centre console
	Doors
	Foot space
	Series (Centre console + Door trims)
	Complete
Mean luminance	Bright (more than 0.04 cd/m²)
	Middle (0.02 – 0.01 cd/m²)
	Low level (0.007 cd/m²)

The lighting colours presented in the test were orange and blue, with dominant wavelengths of 605 nm and 471 nm respectively. Lighting positions were selected among the ones commonly adopted in practice in the automotive industry. The centre console light is placed inside the roof node and illuminates the centre console area, where usually the gear selector lever and the controls for entertainment and conditioning are placed. Foot space lighting was realised with two LEDs placed in the cockpit, on both the driver and passenger sides. The illumination of each door consists of four LEDs and two light guides, which combined provide a homogeneous coverage of the door handles and of the upper part (door trims) and lower part (map case) of the door.

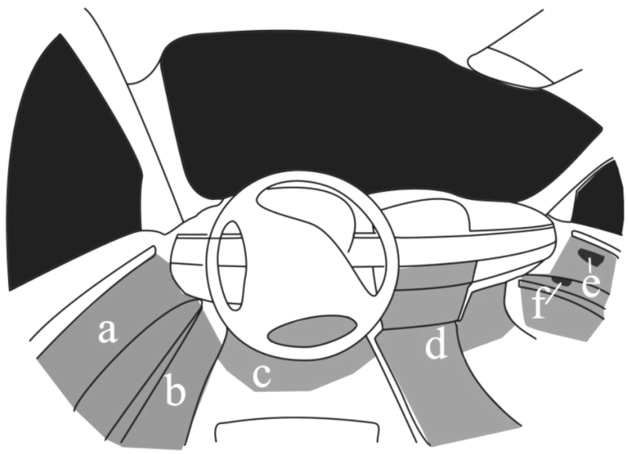

Figure 1 Positions of the ambient lighting. a. door trim, b. map case, c. foot space, d. centre console. With e. and f. the accents on the right door are highlighted (door handle and door pull respectively)

The combination of door trims and centre console lighting are a common setting in series vehicles and therefore was named series lighting. The setting "everything on" included all the above-mentioned lighting fixtures properly adjusted so that they could provide a homogeneous appearance. The setting "everything bright – with accents" provided a few additional points (door handles and pulls) with higher luminance (up to 2 cd/m²).

Cockpit instruments, display lighting and backlit symbols were always turned on, as in a real night drive situation. Anyway their luminosity level was constant during the whole research.

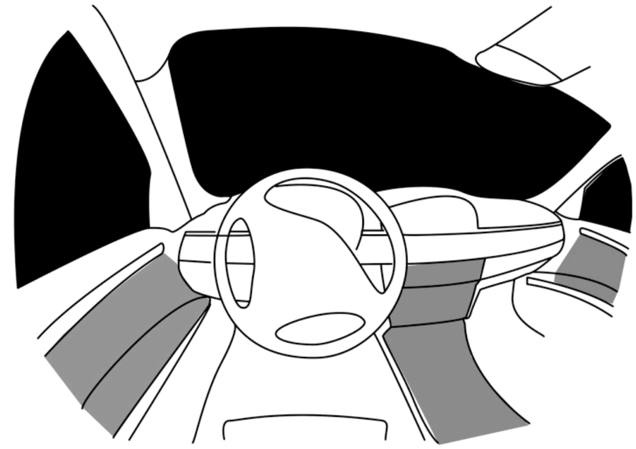

Figure 2 Example of lighting scenario: series setting - centre console and upper door trims are on.

Luminance Measurements

The luminance of the lighting fixtures in the vehicle was measured using a luminance camera provided with fish-eye optic (LMK Mobile Advanced, TechnoTeam, Ilmenau / Germany). In this way, the brightness in the whole field of view could be measured from the driver's perspective. The visual field has been divided into 4 zones (Figure 3). In these 4 zones, only the measure points with a photopic luminance between 0.003 cd/m² and 0.5 cd/m² have been considered. These areas can be considered illuminated by ambient lighting. Luminances below the 0.003 cd/m² have been considered dark, while those above the 0.5 cd/m² have been considered symbol lighting, and so not to be measured together with ambient lighting. In Table 3, the mean luminances L_M for these areas are displayed.

