Assessment Methods for Optimisation of Innovative Vehicle Interior Lighting

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Foreword

This work has been written during my time at the "mechatronical control panels and interior lighting" department at the BMW Group, and in collaboration with the lighting technology department at the TU Ilmenau.

This work would not have been possible without the precious help of many persons, whom I'd like to thank:

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My parents, Alfonso e Lorenza, to whom this work is dedicated, for all their love and dedication.

Grazie anche ad Annette.

Music, which has many aspects in common with light, in particular the capacity of creating deep and moving emotions in all of us.

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Abstract

Ambient interior lighting for vehicles provides an indirect illumination of the passenger compartment in low light settings. It has recently been gaining resonance in the automotive industry. Its advantages are in fact much coveted nowadays: a better orientation in the car, an improved sense of spaciousness, an impression of safety, value, and comfort.

In this work, the influences of ambient interior lighting for vehicles on the driver's perception and his emotional state have been researched. For this goal, three experimental studies have been carried out, two in laboratory conditions and one in real traffic conditions.

In these studies the participants experienced various ambient lighting scenarios while driving in a night time visual environment. For this purpose, two vehicle prototypes equipped with special ambient lighting fixtures have been employed: a BMW 3 series and a MINI Clubman.

The results allowed an insight into the driver's perception of ambient lighting. Lighting colour, luminance and position significantly influenced the perception in various manners. The independent categories *space perception and orientation, attractiveness and perceived quality,* and *perceived safety and attention* resulted from the analysis of the obtained data. Through them, an assessment of the effects of ambient lighting can be provided.

In order to render an objective evaluation, a measurement method was developed which takes into account position, luminance, and illuminated area for the ambient lighting features. The results were correlated to the subjective values of each lighting scenario, in order to define optimum values for such illumination.

Lighting colour also significantly influences perception, though a clear correlation between wavelength and impression cannot be drawn.

The knowledge of the subjective perception obtained within this work will support the industrial development process of ambient lighting from the conceptual layout on.

Zusammenfassung

Die Ambiente Beleuchtung im Fahrzeuginnenraum hat in den letzten Jahren eine zunehmende Bedeutung in der Automobil-Industrie gewonnen. Diese indirekte Beleuchtung des Fahrzeuginnenraums dient der Orientierung und erleichtert die Erkennbarkeit der Bedienelemente während der Nachtfahrt. Darüber hinaus werden das Design und die Wertigkeit des Innenraumes damit unterstützt.

In dieser Arbeit wurden die Einflüsse der Ambiente Beleuchtung auf die Wahrnehmung des Fahrers und auf seine emotionale Empfindung untersucht. Dazu wurden drei experimentelle Studien durchgeführt, zwei unter Laborbedingungen und eine Felduntersuchung.

In diesen Studien konnten die Probanden unterschiedliche Ambiente Beleuchtungsszenarien während realen und simulierten Nachtfahrten erfahren. Dazu wurden zwei Fahrzeugprototypen mit besonderen Ambiente Beleuchtung Merkmale ausgestattet: eine BMW 3er Limousine und ein MINI Clubman.

Die Ergebnisse dieser Untersuchungen ermöglichten einen Einblick in die subjektive Wahrnehmung der Ambiente Beleuchtung. Die Farbe, Helligkeit und Position der Beleuchtung beeinflussten signifikant die Wahrnehmung auf unterschiedliche Art und Weise. Die Analyse der Ergebnisse ergab drei unabhängige Kategorien, in den die Wahrnehmung unterteilt werden konnte: *Raumwahrnehmung und Orientierung, Wertigkeit und Attraktivität, Sicherheitsgefühl und Aufmerksamkeit*. Diese Kategorien ermöglichten eine Bewertung der Ambiente Beleuchtung.

Um die Resultate zu objektivieren wurde eine Messmethode entwickelt, welche die Position, Leuchtdichte und beleuchtete Oberfläche für jedes Lichtelement in Betrachtung berücksichtigte. Die Messwerte wurden zusammen mit den Ergebnissen aus den Probandenbefragungen analysiert, um die Werte für eine optimale Ambiente Beleuchtung zu ermitteln.

Die Lichtfarbe beeinflusst auch die Wahrnehmung, aber eine klare Korrelation zwischen der Wellenlänge des Lichtes und die Wahrnehmung konnte nicht ermittelt werden.

Die in dieser Arbeit gewonnenen Kenntnisse über die subjektive Wahrnehmung werden den zukünftigen Entwicklungsprozess der Ambiente Beleuchtung, von der Konzeptphase an, unterstützen.

1 Introduction

Until recently, interior lighting was the Cinderella of vehicle lighting. (Boyce, 2009) [6]

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 kind of illumination has drastically increased, up to a current maximum of about 25 LEDs, which is very likely to be exceeded by the next generation of vehicles. 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 [137]. 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 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 nighttimes driving.

1.1 Motivation

The development process of automotive ambient lighting components is currently influenced and driven by design, thermal, geometrical, electrical specifications, the willingness of the automotive industry to showcase the newest technologies in their vehicles, the need of delivering a branded interior impression at night, and costs pressure.

The aspect of how much light is really needed by the driver and by the passengers in order to feel comfortable and to add value to the experience of night drive is only marginally considered. Only at the end of the development process the brightness of the various LEDs in the car interior is adjusted subjectively by the developer. This final adjustment is normally on a more conservative level than the optimal one, in order to avoid possible glaring in case of bright colours of the interior materials. Sometimes it is so dark that customers do not even perceive the presence of the ambient lighting. Moreover, the communication between OEMs and lighting suppliers during the development of such lighting functions is somewhat problematic, since it must be dealt with only on a subjective level and not on specified measurable values.

Therefore, a method that clarifies which are the subjective goals of ambient lighting is needed. Also, the objective luminance levels, lighting positions, and colours needed to achieve these goals must be investigated. Such a method will support the development process, enable an objective comparison of market competitors, facilitate the communications between OEMs and suppliers, and guarantee a customer-oriented driving experience.

1.2 Previous research

Ambient lighting (and vehicle interior lighting in general) has not received the same attention provided to headlamps and exterior vehicle lighting in general. Nevertheless, there are several interesting studies which have dealt with the issue.

The main focus of these research studies has always been the conditions in which interior lighting impairs or aids driver's vision of the street and traffic environment. Presently, how ambient lighting is effective for the driver's comfort and subjective perception has not yet been studied.

OLSON [93] describes the effects of different reading lamps and dome lighting on the recognition distance of objects on the street. As a result, it is shown that passenger reading lamps have no significant effect on the recognition distance; dome lighting can reduce this distance dramatically.

DEVONSHIRE AND FLANNAGAN [21] have researched the distance at which a person walking at the edge of a dark street can be detected, while interior lighting causes a disturbing reflection on the windshield. This reflection varied in colour and brightness. The colours red, blue and white were employed, each in four luminance levels (0,5 cd/m^2, 0,13 cd/m^2, 0,031 cd/m^2, 0,0078 cd/m^2 measured on the windshield). The eight participants had to signal the moment in which they detected the person walking on the street, and on which side of the street. Moreover, they had to give an evaluation of the perceived brightness of the disturbing reflection on the windshield. The detection distance was maximal when no veiling luminance on the windshield was presented, but remained high also for small luminances. It diminished evidently on the two higher luminance levels. At a similar photopic luminance level, blue was always perceived brighter than red and white, due to the fact that photopic photometry misrepresent the perception of colours at mesopic adaptation levels. Nevertheless, colour had no significant effect on the detection distance.

Concerning ambient lighting issues, the following works can be cited.

GRIMM AND LÖBIG [46] stated that vehicle ambient lighting with luminances under 0,1 cd/m^2 has no effect on the readaptation time. This considers the changes in adaptation when the driver glances from the street surface to the vehicle interior and back. Therefore, the driver does not change his adaptation level while doing this, not wasting time in the readaptation.

GRIMM [45] [44] thoroughly investigated the discomfort glare caused by ambient lighting. The parameters used in his research are luminance, colour, position and dimension of the light source. In his experimental studies the test persons could rate their perception of the lighting area on a De Boer scale: 9 steps from *not perceived* (9), *just perceived* (7), *optimal* (5), *disturbing* (3), and *intolerable* (1). The results underlined that the most influential light sources are near the driver vision axis, and their influence grows with their dimension. Orange was the most accepted colour, followed by red, white and yellow. Green and blue negatively influenced the assessment. As a conclusion, he proposed a method for calculating, through luminance measurements, the discomfort glare of light sources in different positions and providing a global assessment on the glare, and therefore acceptance, of the whole ambient lighting system.

KNOLLMAN AND IVENZ [70] provided optimal luminance values for ambient lighting in different positions (headliner, footwell and door trims), discriminating between the age of the driver (young – old) and the driving situation (country road – city street). They also used a De Boer point scale for the brightness rating, *1* being too dark, *5* optimal and *9* too bright lighting. They pointed out that older people feel comfortable with a luminance about three times higher than younger people. In a city drive higher luminances are preferred. For example, an optimal luminance for the door trims is indicated at 0,066 cd/m^2.

The research carried out at TU Karlsruhe [36] [68][69] [74] [105] focused on the effect of ambient interior lighting in determining the contrast threshold of the driver. In these experimental studies, ambient lighting was displayed in different positions, colours, and luminances, while the participants had to detect the opening of a Landolt ring displayed on a monitor 20 metres away. The colours red, green, blue, turquoise, warm white, and cold white were tested. This research showed also that a luminance level which is subjectively accepted by the driver does not lead to any impairment of the contrast vision capability. In fact, in this case discomfort glare occurs at a lower luminance than disability glare. Moreover, this study suggested that short-wavelength light should be avoided for elderly people, since it led to a significant impairment of contrast vision. Though, for people younger than 40, this impairment was not verifiable. On the contrary, ambient lighting, despite the light colour, enhanced significantly contrast vision for people between 30 and 39 years-old. The proposed luminance levels in this experiment were however higher than normally presented in an ambient illumination: the measured spherical illuminance at the driver's eye spanned between 0,002 and 1,3 lx, while the maximum luminance of illuminated surfaces spanned between 2 to several hundred cd/m^2 [74].

WAMSGANß, EICHHORN AND KLEY [134] researched the acceptance by customers through a market study, stating that "*87% of car drivers would appreciate ambient interior lighting functions*". The most important advantages perceived by customers are: a better orientation in car interior (for 28% of the interviewed persons); an improved atmosphere (25%); an improved roominess (17%); a prevention of fatigue during long night time driving (12%); an improved visual acuity (9%); a better look (9%). Moreover, they study the effects on contrast threshold and subjective sensation (30 test persons). No negative effect can be detected under 0,1 cd/m^2, and *the measurement clearly points out that high luminance values are uncomfortable much earlier than a decrease of the objective contrast sensitivity is detected.* Furthermore, white light has a higher optimal luminance than green and red. Lowest luminance values are accepted for blue lighting. It is not explained in which point of the car the luminance was measured.

1.3 Task definition

From the above described research, it appears clearly that in the last decade a growing interest in vehicle interior lighting and ambient lighting has emerged. Obviously, this interest is continuously increasing due to a bursting implementation of these features in the automotive industry.