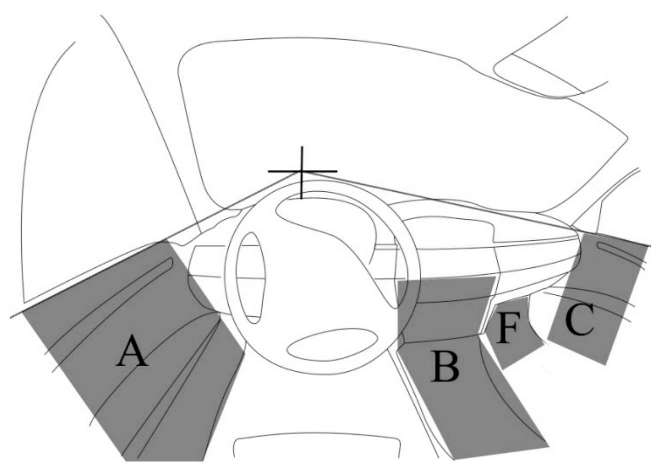

Figure 3 Luminance measure zones. A: left door; B: centre console; C: right door; F: foot space.

Table 3 Mean Luminance L_M for the different measure zones and the different lighting scenarios [cd/m²].

Scenario	1	2	3	4	5	6
A	0.023	0.009	0.023	0.022	-	0.023
B	0.012	0.011	0.009	-	-	0.010
C	0.023	0.006	0.029	0.017	-	0.026
F	0.008	-	-	-	-	0.008
Scenario	**7**	**8**	**9**	**10**	**11**	**12**
A	0.021	0.015	-	-		0.028
B	0.008	0.010	-	-	0.010	0.013
C	0.017	0.017	-	-	-	0.016
F	-	-	0.008	0.004	-	-

Since the lit area changes with the intensity of the illumination, the solid angle under which the area is seen by the driver (Ω) has also been calculated. The product of the solid angle and the mean luminance $L_M\Omega$ for each considered zone, displayed in Table 4, gives the eye illuminance, measured in the direction of the area.

Cockpit lighting as well as backlit symbols have not been considered in the measures, since they did not vary in intensity for the whole experiment.

Table 4 Eye illuminance (measured in the area's direction)($L_M\Omega$) values for the different measures zones and the different lighting scenarios [10^{-3} cd·sr/m²].

Scenario	1	2	3	4	5	6
A	3.17	0.65	2.60	0.62	-	2.64
B	0.71	0.50	0.04	0.03	0.02	0.54
C	1.11	0.05	0.91	0.31	-	0.92
F	0.27	-	-	-	-	0.27
Scenario	**7**	**8**	**9**	**10**	**11**	**12**
A	0.63	1.41	0.01	-	-	0.86
B	0.13	0.49	0.03	0.03	0.48	0.69
C	0.31	0.48	0.01	-	-	0.37
F	0.05	0.05	0.26	0.04	-	0.01

Questionnaire

Subjective perception of the lighting

After each experimental run, each test person was asked to fill out a questionnaire in the form of 18 semantic differential pairs, which were arranged according to the following criteria: space perception, perceived interior quality, interior attractiveness, perceived safety, alertness and functionality.

The questions were the following: the displayed light situation...

- *(Space perception)* ...allows the perception of the whole car interior / does not allow the perception of the whole car interior; ...causes a small impression of interior space / causes a big impression of interior space.
- *(Perceived interior quality)* ...looks cheap / looks luxurious; ...gives a lesser quality impression / gives a good quality impression.
- *(Interior attractiveness)* ...has a really unpleasant light colour / ...has a really pleasant light colour; ...is too dark / is too bright; ...appears pleasant / appears unpleasant; ...is comfortable / is uncomfortable; ...I really liked / I really disliked.
- *(Perceived safety)* ...increases the perceived safety / decreases the perceived safety.
- *(Functionality)* ...enables a better orientation in the car interior / complicates the orientation in the car interior; ...facilitates the finding of controls / complicates the finding of controls; ...makes me more powerful / makes me less powerful; ...causes distracting reflections in the windshields / does not cause reflections in the windshields;
- *(Alertness)* ...distracts me from driving / keeps my attention on the driving; ...complicates the concentration / enables concentration; ...makes me tired / activates me; ...makes me sleepy / animates me.

The questions were presented in random order and so arranged that the positive sentences were equally distributed on both sides of the questionnaire.

The answers were given by the test persons on a continuous scale with a vertical line signalising the middle, as represented in Figure 4.