Many researchers focused on how new lighting features can positively or negatively affect the visual performance of a driver in night conditions and whether it causes secondary effects which could be dangerous, disturbing, or simply not wanted. This underlines the importance of safety during night driving, where an overproportional part of the car accidents and related fatalities in traffic happen [17] and where the visual task of driving is significantly more demanding than during the daytime [14]. Regarding this aspect, it has been reasonably proven that ambient lighting will not cause visual impairments, without being extremely uncomfortable and causing discomfort glare.

All of the researchers stated the importance of ambient lighting for the subjective perception of the car interior. Several also asked the participants of their studies how comfortable ambient lighting can be. Most of the researchers indicated optimal luminance values, but did not explain how to measure them in the real situations. Only GRIMM [45] outlined a method for measuring and verifying the luminances of different lighting elements in a car. KÖTH [74] eliminated the problem by measuring spherical illuminances at the driver's eye. These measures are however not easily replicable in a real situation, since no position information is given.

The problem presents two sides: a subjective and an objective side.

On the subjective side, we know that ambient lighting is *good*: improved orientation, space perception, value perception and many more advantages. It is still unknown if these improvements are significant and if there are particular lighting elements which influence more some aspects than others, and if there are colours which work differently than others. In fact, it should not be forgotten that at the mesopic adaptation level colours are perceived differently than in normal daylight, depending on their brightness and position in the visual field. The above mentioned researchers always ask if the lighting is too dark, too bright or optimal, but do not specify what optimal means, and that for every person could mean something different. Moreover, the emotional aspects of the perception of ambient lighting have not been yet researched.

On the objective side, it is known that ambient lighting is safe and does not affect the visual performance if it remains below certain luminance levels. In account of that, many ambient lighting systems are designed so that they are almost invisible. Still, the most difficult aspect in a real development process of ambient lighting is actually fixing an optimal brightness value for the lighting elements. No optimal value is specified and measured on a vehicle. The developers have to assess them on a subjective basis. Despite the thorough work of GRIMM [45], still no standard measuring method has settled in this area. The same problem is present in the homogeneity evaluation of the illuminated area, where no standard measurement is regularly employed. These issues account for difficult interactions between car manufacturers and suppliers during the development process of the lighting components.

In Figure 1.1 the two sides, subjective and objective, are show on a *components* level and on a *whole car* level. The grey area highlights which will be the topics of this work. The subjective impression of the single components is not considered, since it is difficult to correlate it to the perception of the whole interior.

The aim of this work is then:

- to point out which are the most influencing parameters in the subjective perception of ambient lighting and how they influence it
- to outline a consistent measuring method for ambient lighting elements
- to correlate the two aspects, in order to find a feasible optimum and have goal values for a development process.

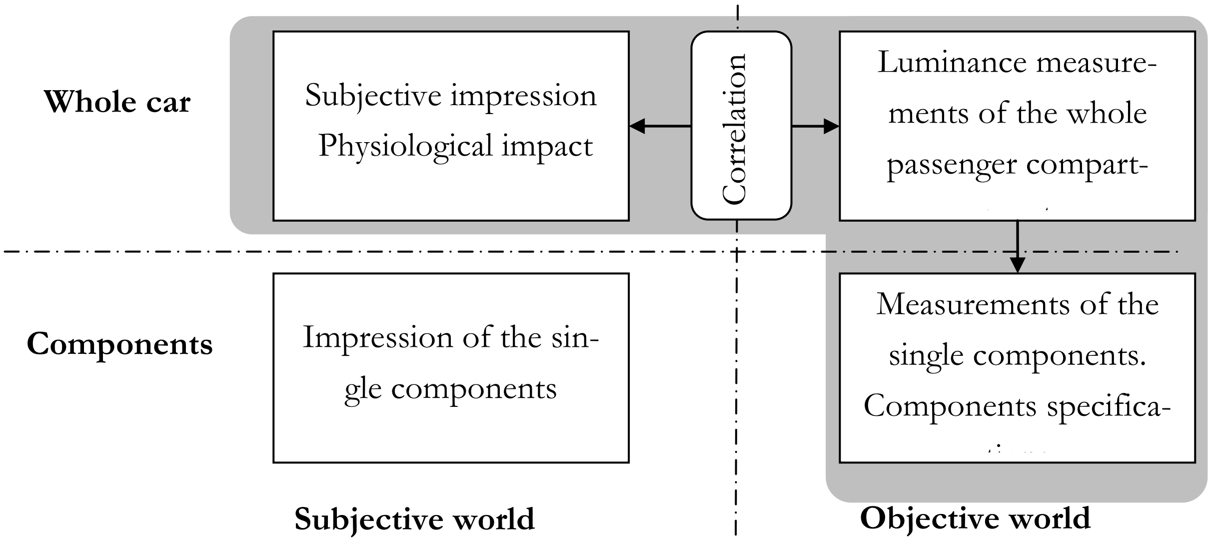


Figure 1.1: Overview of the aspects of ambient lighting considered in this work.

1.4 Outline

In chapter 2 the basis of visual perception will be described, in order to give a better understanding of the task of seeing in traffic. An overview of the state of the art of vehicle interior lighting will be also provided: technologies, functions and applications. Moreover, the current state of luminance measurements and similar research about interior lighting in architectural environment will be discussed.

In chapter 3 three experimental studies are described. These studies have been carried out in order to understand the subjective perception of ambient lighting, by varying the lighting parameters colour, brightness, and position. Two of the experiments have been carried out in a driving simulator in laboratory conditions, while the third was performed in real traffic conditions. These research studies employed a real vehicle, which guaranteed a real feeling and therefore realistic subjective assessments.

Chapter 4 deals with the mathematical analysis of the experimental data, the luminance measuring technique for car interior, and discusses the correlations between measured values and subjective impressions.

An outline of the method for measuring the lighting homogeneity of the single ambient lighting elements is provided in chapter 5.

In chapter 6 the conclusions from the whole work will be drawn, comparing them to the previous literature and suggesting an outlook on what future research should investigate and how future automotive ambient lighting could look like.

2 Basics

2.1 Visual perception

> *We take it for granted when we drive, that the world through which we travel contains objects. Indeed it does. But the objects you see in that world are entirely your creation. And that creation though usually useful, is nonetheless fallible. It is critical therefore, to understand the principles by which human vision creates its objects, and how automotive lighting can affect the process of object creation.*[137]

Humans perceive the majority of information about the external world through the visual system [116]. Visual perception is an extremely complex process, which involves the eyes and the brain, perception and interpretation.

In the following section the fundamental aspects of visual perception will be examined. These are needed to understand the driver's perception of his environment and of the car interior during night driving.

2.1.1 Visual system

The human visual system is constituted by the eyes, visual nerves and the brain. The visual information gathered by the eyes is communicated through the visual nerves to the brain, where it is interpreted.

In Figure 2.1 a section through the eye is shown. The eye is basically spherical with a diameter of about 24 mm. The light enters through the cornea, which is the front transparent area. Inside it a hole in the iris constitutes the pupil. Its size varies with the amount of light reaching the retina. After passing through the pupil, light reaches the crystalline lens, which can vary its focal length by changing its shape. The space between the lens and the retina is filled with the transparent vitreous humour. After passing through the vitreous humour light reaches the retina, where light is absorbed and converted to electric signals. The retina is a complex structure (Figure 2.2). It can be considered as having three layers: a layer of photoreceptors, a layer of collector cells which provide links between multiple photoreceptors, and a layer of ganglion cells. The axons of the ganglion cells form the optic nerve, which produces the blind spot where it passes through the retina out of the eye [6].

In the retina there are four photoreceptor types, each containing a different pigment and hence having a different spectral sensitivity. These types are grouped into two classes: rods and cones. Cone photoreceptors are divided in three types called short (S), medium (M) and long (L) wavelength cones, after the wavelength region where they have the greatest sensitivity.

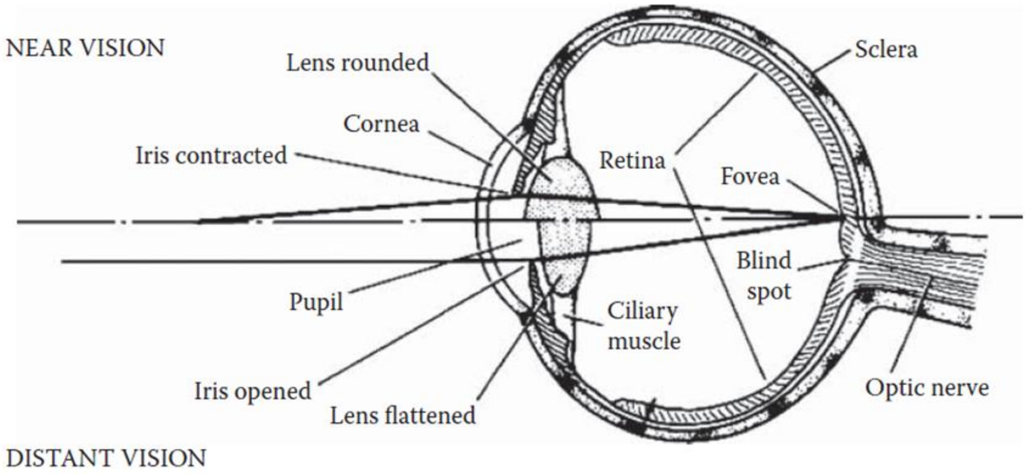


Figure 2.1 A Section through the eye adjusted for near and distant vision [6].

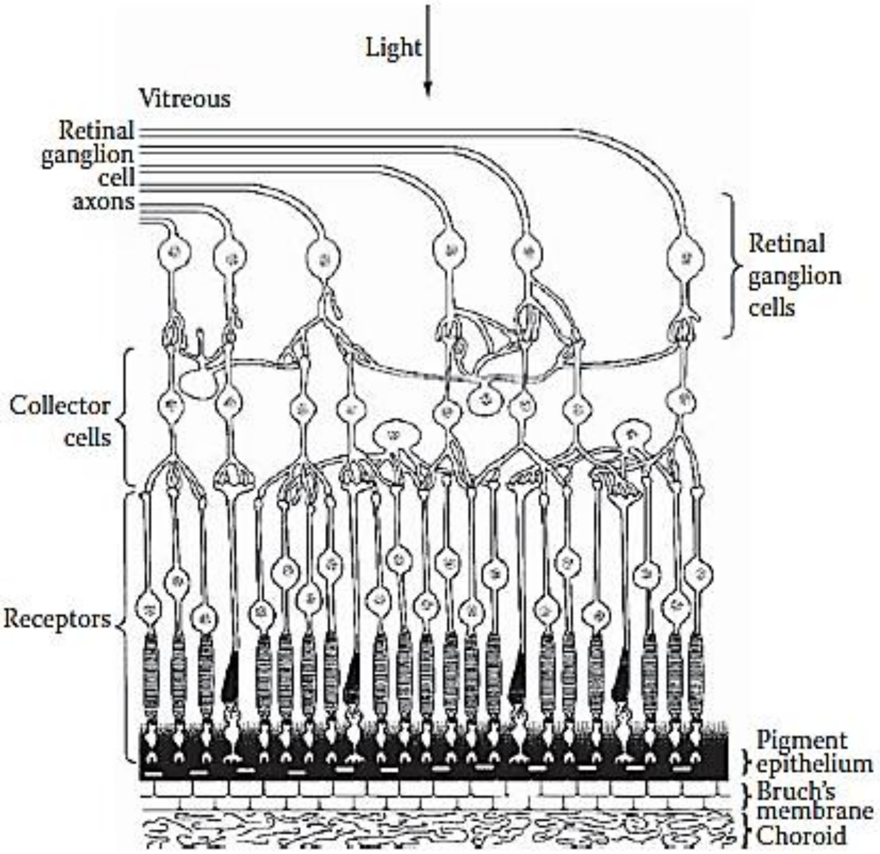


Figure 2.2. Cut of the retina. Light is coming from above, the receptors rods and cones are on the bottom. In the middle the nerve cells which gather the stimuli and bring them to the visual nerve [114].

The receptors are displaced on the surface of the retina in a non-homogenous way. This leads to a spatially non-homogeneous perception of colour and brightness between central

field of view (fovea), where only L- and M-cones are present, and the periphery, where almost only rods are present. S-cones have a maximum concentration just outside the fovea. Over the whole retina there are approximately 120 million rods and 8 million cones.
Human colour vision is based on the three different cone photoreceptors and therefore is trichromatic. Night vision, being based on rod photoreceptors only, is achromatic.

2.1.2 Spectral sensitivity

The *Commission International d'Eclairage* (CIE) in 1924 published, after a comprehensive research, a function for the spectral sensitivity of the normal observer for the day vision [16].The relative luminous efficiency function *V(λ)* (Figure 2.3) gives the basis for the photometric system, enabling the conversion from spectral radiometric quantities to photometric quantities. This function was defined with these conditions: eyes adapted to at least 10 cd/m² and foveal observation, with an angle of 2°. For scotopic adaptation level, which corresponds to night vision, the function *V'(λ)* was defined [16]. Its maximum is shifted in the blue area (Purkinje effect). Therefore, human eye is more sensible to blue light at a scotopic level.
In lighting practice all photometric quantities are measured using the CIE Standard Photopic Observer.

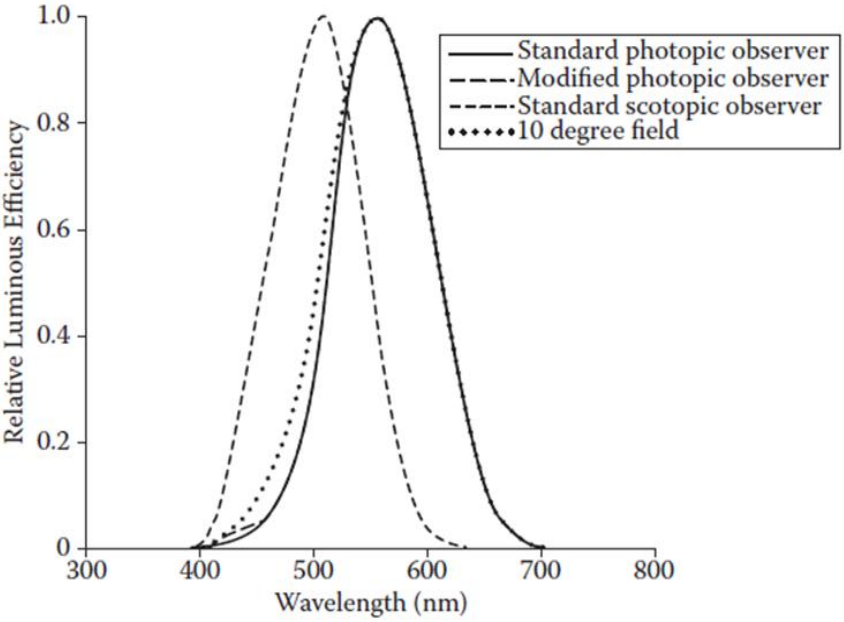


Figure 2.3 The relative luminous efficiency functions for the CIE Standard Photopic Observer, the CIE Modified Photopic Observer, the CIE Standard Scotopic Observer, and the relative luminous efficiency function for a 10-degree field of view in photopic conditions. [6]

2.1.3 Adaptation

In photopic conditions, i.e. during the day, the human vision employs almost only cones receptors, which enable colour vision. When the environmental light level diminishes, the visual system adapts to it with different mechanisms. These comprise the variation of the dimension of the pupil, neural adaptation, photochemical adaptation in the receptors and the switch of the receptors from cones to rods [71]. Under luminances less than 0,001 cd/m² scotopic vision occurs. For these luminances only rod photoreceptors respond to stimulation. This means that the fovea is blind and only shades of grey are perceived and not colours.

Mesopic vision is an intermediate between the photopic and scotopic states. In this adaptation level both rods and cones are active. However, their interaction and the combination of their signals in the brain is not linear. Therefore, the mesopic spectral sensitivity depends on environmental luminance, colours, solid angle under which the objects are seen, and their position on the retina. The threshold between scotopic and mesopic adaptation lies between 0,001 and 0,03 cd/m², while the one between mesopic and photopic vision lies between 3 and 10 cd/m² [100].

During a night drive the visual environmental conditions are mostly mesopic. In fact, street lighting, diffuse lighting or at least the headlamps on the street and the instrument lighting in the interior of the vehicle guarantee that the adaptation level is not scotopic [91] [130]. Therefore, it is important in the context of this work to understand the state of the art of the research on mesopic perception. In fact, even if photopic and scotopic vision characteristics are well known (cf. section 0), there is no such univocal standard analytic description of the mesopic vision [15].

ELOHOLMA AND HALONEN [28] as well as GOODMAN ET AL. [40] (MOVE consortium) defined a performance model based on driving tasks. Contrast threshold, reaction time and recognition of objects are used as criteria for defining the visual performance at different adaptation levels, from 0,001 to 10 cd/m². As a result they propose two models: a chromatic one which shows a three-peaks-behaviour for the spectral sensitivity and a simpler "practical" method in which the spectral sensitivity curve at mesopic level (named $V_m(\lambda)$) has a similar form to the photopic one. Although not precise in considering all the chromatic differences, the latter is presented as more useful in assessing most of the real driving situations. The practical model is based on the following formula, where $M(x)$ is a normalising function such that $V_m(\lambda)$ attains a maximum value of 1. The parameter x is a function of the photopic and scotopic values of the background.

$$M(x)V_m(\lambda) = xV(\lambda) + (1 - x)V'(\lambda) \quad (3.1)$$

Another model for mesopic vision was proposed by REA [100] [99], based on the work of HE ET AL. [51] [54]. This system, based on reaction times measured for off-axis recognition tasks, has also a similar approach as the MOVE, but considers the large field photopic luminous efficacy instead of the foveal:

$$V_{mes}(\lambda) = xV_{10}(\lambda) + (1 - x)V'(\lambda) \qquad (3.2)$$

The interpolation parameter x is different from the one proposed by MOVE, and has a value of 1 (photopic vision) at 0,6 cd/m^2.

Both formulas seamlessly link photopic and scotopic vision at the extremes of the mesopic field ($x=1$ and $x=0$ respectively). Both models fail to describe properly the brightness impression of the targets [99]. The different methods for calculating mesopic luminances were compared several times, but despite having different points in common, still a standard wide accepted model for mesopic vision is missing [29] [100] [127].

Other aspects have to be taken into consideration, although not described by the formulas. In fact, while mesopic vision in the foveal region is said to be similar if not the same as the photopic [49] [28], peripheral vision changes considerably in mesopic adaptation level [2] [11]. For example at 0,1 cd/m^2, the visual field is around 55° for red and 70° for blue and green [64], while in the periphery the contrast threshold increases, although not for the colour blue [98].

In general, in order to study night driving, it is of primary importance to understand how mesopic perception works. In particular, now that several technologies, such as LEDs, HID lamps, as well as normal halogen lamps, are competing in the fields of street lighting [88] and vehicle front lighting, it is most interesting how their different spectral distributions can affect the vision in mesopic condition and therefore the safety of night driving [47] [65] [67] [129].

Ambient lighting for vehicle interior generates luminances which lie in the mesopic adaptation level. Therefore, these pieces of research have to be considered, while presenting and commenting the results, since some effects of the lighting can be explained only by the different perception we experience in mesopic vision.

It could even be interesting from a scientific point of view also to measure the different ambient lighting scenarios employing the different models of mesopic photometry. Though, on one hand, there are still many uncertainties in the practical use of the above-mentioned models (which situation they best represent, which characteristics of perception are considered, if the perception of brightness can be represented, etc.). On the other hand, there is no practical interest in the automotive industry in proceeding in such a complicated and expensive way, at least concerning the ambient lighting applications. Therefore, in this work a method for measure and qualify ambient lighting luminance will be proposed, albeit only on a photopic basis.

2.1.4 Visual field

An important aspect about ambient lighting is that it is mainly perceived peripherally by the driver, who is mainly focused on the driving task. Therefore, a better understanding of the visual field is required. Due to the distributions of cones and rods on the retina, each colour has a different visual field. Moreover, these fields change between photopic and mesopic light levels.

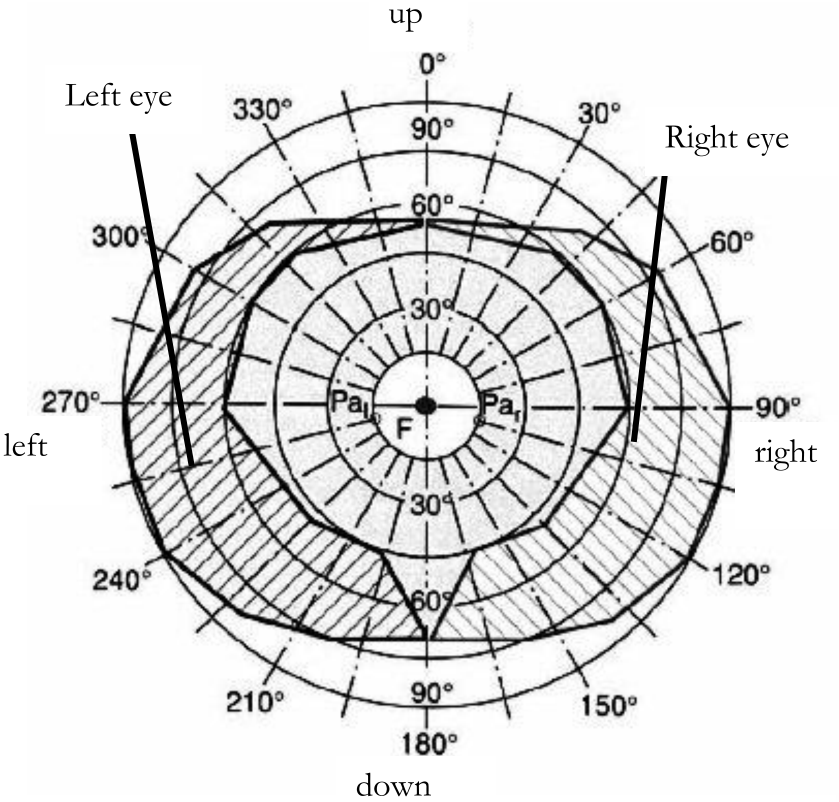


Figure 2.4 Visual field for binocular vision. *F* indicates the foveal area. *Pa* stands for the two eye blind spots [80].