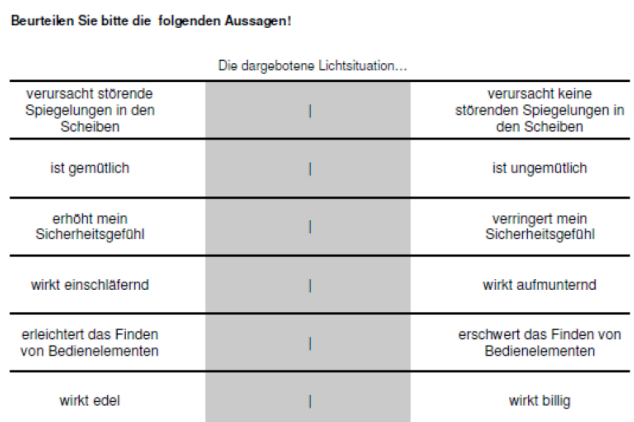

Figure 4 Example of the differential pairs questionnaire

Emotional state

Influences of the three lighting parameters on the emotional state of the test persons were also researched, using a Self-Assessment Manikin (SAM) procedure [4]. This questionnaire method, displayed in Figure 5, is based on the PAD Model (Pleasure-Arousal-Dominance), which has been already adopted to describe the emotional state caused by colours [17] and lighting situations [5] [6].

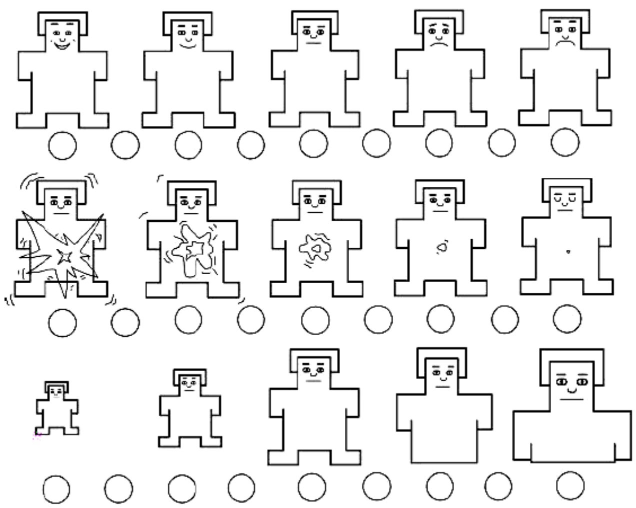

Figure 5 Self-Assessment Manikin (SAM) questionnaire **[4]**.

The three independent dimensions pleasure, arousal and dominance are assessed separately, by checking the box under the manikin which the test person feels more to his or her state. The pleasure dimension spans from happy, content (corresponding to 1 on its scale) to unhappy, displeased (9). Arousal mirrors the activity of the person, ranging from agitated, wide awake and aroused (1) to sleepy, calm and inactive (9). Dominance states if a person feels controlled (1) or rather in command of the situation (9).

The test persons were asked to fill out this form at the beginning of the test (in order to know the emotional state at the starting point) and after each experimental run.

RESULTS

Although the influence of ambient lighting on the emotional state of the test-persons could not be verified, this study confirmed that the different light scenarios significantly influenced space perception, perceived interior quality, interior attractiveness, as well as perceived safety and functionality. In particular the parameter colour had a great influence on the space perception and the attractiveness of the interiors.

Subjective perception of the car interior

In the following the results of the questionnaire on the subjective perception will be displayed. Different scenarios were compared in order to understand the influence of each parameter: brightness, position and colour of the lighting.

The significance of the results was assessed using a Wilcoxon test for two related samples of nonparametric data. No significant differences originated from differences in the test persons' gender or age.

Effects of brightness

The effects of luminance variations were verified by comparing the following settings: without lighting – everything on low level – everything on bright level with accents (scenarios 5 – 7 – 1).

The comparison between the scenarios "without lighting" and that "everything on – low level" showed highly significant ($p<0.01$) improvements for the second one in five criteria: space perception, interior attractiveness, functionality, perceived interior quality and perceived safety. Regarding the criterion alertness, no clear trend could be found: no degradation could be seen either.

Increasing the luminance and getting to the "everything on - bright level" scenario brought a significant ($p<0.05$) decrease in comfort, pleasantness and safety perception, increasing the distraction and complicating the concentration for the drive.

Luminance variations on single lighting elements produced no significant differences in the answer distribution, apart from the brightness assessment, in which the test persons recognized which scenario was actually brighter. Two comparisons were employed for this evaluation: doors bright – doors low level (scenarios 3 – 4) and foot space bright – foot space low level (scenarios 9 – 10).