While at a luminance of 5 cd/m² all the colours have a visual field of about 80°, at 0,1 cd/m² blue has a 70° visual field while red reaches 55°. On the other hand, blue has a higher contrast threshold in the foveal field: for blue light in mesopic conditions, peripheral vision becomes better than foveal vision [64]. The binocular visual field, for achromatic stimuli, is displayed in Figure 2.4. For achromatic stimuli, the visual field can reach 90°.

2.1.5 Perception

The perception serves the orientation. It makes a mental representation of the physical environment possible. This representation is in some aspects extremely reliable, in other aspects leads to false conception of the world. [61]

Since the perception of the environment while driving is extremely important for safety reasons, in the automotive field this topic has been and still is extensively researched. Pieces of information and possible risks have to be detected, recognised and elaborated by the driver, while reactions have to take place readily and without any useless error. This way of analysing the perception is called reflex system and is based on the causality chain of an input-output process: perception, detection, reconnaissance, elaboration and reaction are seen as a consequence of each other. The research in this field looks for methods to enhance each step of this process, in order to make it as fast and reliable as possible.

Sensations of comfort and well being are perceived through the visual system as well [110], in the form of visual comfort and through association patterns [55]. The perception of visual environment is realised through a model recognition process called "Look-Up"-Model [108]. According to this model the environment is perceived as a whole impression and is compared to mental concepts in 0 seconds [42]. These concepts are assimilated to semantic attributes (a qualitative aspect) and affective attributes (an emotional aspect), as displayed in Figure 2.5. A similar concept is used by GREGORY [41] for describing the interactions between knowledge and perceived reality, which then results in the behaviour and actions of a person (Figure 2.6).

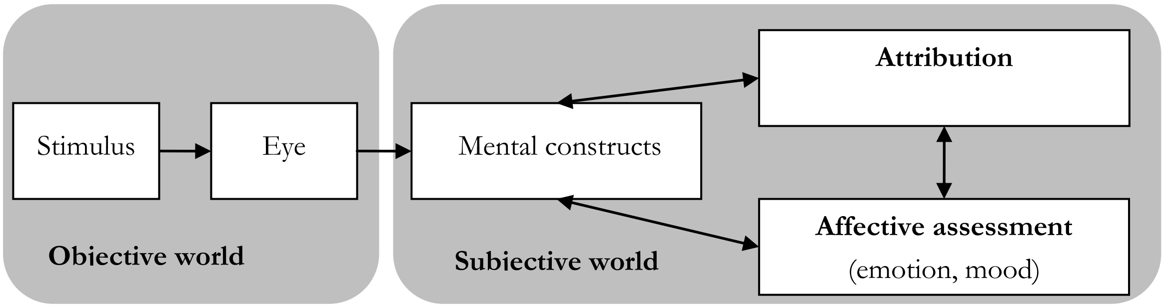


Figure 2.5 Visual perception model according to SCHIERZ AND KRÜGER.[111]

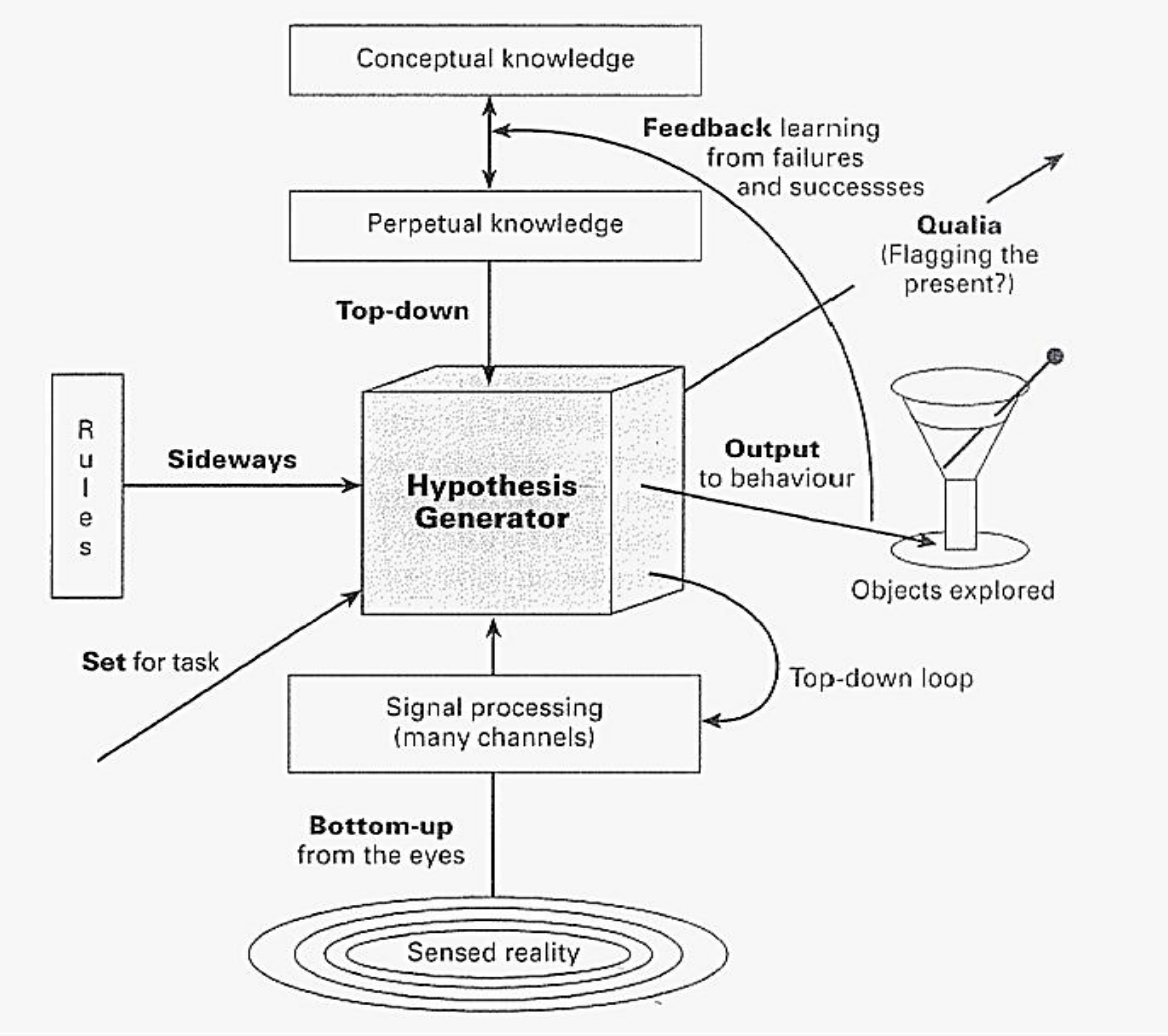


Figure 2.6 Perception model according to GREGORY [41]. Signals from the eyes are processed physiologically and interpreted cognitively by object-knowledge (top-down) and by general rules (side-ways). Feedback from successes and failures of action may correct and develop knowledge.

The qualitative aspect of the perceived reality can be described with adjectives, attributes or associations [110]. As an example of this, it can be considered the aspect of lighting colour. Colours communicate and are associated with moods, emotions, and concepts. Therefore, before implementing a specific colour in vehicle lighting, it is useful to know how it will interact with the customers' perception.

HELLER [53] collected the opinion of around 1000 persons about the association of 200 different words and concepts to colours. It is evident from her research that colours bear emotional, cultural and also functional messages. Although this aspect is not strictly quantifiable, it must be taken into consideration when evaluating colours for a vehicle illumination. In Table 2.1 some examples of which concepts are associated with determined colours are provided.

Considering all these aspects, it appears clear that the visual impression has to be analysed as a whole. This thought had a big influence on the design of the experiment performed in this research: real cars were employed, with ambient lighting systems properly integrated in the interior trims and realistic immersive environment has been employed. In this way no inconsistencies were introduced, due to for example possibly awkward experiment conditions. As an example, no proper assessment of perceived value can be conducted on an experimental rig with only a rudimentary vehicle form.

Table 2.1 Different colours and their emotional associations [53].

Colour	Association
White	Neutrality, truth, new, functionality, pureness.
Blue	Far, harmony, sympathy, trust, sportiness, power, cold, freshness.
Red	Love, energy, aggressiveness, danger, dynamic, attractiveness, warmth.
Yellow	Light, optimism, acid, dishonesty.
Green	Nature, lively, young, comfortable, relaxing, safety, venom, hope.
Orange	Extroversion, funny, cheapness, sociability, delight
Black	Might, magic, elegance, conservative, heavy, empty, brutality, bad.

2.1.6 Emotional aspect of the visual perception

The emotional aspect of the visual perception can be described by the Pleasure-Arousal-Dominance model by RUSSELL AND MEHRABIAN [85] [86], which classifies each emotional state, mood, and emotional association in a three dimensional space. The three independent dimensions are *pleasure*, spanning from joy and satisfaction to pain and sadness; *arousal*, which measures the activity or sleepiness; *dominance* quantifying the feeling of control upon the situation.

VALDEZ AND MEHRABIAN [123] proposed several formulas which connect hue, brightness and saturation of a given colour to the emotional parameters pleasure, arousal and dominance which the colour induces. 250 persons were interviewed, giving their impression of the proposed colours on a semantic differential questionnaire. The colours were shown in the form of 8 x 12 cm cards. As a result, it was stated that bright and saturated colours give a higher pleasure score; blue, green, red, and violet colours have a better pleasure assessment than yellow and yellowish-green; brighter not saturated colours cause less arousal; darker saturated colours cause a dominant feeling.

The following formulas were provided: $Pleasure = 0{,}69B + 0{,}22S$; $Arousal = -0{,}31B + 0{,}60S$; $Dominance = -0{,}71B + 0{,}32S$; where B stands for brightness and S

for saturation. Regarding the hue: $Pleasure = 1561 - 5{,}48w + 0{,}0048w^2$; where *w* stands for the wavelength in nm. Effects of hue on arousal and dominance were extremely weak.

Similar results, especially the weak influences of hue on emotions, were found by SUK [119] in an international research study. Notably, colours in the blue hue category turned out to be significantly more positive and more dominant than the others. Due to the international character of this research (persons from Germany and South Korea were interviewed), an extensive use of the SAM Manikin [79] was made, in order not to introduce biases due to the different languages.

2.1.7 Circadian effects of lighting

Light has a significant influence on the melatonin suppression of the human body, and therefore on the sleep-wake rhythm of a person [117] [109]. In particular, exposure to blue light determines a shift of this rhythm [10] [121].

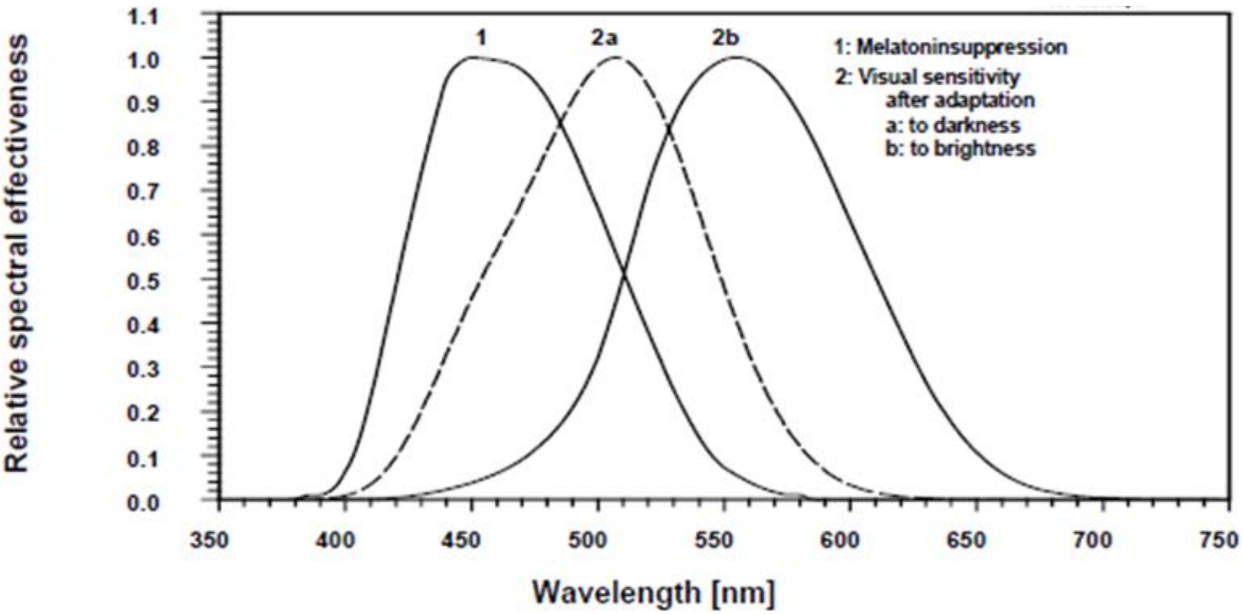


Figure 2.7 Circadian relative sensitivity $S_{ms}(\lambda)$ (1) for the suppression of melatonin, compared to $V(\lambda)$ (2b) and $V'(\lambda)$ (2a) [25] [38].

The sensitivity of the eye for this effect is displayed in Figure 2.7. It has been a common thought, that applying such blue light in vehicle interior could help maintaining the driver awake during a night drive, increasing safety [136], as happens in an office environment, where cold white or blue enriched lighting can increase alertness [128] and sleep quality [57]. In a vehicle, a predestined position for this kind of awakening light would be in the centre roof node. Though, in order to have a significantly physiological effect on the driver, there should be at least 200 lx [84] [129] or 500 lx [101] at the eye level of the driver. Similar results were obtained by POPP [97], who studied the effect of blue light on the driver's alertness and vigilance. Significant effects were obtained starting from 2500 lx on the eye of the test person.

It has not been a goal of the present research to determine whether a particular ambient lighting could affect the physiological alertness state of the driver, since the necessary illuminances for this effect to appear are far too high for such lighting in a vehicle. These would surely lead to a strong disability glare. Nevertheless, the test persons were asked if lighting can generate a subjective impression of alertness.

2.2 Vehicle interior lighting - State of the art

2.2.1 Functions of vehicle interior lighting

No law regulations exist nowadays for vehicle interior lighting, although 36% of all drives take place during night time [50]. The lighting functions present in modern vehicles can be grouped in two categories: functional lighting and emotional lighting. From this consideration are excluded the backlighting for symbols in buttons and controls, and the illumination of instrumentation and displays. These kinds of lighting contribute to the illumination of the vehicle interior as well, but their function is basically providing information for the driver and the passengers, so they won't be considered here.

Functional lighting

Functional illumination is normally white and has the precise function to provide a definite brightness in the car interior. So the general interior lighting, which is normally located in the roof node, provides a diffuse illumination of the whole interior. The reading light (or map light) provides a focused illumination on the passenger's lap. Similarly the glove compartment illumination, the trunk light and foot space lighting provide illumination in their aim areas. Make-up light is used in combination with a convenience mirror.

All of these lighting functions have common specifications: they have to be glare-free, provide enough light in a specified area with certain homogeneity, and with a defined colour rendering index. These specifications are easily derived from their function. For example a reading lamp should provide around 30 to 50 lx on the passenger's lap, without causing glare or distraction for the driver; moreover an homogeneous light distribution is required, so that the passenger can read comfortably. The make-up light needs a really high colour rendering index.

Some authors describe as *orientation lighting* [131] [137] a functional illumination which helps finding control elements in the centre console and provides a spatial and three dimensional impression of the interior. This kind of lighting is normally associated with ambient lighting and actually cannot be distinguished properly. Therefore, it will be treated here as part of emotional lighting. In fact, the first examples of ambient lighting in vehicles were mainly conceived as an orientation illumination for the centre console.

Emotional lighting

The main goal of emotional lighting is to underline the interior design and provide comfort and well-being impression to the driver and passengers. Its peculiarity is to be active while driving, constituting an orientation in the dark passenger compartment. The emotional aspect is underlined by the fact that different lighting colours are employed for it, conveying to the car interior often a brand specific atmosphere.

Ambient lighting is an emotional lighting which provides an indirect illumination of the vehicle interior. Such illumination has been implemented in premium cars since the mid-nineties. The first examples of ambient lighting were constituted by a centre console lighting, placed in the interior lighting module [78]. Nowadays, different ambient lighting elements are implemented in the interior of premium cars: the centre console, as well as the door trims and foot space and parts of the roof can be illuminated with indirect lighting.

The emotional lighting elements which provide direct illumination are referred to as accent lighting. These were employed in several series vehicles in the last years. The main issues connected to the implementation of such lighting are mainly the avoidance of glaring and the conveyance of homogeneity to the whole lighting surface.

Control strategy

Currently the control of interior lighting systems is relatively simple, and is realised by connecting them to simple triggers: opening the doors or stopping the motor usually triggers the interior lighting, while ambient lighting is often connected to the front lighting system.

The idea of using the numerous light sources in car interior for a dynamic staging is not new: automatic interior lighting control has already been proposed on a conceptual level [4] [20]. A further concept is the *leading light,* which shall lead the attention of the driver to the controls or information he needs or should activate [132]. Premium car manufacturers are introducing these features in higher segment vehicles since few years: the driver can decide which colour and intensity shall illuminate the single parts of the vehicle interior. Though, due to cost factors these features are still not wide available on series production vehicles. An automatic lighting control shall include: *control of light functions, change of light colours, adaptation to the psychological conditions, change of light intensity, individual change of presets, respect the physiological boundaries, consideration of the environment* [133].

2.2.2 Light sources in vehicle interiors

In today's vehicle interiors more than 200 light sources can be found [131]. The majority is constituted by symbols backlighting for buttons, controls, and instruments.

For the technical implementation of interior lighting concepts with new lighting functionalities, new requirements for light sources and optics unfolds. Thus, requirements for minimum installation dimensions, high light intensities and homogeneous appearance are generated.

The technologies most commonly adopted in vehicle interior lighting nowadays and their technical advantages and drawbacks in this particular application are shortly discussed in the following.

Filament bulbs

Light bulbs produce light by heating a thin tungsten filament to incandescence in an inert gas atmosphere. The spectral emission of this light source is a continuum over the visible spectrum. The exact spectrum is determined by the temperature of the filament.

Light bulbs are still the predominant light sources inside the vehicle for functional applications, such as interior light and reading light. Advantageous are the broad spectrum, the available high luminous flux and the low cost [3]. On the other hand, the short lifetime and low efficiency, the needs for large installation space, and the high temperatures generated are problems.

Electroluminescence foils

Electroluminescence (EL) foils are characterized by small installation depth, low-current consumption, homogeneous luminance, and a variety of colours which can be manufactured using different pigmentations. Because of poor lighting performance, the relatively poor colour rendering, and the critical characteristics with high temperature and humidity (i.e., short circuits in case of penetration of moisture in the casing) EL foils are not well suited for functional applications in the interior lighting. Though, the implementation of EL foils in the vehicle interior is conceivable for surface ambient light and even various orientation applications. This technology can also be used in the backlighting of materials used for trim components (e.g., wood or chrome strips), which can have a natural appearance in daylight, and backlit providing ambient lighting during the night time.

EL foils are typically driven with a frequency of 400 Hz and a voltage of 115 V. This causes problems on its electromagnetic compatibility with other electrical devices in the vehicle [131]. In this configuration, the EL foil can generate a luminance 10 to 60 cd/m² [31]. A further drawback is constituted by the high manufacturing costs.

Light Emitting Diodes (LED)

Due to their small size, high durability, low power consumption, low heat development, and fast response time, LEDs are suitable for an always increasing number of functions in the interior lighting [131]. Nowadays LEDs are mainly employed for backlighting of symbols, buttons, and displays. Ambient lighting as well is a main application area for LEDs. Some manufacturers have recently begun to introduce white LEDs also for functional lighting. Though, their application in this area has been slowed down by the still relatively high production costs in comparison to filament bulb lamps, and their lighting properties, notably colour rendering and spectral power distribution. Nevertheless, the improvements that this technology has undergone in the last years speaks for an always more intensive application in the automotive industry, in the car exterior as well as in the car interior.

New measuring systems and scales are being investigated, in which the characteristics of the LEDs should be best identified [24] [72]. New colour rendering indexes are also being investigated, which take into account the positive effects of LEDs light, and not just their difference to a glowing light source [82] [90] [120] [125].

LEDs are usually controlled through Pulse Width Modulation (PWM) signals. Though, on account of their fast response time there can be disturbing effects if the employed frequency of the impulse carrier is too low (e.g. 80 Hz) [135] [137]. This phenomenon is sometimes referred to as *Ghost Lighting*. Ambient lighting does not cause such phenomenon in normal applications. Though, if the passengers can look directly in the light source, or if a large part of their body is illuminated and they move quickly or if they move their eyes quickly, they can perceive a kind of disturbing stroboscopic effect. A small portion of persons (just 1‰ of the whole population) can resolve more than 90 Hz. Research in this field has been carried out and is being carried out, though still not giving a threshold frequency above which all ghost effects in all applications are not perceived. By using a frequency above 150 Hz and reducing the LED luminance, this disturbing effect diminishes and eventually disappears [113].

Organic light emitting diodes (OLED)

Organic light emitting diodes (OLEDs) use organic materials for light generation, in contrast to the above described inorganic light emitting diodes. Given their flat form and homogeneous lambertian light emission, they are particularly well suited for backlighting and luminous displays [89] [48]. In fact, they are currently widely adopted for displays in consumer electronics products. The current photometric properties of OLEDs are still too low, especially in comparison with LEDs, [52] to allow their implementation in series production vehicles, although having a broader emission spectrum.