The comparison between the scenario without ambient lighting and that with the centre console illumination (scenarios 5 – 11) is also interesting, because the latter represents the minimal ambient lighting that can be found in today's series cars. This kind of illumination provided better interior attractiveness and functionality ($p<0.01$), and improved perceived interior quality and space perception ($p<0.05$). This means that a minimum quantity of light in the car interior constitutes already a considerable advantage, regarding the subjective perception, in comparison to dark.

Effects of Colour

Two particular scenarios were assessed, which provided the same luminance level and same light positions, but different colours: orange and blue (scenarios 7 – 12).

It could be verified that the blue lighting appeared brighter than the orange and facilitated the finding of control elements, although being uncomfortable ($p<0.01$). Orange light colour looked more luxurious and gave a better quality perception ($p<0.05$). Few other effects could be told from the comparison of the mean answers, although they resulted not significant: blue light allowed a more complete perception of the car interior and enhanced the orientation, while orange light had a more pleasant light colour and was found more appealing.

Effects of Position

Three different lighting positions were evaluated: doors, centre console and foot space (scenarios 4 – 9 – 11). The differences between these three scenarios were quite small. As a trend it can be said that the more peripheral doors lighting offered a better perception of the whole interior and a higher perceived value, appeared more comfortable and pleasant and offered a better orientation. On the other hand the central illumination of the centre console facilitated the finding of control elements. The foot space lighting obtained slightly lower assessments than the other two illumination places, although the differences were not significant.

Effects on Driver's Emotional State

The results obtained from the Self-Assessment-Manikin test showed two aspects. On one side, there was quite a wide variance of the answers on the Pleasure and Arousal axis, this probably due to the different sensations and feelings which animated the different participants, independently from the test and the tested scenarios. On the other side the answers on the Dominance axis concentrated more on the middle point, this effect explained by the apparently difficult understanding of this dimension by the test persons.

In order to understand the change in the emotional state of the participants, each scenario rating was compared to the answer given at the beginning of the experiment. The difference between these two ratings gave a dimension of the emotional change caused by the scenario ($Δ = − 0$; $Δ = − 0$; $Δ = − 0$, where 0, 0, 0 are the values gathered at the beginning of the test).

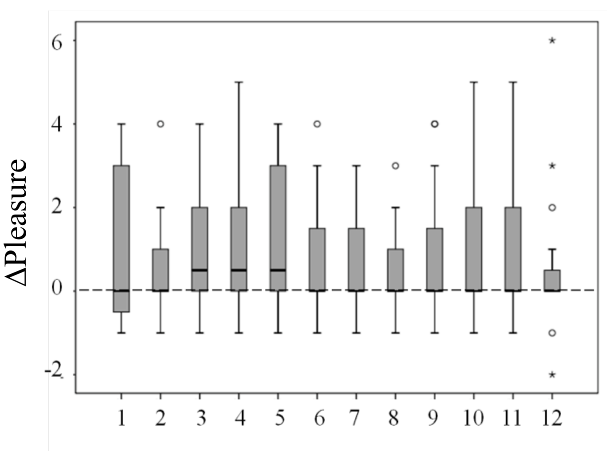

Figure 6 Boxplot graph of the distribution of the difference in the Pleasure rating between each scenario and the answer at the beginning of the experiment.

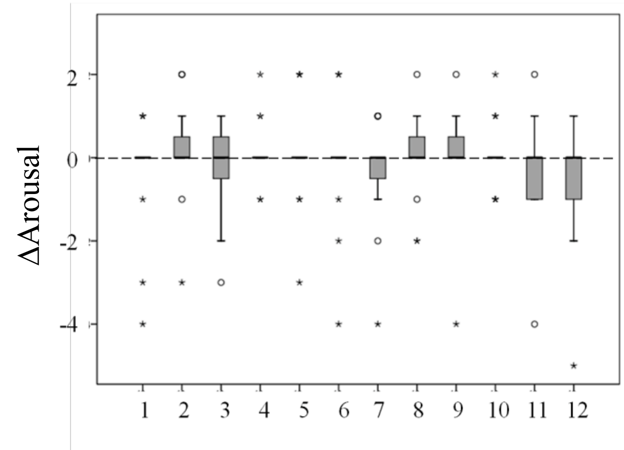

Figure 7 Boxplot graph of the distribution of the difference in the Arousal rating between each scenario and the answer at the beginning of the experiment.