Their use for illumination purposes is currently still associated with high costs. However, further developments can be expected in the medium to long term [75], which will bring flat lighting solutions in vehicle interiors, but presumably not before 2015 [87].

2.2.3 Typical light levels during night driving

Depending on the environmental situation, on the road surface and in vehicle interiors different light levels are present. A drive on a highway presents different lighting values as a drive on a city street or a country road, depending on the street lighting fixtures and their placement, the traffic in opposite direction, etc. In these three situations the driver's visual behaviour changes[22] [23].

Table 2.2 Typical luminance values in a street environment [118].

Light source	Luminance [cd/m²]
Starlit night sky	ca. 10-11 … 0,02
A pedestrian lit by dipped beam	0,05 … 1
Unlit street surface by night	0,01 … 2
Street with artificial lighting	0,2 … 5
Road markings (lit)	3 … 30
Road signs lit by headlamps	5 … 100

The environmental light alters the driver's adaptation state and therefore has an impact on the perception of ambient lighting.

The luminance level of a normal street surface is between 0,01 cd/m² und 0,1 cd/m² without street lighting and between 0,1 cd/m² und 5 cd/m² if the street is provided with fixed lighting [11] [30] [60] [63] [129]. In Table 2.2 typical luminances of a night drive are listed.

In the vehicle interior the environmental light is reflected by the interior trims, which have very different reflection properties, depending on their colours and materials. In Table 2.3 the reflection coefficients of several interior materials are listed, in relation to LED sources of different colours. It can be appreciated how these reflection properties depend on the lighting spectra.

Table 2.3 Reflection coefficient of different vehicle interior materials, depending on the illumination colour. All the light sources are LEDs. White is generated by the combination of red, green and blue light.

Lighting colour (LED)	**White**	**Red**	**Green**	**Blue**	**Orange**
Dominant wavelength	632 + 523 + 465 nm	632 nm	523 nm	465 nm	605 nm
Brown leather	0,13	0,16	0,11	0,04	0,15
Green leather	0,43	0,31	0,40	0,20	0,32
Walnut leather	0,29	0,40	0,22	0,06	0,38
Red leather	0,20	0,42	0,08	0,04	0,24
Yellow plastic	0,68	0,78	0,56	0,11	0,76
Dark Blue plastic	0,08	0,06	0,07	0,07	0,06
Green plastic	0,13	0,06	0,13	0,05	0,08
Black textile	0,04	0,03	0,04	0,02	0,04
Beige textile	0,47	0,46	0,42	0,16	0,47
Gray textile	0,28	0,22	0,29	0,15	0,26

2.3 Spatially resolved luminance measurement

Luminance measurements are fundamental for this work and its implications in the industry. In fact, by means of this technique, all the lighting sources in the car can be measured by their luminance and their luminance distribution in the visual field of the driver.

This lighting measure technique has been allowed by the last technological steps in the field of CMS sensors. It consists in taking digital pictures through cameras and objectives calibrated against $V(\lambda)$ (CIE Standard Photopic Observer, cf. Section 0) and then evaluating them with dedicated software. In this way, luminance pictures are obtained, in which every pixel represents a measured value. The main advantage of this measuring system is that it offers a representation similar to the brightness impression of the human eye. Though, adaptation level and perception mechanisms are not taken into account. In the automotive industry this kind of measurement is already extensively in use to qualify the instrumentation lighting and symbols backlighting [76] [112], as well as the light emission and appearance of headlamps and rear lamps [66] [102]. This measurement technology is currently also used in the analysis and qualification of workplace illumination [37] [111] [92], street illumination [88] and circadian effects of lighting [39].

A similar technique has already been employed for the evaluation of vehicle ambient lighting [45] [70], though providing only mean luminances indications and not clear indications on the luminance distribution and position. For the same purpose, KÖTH [74] preferred spherical illuminance measurements, connected to maximum luminances by a factor which is comprised between 1 and 5 cdm^{-2}/mlx. Also here, spatial information is missing.

2.4 Assessment methods for interior lighting systems

Although the task of evaluating the subjective impact of a lighting system is a novelty in the field of automotive interior, numerous research studies have already been carried out within the scope of lighting design in buildings and in office environments. In these studies it was shown that lighting has significant effects on comfort, mood, emotion, and the perception of the space, value and function of the rooms in which the lighting is installed.

MCCLOUGHAN et al. [83] declared that room illumination has systematic influences on the mood of the persons. Significant changes in it can take place even in a time span of 30 minutes. KÜLLER et al. [77] researched these influences in a long time study with about 1000 test persons in offices in Great Britain, Argentina, Sweden and Saudi Arabia. The psychological mood was measured through 12 semantic differential pairs. It was at its minimum when the illumination was perceived as too dark. The mood was at its maximum when the light level was perceived as just right. With a brighter lighting the mood was assessed low again. The decisive factor was the perceived brightness and not the measured illuminance at the workplace.

VEITCH et al. [126] studied systematically the interactions between illumination and well-being, acceptance, and work performance of the workers. The illumination influenced not only the visual performance and through it the work performance, but also the acceptance and therefore the mood and well-being. Moreover, these aspects influenced themselves reciprocally.

FLEISCHER [33] studied the effects of different combinations of natural and artificial lighting and their dynamic variation during the daytime on the motivation and emotional state of staff members in office environment. She found out that the emotional state was influenced by the lighting set ups, and that their effect was dependent on the time of the year and on the weather situation.

GREULE [43] carried out similar research studies for the application of coloured LED technology in interior lighting for airplane passenger compartments. A coloured illumination was projected on a cabin mock-up and was assessed by participants in a PAD Model (cf. section 2.1.6) by means of a SAM-Manikin questionnaire [79]. As a result, blue and cyan colour were assessed more comfortable than yellow and red, while red was followed by green as most inspiring and stimulating colour and blue was assessed as not stimulating. Of interest 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.

LOE and ROWLANDS [81] proposed a lighting design which is based on the criteria of architectural integration, visual function, energy efficiency, installation maintenance, costs and visual amenity in an holistic approach. BOYCE [7] tried to define lighting quality, by putting lighting parameters in connection with visual performance and human performance, mood and task performance in a suggested conceptual framework.

Regarding vehicle interior lighting the following quality criteria have been provided. KLEINKES [66] indicates colour, pulsation, illumination level, illumination distribution, absence of glare, rendition of the space. WÖRDENWEBER et al. [137] group three main criteria: visual environment (shadows, light direction, light colour), visual comfort (harmonised light levels, colour rendition), visual performance (brightness levels, contrast, and glare reduction). A very similar picture is given by NACHTIGALL [89]. Although giving important hints on what to give attention to in the development of lighting systems, these authors do not provide recommended values.

3 Experimental studies

Ambient lighting is said to increase perceived value as well as space perception. Though, no precise studies were made on these effects, and it is not effectively known if and how ambient lighting is really perceived.

Therefore, in order to understand the influences of ambient lighting on the driver's perception of the car interior, three experimental studies were carried out.

The first one –which in the following will be called study A – will be described in section 3.3. It was carried out in laboratory conditions, in a driving simulator, employing a BMW 3 Series. It focused on the effects of different luminance levels and lighting positions [12] [27].

The second experimental study – study B – is dealt with in section 0. It was carried out in laboratory conditions using a MINI Clubman prototype as test vehicle. The study focused on the perception of different colours, while maintaining constant luminance level [58].

The third experimental study – study C – will be described in section 3.5. It was carried out with the same vehicle and with the same design of experiment which was used in study A, on a real street with real traffic conditions. This study was conceived as a verification of the results of the laboratory studies.

3.1 Evaluation objectives

The literature provides several pieces of research focused on ambient lighting (cf. section 1.2). All of them concentrate on possible impairments or improvements to the driver's visual performance caused by internal illumination while driving.

In the tests featured in this work, influences on visual performance were researched only marginally. The focus laid in the experience of night driving with or without various feature of ambient lighting.

Therefore, several choices were made, which defined the experimental design. In particular:

- The test persons shall experience the lighting while driving, in order to provide real assessments on what they saw and perceived, and not just a vague rating on "how could it feel like to drive in an environment like this". The studies aimed to create realistic conditions, in order to enable realistic reactions in the participants and therefore their realistic assessments. This is also the reason why it was chosen to let the participants drive and not just sit in the car, looking around and assessing the ambience.
- The lighting equipment shall be perfectly integrated in the vehicle's interiors. Only real cars were employed, which provided the quality feelings of series productions vehicles.

> The ambient illumination elements which were installed were integrated in the trims and fugues and were not directly visible by the driver.

The main targets of the research were the subjective impression and emotional state. Additionally, in studies A and B an indicator of the driving performance in the driving simulator was gathered. Preference of the brightness level for orange, red, blue and green lighting colours in static conditions were also asked, and also the favourite ambient lighting colour in the RGB colour space. Moreover, in study A it was also asked which lighting elements were consciously recognised during the drive, providing material for a comparison between the conscious perception and unconscious effects of ambient lighting.

3.2 Method

Research studies A and B featured similar methods and conditions, while differing in the purpose of evaluating different influence parameters. Therefore the research methods and the common parts will be described in this section, while the dissimilar aspects, like the featured ambient lighting scenarios, the specific questionnaires and the demographic description of the test persons, will be dealt with separately in the dedicated sections.

Both studies featured an immersive virtual test environment, in which the 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 experimental run.

3.2.1 Experimental setup

Both tests A and B took place in a static driving simulator at the BMW Group research and innovation centre [59]. 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 reliability of the results.

The test vehicle was connected to the driving simulator by means of sensors attached to the steering wheels. These sensors provided the instantaneous steering angle of the car. In this way, it was allowed to the driver to steer the car, but not to accelerate and brake, since the brake and acceleration pedals were not connected. A collision with the preceding vehicle (which the driver had to follow) was impossible because of the control logic 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 recommended [30] [60] as well as the measured street luminances in reality [17] [19] [26].

In Figure 3.1 a schematic representation of the experimental setup is given. The test person sat in the vehicle, while the experimenter sat in a separate control room. The communication with the test person took place through a microphone and loudspeaker system which was housed in the back of the car. From the control room the experimenter could start and stop the simulation program, set the lighting scenarios and control the acceleration and braking of the test car. In study B a particular toggle pad control, mounted on the steering wheel, was provided, so that in static situations the brightness and colour of the lighting scenario could be controlled also by the test person.

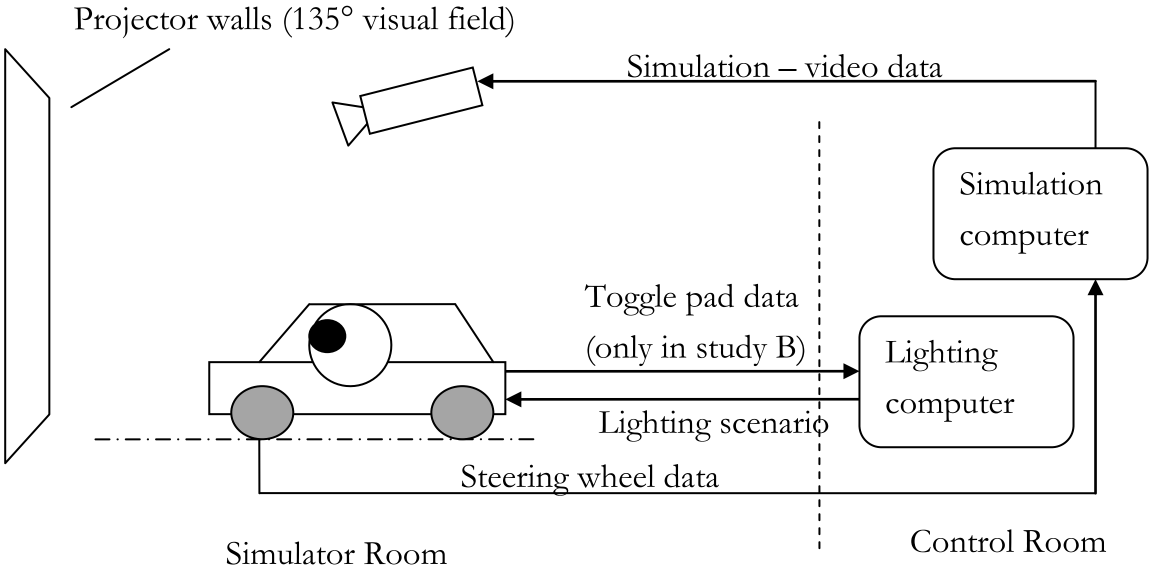


Figure 3.1 Schematic layout of the experimental setup for studies A and B. A computer situated in a separated control room was controlled by the experimenter. It generated the simulation which was projected on the screen. The sensors placed on the front wheels provided direction data. The lighting scenarios inside the car were also controlled by a computer in the control room. In study B it was also possible for the driver to influence the lighting by pressing a toggle pad on the steering wheel.

3.2.2 Execution of the test

At first the test persons were asked to fill out a general questionnaire, dealing with their data and the general attractiveness of ambient lighting. After the execution of the Ishihara Colour Vision Test [62] (all the participants had a good colour vision) the simulator room was darkened. The test persons had ten 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 three 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, 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 three minutes, the ambient lighting was turned off and the vehicle was stopped by the investigator and brought on the side-strip. The simulation carried on, like in a normal traffic situation. The participants then completed the questionnaire relating to the perceived lighting scenario. To allow this activity the driver reading lamp was dimmed on. Its brightness was chosen as low as possible, in order not to change the driver's adaptation level, but still enough to guarantee an adequate readability of the presented questionnaire (10 lux measured at the reading point, 15 cm above the driver's knees). Since the aim of the experiment was to collect the impressions of the driver while he was focused on the driving task, ambient lighting was turned off during the filling of the questionnaire. In this way, the perception gained during the actual experimental run was not influenced by possible different aspects noticed or discovered during the stop. Contrarily, the lighting scenario displayed in the stop situation was clearly acknowledged as not to be assessed. Moreover, the questionnaire was proposed during a stop in order not to influence the driving performance.

The whole process was repeated with all the proposed lighting scenarios (twelve in study A, ten in study B), which were presented in random order to each test person.

3.2.3 Questionnaire

Subjective impression

As the main instrument for gathering evaluations on the impressions of ambient lighting, semantic differential [94] was used. Semantic differential scales and questionnaires are employed as valid instruments for describing subjective impressions related to lighting situations in many different contexts, from street lighting [8] to interior lighting [37] [56] [104] [111], and for developing an understanding of higher-order human reactions to illuminated environments [122].

In the studies A and C the same questionnaire was used, which consisted of 18 differential pairs. It featured a continuous scale, as shown in section 3.3.3. In study B the questions were twelve, on a seven steps scale (cf. section 3.4.4). These modifications were originated by the feedback obtained in study A, in order to make the filling of the questionnaire easier and faster.

Emotional state

Influences of the lighting parameters on the emotional state of the test persons were also researched, using a Self-Assessment Manikin (SAM) procedure [79]. This method, displayed in Figure 3.2, consists of a non-verbal graphic questionnaire based on the PAD Model (Pleasure-Arousal-Dominance) [86] [85] (cf. Section 2.1.6), which has been already adopted to describe the emotional state caused by colours [123] and lighting situations [43] [34].

The Self-Assessment Manikin was chosen since it can be answered in a shorter time than other methods for assessing emotional states, like the Semantic Differential Scale devised by Mehrabian and Russell [86], which consists of 18 bipolar adjective pairs. Nonetheless, the results acquired with this simple method hold a strong correlation to the results obtained through more complex tests [9].

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.

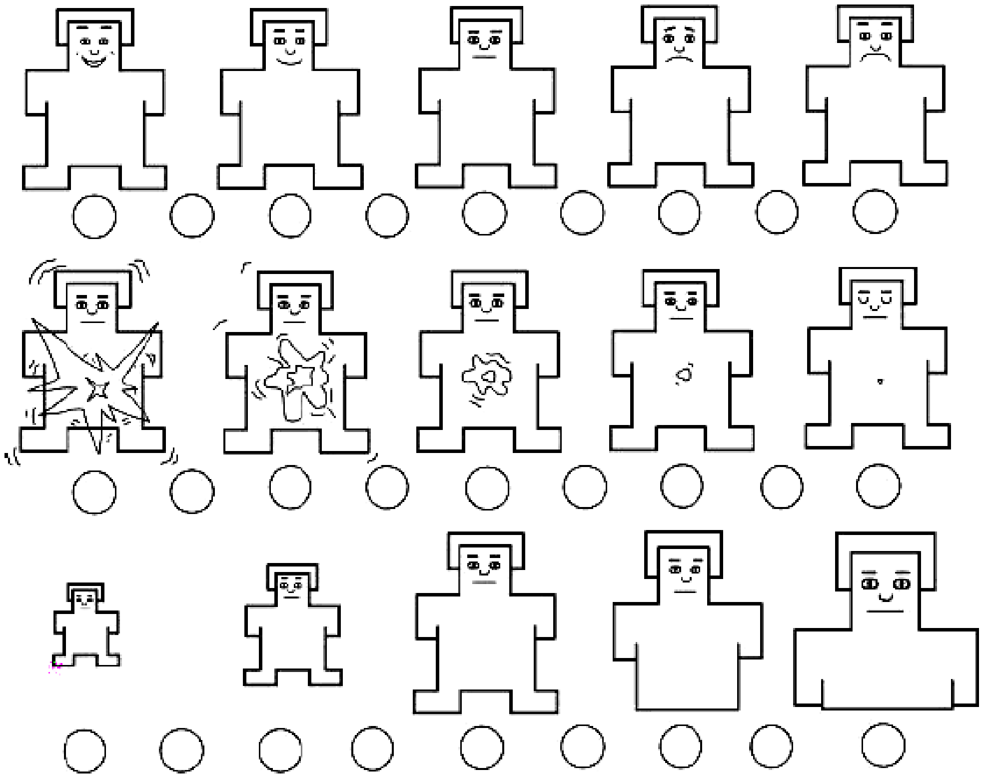


Figure 3.2 Self-Assessment Manikin (SAM) questionnaire [79][32]. The three manikin rows refer to pleasure, arousal and dominance dimensions, from top to bottom.

3.2.4 Driver's performance

In studies A and B, a measure of driving performance was calculated by interpreting the data protocols of the simulator. 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 3.3). Its standard deviation $\sigma(D_e)$ evaluated over the whole three minutes experimental run is indicative of the driver's performance in following the street lane in a specific lighting scenario.

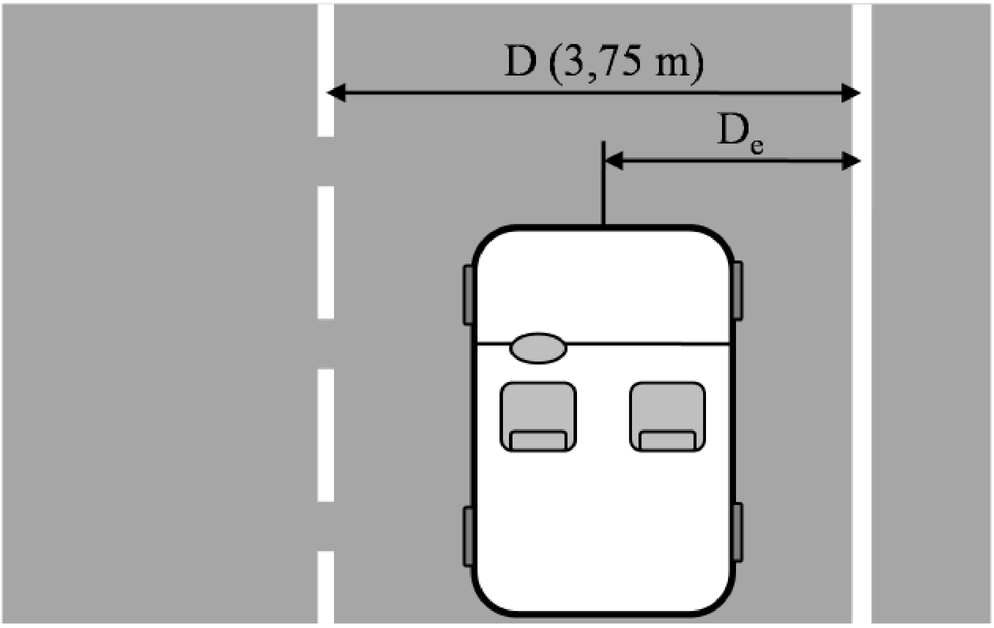


Figure 3.3 Distance from the edge of the lane, as measured on the simulator. The measure was taken from the middle of the car bumper to the virtual white line on the right side of the street.

3.3 Experimental study A: driving simulation with a BMW 3 Series

3.3.1 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.

3.3.2 Ambient lighting scenarios

In the test vehicle, which was provided with a brown leather interior and black plastic trims, twelve different ambient lighting scenarios were realised (Table 3.1). Three parameters were varied: colour, position of the lighting sources, and luminance as described in Table 3.2.

Table 3.1 Description of the tested lighting scenarios. Each scenario apart from A12 featured orange lighting colour.

Nr.	Lighting Scenario
A1	Everything on – bright level with accents
A2	Series (Centre console + Door trims)
A3	Doors only – bright level
A4	Doors only – low level
A5	Without lighting
A6	Everything on – bright level
A7	Everything on – low level
A8	Everything on – middle level
A9	Foot space only – bright level
A10	Foot space only – low level
A11	Centre console only
A12	Everything on blue – low level

Table 3.2 Experimental parameters. Areas are considered illuminated by ambient lighting only when their luminance lies between 0,002 and 0,3 cd/m²

Parameter	States
Colour	Orange (605 nm) Blue (471 nm)
Position	Centre console only Doors only Foot space only Series (Centre console + Door trims) Complete
Mean luminance in the illuminated area	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. The spectra of the LEDs mounted on the experimental vehicle are shown in Figure A.1 in the appendix. Each light source was provided with both colours.