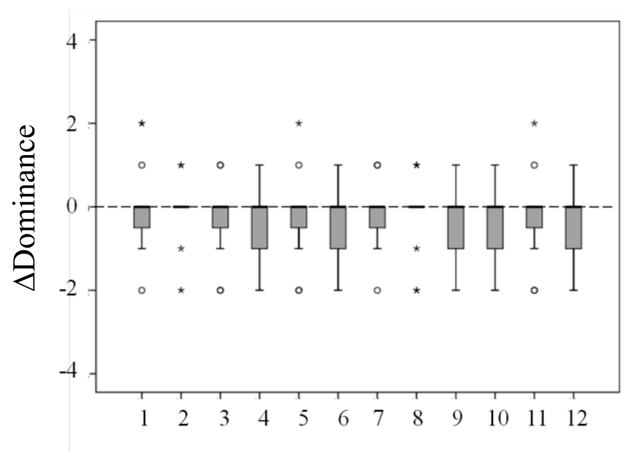

Figure 8 Boxplot graph of the distribution of the difference in the Dominance rating between each scenario and the answer at the beginning of the experiment.

The differences distributions are displayed in Figure 6, Figure 7 and Figure 8. Small changes can be seen in the dimensions of arousal and dominance, while in the pleasure dimension the distribution is wider. Though, the median value, represented in the graphs by the solid middle line, remains in most cases 0. Moreover, this distribution should not mislead in finding a negative trend in the influences of ambient lighting: many test persons judged their state at the beginning already "happy" (values 1 and 2 on the pleasure dimension) and therefore there was no room for improvement in the scenario ratings.

The data were analysed through a Friedman-test with p=5%. No significant effect could be found on any of the three dimensions. This has probably been caused by the short time (3 minutes) in which the participants tested the light scenario added to the lighting small luminance (maximum 1 cd/m²) and mostly peripheral position.

Effects on Driver's Performance

During the whole experiment the following data was collected by the simulator system: elapsed time, car position (x,y,z), absolute velocity, steering wheel angle, road curvature, distance from the road's edge and covered distance. Every parameter was collected with a frequency of 25 Hz.

The primary driver's task was to drive in the middle of the right lane of a three-lane highway, following another vehicle. The aim of the task was to focus the driver's attention on the street, thus enabling him to perceive ambient lighting only peripherally or through the secondary tasks.

These secondary tasks were designed to make the driver aware of the functionality of ambient lighting, in recognizing controls and objects inside the car. Without a proper lighting the test persons could not be able to push the right button, or find the control for the air nozzle.

Since the test persons could not accelerate and brake, the only parameter indicative of the driving performance is the distance from road's edge (D_e), measured in meters (Figure 9). Its standard deviation $\sigma(D_e)$ evaluated over the whole 3 minutes experimental run is indicative of the driver's performance in following the street lane in a specific lighting scenario.

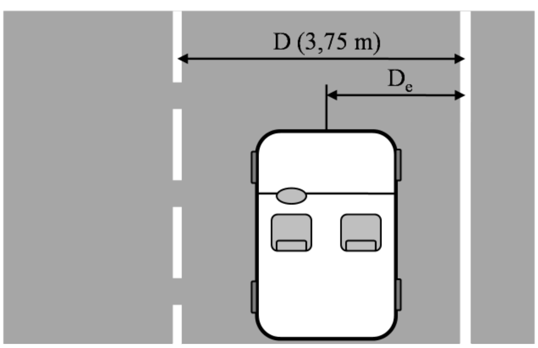

Figure 9 Distance from the edge of the lane, as measured on the simulator. The measure was taken from the middle of the car bumper to the virtual white line on the right side of the street.

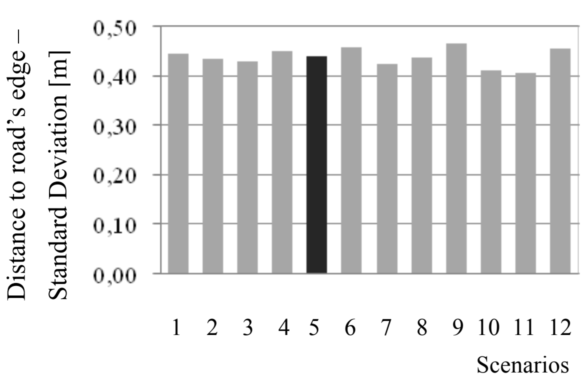

Figure 10 Values of $\sigma(D_e)$ in relation to lighting scenarios. With number 5 is highlighted the scenario without ambient lighting.

This data (shown in Table 5 and Figure 10) has been analysed through one-way ANOVA for the lighting scenarios. The results showed no significant dependency of the driving performance from the lighting situation in the car ($F= 0.226$ $\alpha=0.996$).

However, since this measure was not the primary goal of the research, it is difficult to assess its importance. For sure the driver's performance has not been influenced either way by the lighting scenarios.

Table 5 Mean values of $\sigma(D_e)$ in meters for each lighting scenario.

Lighting Scenario	**(D_e) [m]**
Everything on – bright level with accents	0.45
Series	0.44
Doors – bright level	0.43
Doors – low level	0.45
Without lighting	0.44
Everything on – bright level	0.46
Everything on – low level	0.43
Everything on – middle level	0.44
Foot space – bright level	0.47
Foot space – low level	0.41
Centre console	0.41
Everything on blue – low level	0.46

CONCLUSIONS

The presented study showed significant influences of ambient lighting on driver's perception. In particular the advantages of ambient lighting concerning space perception, functionality and perceived interior quality were clearly stated, even with low luminance levels. These advantages do not grow by simply using more brightness or by employing more light sources.

In the following the main conclusions which can be drawn by this experiment are listed.

- The whole perception of the car interior is improved through the use of ambient lighting while driving. It intensifies the space perception, enhances the perceived quality of materials and design, facilitates the finding of controls and the orientation in the car, and gives an improved perceived safety.
- A small number of light sources placed in order to cover the whole field of view can give equal results, in terms of perceived space and quality, as many overlapping light sources. Thus an aimed ambient lighting can use fewer components and reduce the production costs and though create a welcoming pleasant atmosphere in the car interior.

- A higher luminance level (mean values of 0.04cd/m²), while increasing the chance of creating discomfort glare and distraction during the driving, does not bring improvements to the driver's perception of the car interior or a better orientation and functionality. This means that darker, less expensive light sources can achieve the same comfort effects.
- The influences of different colours affect more criteria in different way. This has several causes: the diverse field of view and intensity of perception for each colour in the mesopic adaptation level (blue is perceived more intensively and on a wider angle as orange or red), the various emotional values and the different interaction with interior materials through reflection. Thus the choice of colour for ambient lighting has to meet more requirements, nonetheless brand identity and design compliance.
- Influences on the emotional state could not be verified, probably due to the short time available for the evaluation and the focus that the test-persons gave to the primary driving task. In other research studies, where the light stimuli constituted the main focus and the test was longer, such effects could be verified. Probably in order to discover more on this particular aspect, a different experimental design has to be employed.
- The driver's overall performance resulted to be uninfluenced by the ambient lighting, although this measure did only assess how the test persons followed the lane line. No measurements were made on the visual performances, since these have been already verified in other studies.

These results can be considered and used in the future development of such illumination systems, in order to optimize their design, reducing costs and energy consumption and though achieving an optimal subjective perception by the drivers.

On a practical level, from the investigated scenarios a guideline for developers and manufacturers, suggesting luminance levels and their tolerance ranges for ambient lighting systems will be derived.

Further researches should enlarge the spectrum of the investigated colours, which in this research were limited to only orange and blue. This comparison alone, although juxtaposing short wave and long wave colours, cannot describe completely the possible effects that different lighting hues have on the driver's perception of space and quality. In this perspective also the influence of the interior materials is important. Indeed, the most part of ambient lighting comes to the eye after the reflection on completely different kinds of material (e.g. from black plastics to beige or white leather). Thus the perceived situation should be considered not only in function of the lighting colour but also of the combination lighting-material. This topic is currently being investigated.

Moreover, dynamic interior lighting changes (in brightness, position and colour) and their effects have to be investigated. A further step in this direction will be the connection of these changes with inputs from the environment, the car and the passengers. This will provide on one hand adaptation of the interior lighting to the surrounding conditions and to the vehicle settings, enhancing safety and possibly giving a visible feedback of the car status. On the other side, flexibility and compliance to the customers' individual tastes will be ensured. The advantages and problems arising from such systems, as well as theirs acceptance by the drivers have still to be tested and verified. Nevertheless, they offer a new, interesting, emotional and much more coloured way of understanding and developing vehicle interior lighting.

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