Lighting positions were selected among the ones commonly adopted in practice in the automotive industry (Figure 3.4).The centre console light consisted of two LEDs hidden inside the roof node and illuminated 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 inside the cockpit and faced downwards illuminating the pedal area, on both the driver and passenger sides.

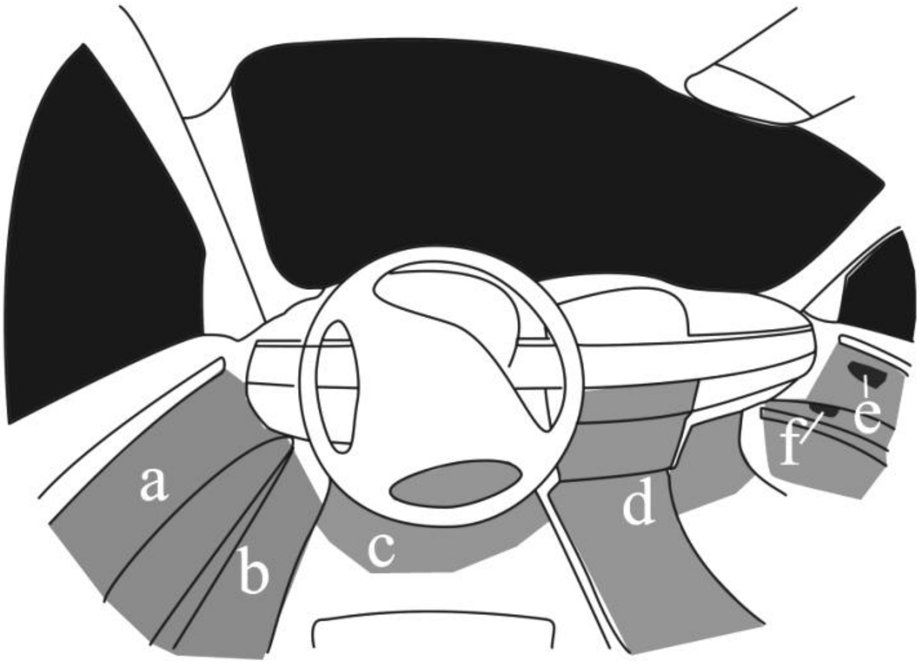


Figure 3.4 Positions of the ambient lighting. a. door trim, b. map case, c. foot space, d. centre console. With e. and f. the accents on the right door are highlighted (door handle and door pull respectively). These two zones were present on both doors; on the driver door they are omitted for more clarity.

The illumination of each door consisted of two modules, each composed by one LED feeding a linear light guide which distributed homogeneously the light from its side. One of these modules illuminated the upper part (door trims), the other illuminated the lower part (map case) of the door. Both modules were hidden under specific gaps realised in the geometry of the door. Their combination provided a homogeneous coverage of the whole door zone. All light sources were hidden to the driver's view and the ambient lighting was perceived only through the reflection on the interiors.

The particular combination of door trims lighting and centre console lighting is a common setting in series-production vehicles of different car manufacturers and therefore was named series lighting (displayed in Figure 3.6). The setting "everything on" included all the abovementioned 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, each illuminated respectively with one LED) with higher luminance (in some points up to 2 cd/m^2). Cockpit instruments and backlit symbols were always turned on, as in a real night drive situation. It could be argued that the perception of ambient lighting and of the whole car interior is influenced by the instrumentation lighting and its reflections. In order to solve this problem, the luminosity level of these elements was kept constant during the whole esperiment. This luminosity was chosen to be the middle value in the range of the series-production settings. The navigation system display was turned on and showed a constantly black screenshot. An example of ambient lighting scenario and its interaction with instrumentation lighting is provided in Figure 3.5.

Figure 3.5 Experimental vehicle interior. Scenes without any ambient lighting (left) and with an ambient lighting scenario provided with centre console and doors illumination, including door handles and pulls (right). The instrumentation lighting is always turned on at a constant luminosity level. The display in the centre is on, showing a constant black screenshot.

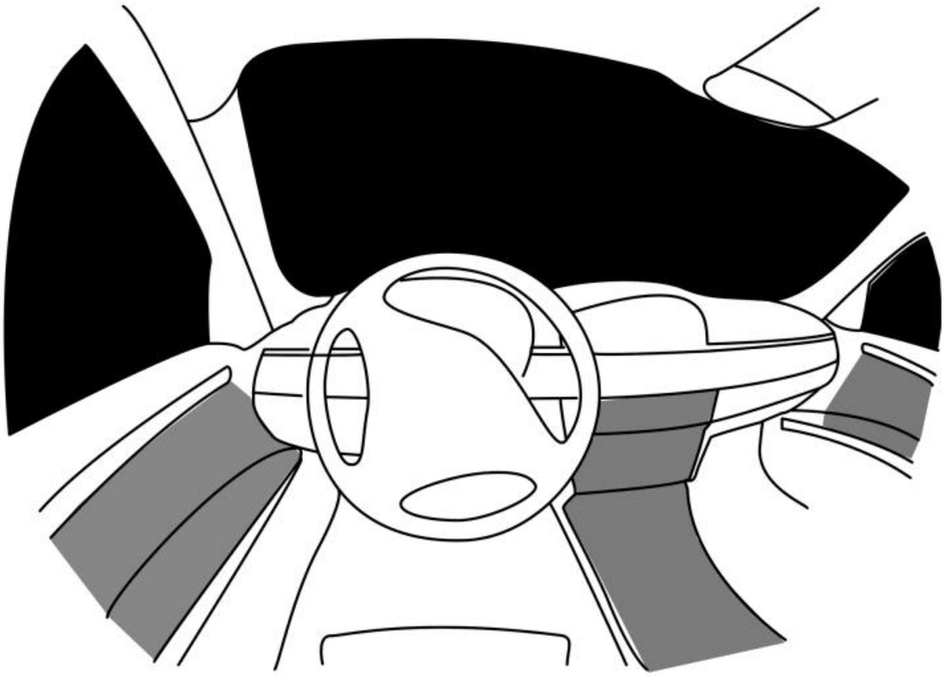


Figure 3.6 Example of lighting scenario: series setting - centre console and upper door trims are on.

3.3.3 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 ratings, listed in Table 3.3, were normalised in a scale going from 0 to 1, 0 being the worse quality of the differential pair and 1 the optimal quality. Only in one case the optimum was in the middle of the scale, namely the question *is too dark/is too bright*.

The questions were grouped in the six criteria as 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 3.7.

Table 3.3 Semantic differential pairs proposed in the questionnaire. The ratings were given between the two extremes 0 and 1, proportionally to the point where the test persons crossed on the continuous scale (see Figure 3.7). *The displayed light situation...*

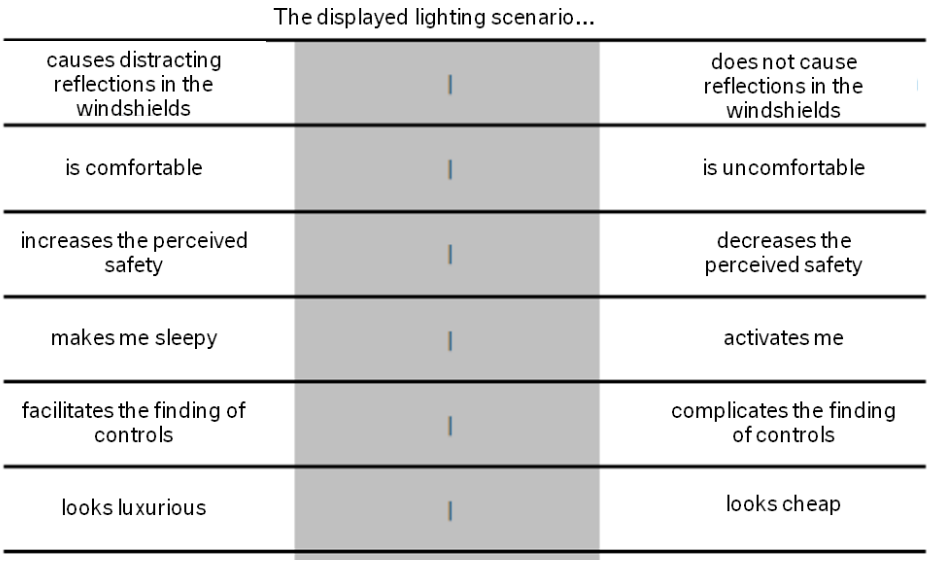
Question number	**Element (0)**	**Element (1)**
1	causes a small impression of interior space	causes a big impression of interior space
2	does not allow the perception of the whole car interior	allows the perception of the whole car interior
3	has a really unpleasant light colour	has a really pleasant light colour
4	I really disliked	I really liked
5	is too dark	is too bright
6	appears unpleasant	appears pleasant
7	is uncomfortable	is comfortable
8	gives a lesser quality impression	gives a good quality impression
9	looks cheap	looks luxurious
10	makes me less powerful	makes me more powerful
11	complicates the orientation in the car interior	enables a better orientation in the car interior
12	complicates the finding of controls;	facilitates the finding of controls
13	causes distracting reflections in the windshields	does not cause reflections in the windshields
14	distracts me from driving	keeps my attention on the driving
15	complicates the concentration	enables concentration
16	makes me tired	activates me
17	makes me sleepy	animates me
18	decreases the perceived safety.	increases the perceived safety

3.3.4 Effects on the subjective perception

In the following the results of the questionnaire on the subjective perception will be displayed.

The mean values and standard deviations of the answer distribution are listed in Table A.4 in the appendix.

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 nonparametrically distributed data. No significant differences originated from differences in the test persons' gender, age, experience in lighting technology, or use of glasses. The significance levels of each comparison are listed in Table A.6 and Table A.7 in the appendix.



The displayed lighting scenario...

causes distracting reflections in the windshields	|	does not cause reflections in the windshields
is comfortable	|	is uncomfortable
increases the perceived safety	|	decreases the perceived safety
makes me sleepy	|	activates me
facilitates the finding of controls	|	complicates the finding of controls
looks luxurious	|	looks cheap

Figure 3.7 Example of the differential pair questionnaire

Effects of brightness

The effects of luminance variations on the whole vehicle interior were verified by comparing the following settings: *without lighting, everything on - low level, everything on - bright level with accents* (scenarios A5 – A7 – A1). This comparison can be seen in Figure 3.8.

Between the scenarios *without lighting* and that *everything on low level* there are highly significant (p<0,01) improvements for the second one. Only in the questions 14 and 15 (attention on driving, enables concentration) no significance was obtained. Only in the question 13 (reflections in the windshield) the scenario with everything on scored less than the scenario without lighting. This showed a clear preference for ambient lighting in every 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 scenario *everything on - bright level with accents* brought a significant (p<0,05) decrease in comfort, pleasantness and safety perception, increasing the distraction and complicating the concentration for the driver.

The intermediate steps between scenarios A7 and A1 are now examined: scenarios *everything on – middle level* (A8) and *everything on – bright level* (A6), shown in Figure 3.9. Increasing luminance from *low* to *middle* level (A7 - A8) provided slight increases in the scores, but without significant differences, apart from question 15 (enables concentration).

Increasing again the luminance from *middle* to *bright* (A8 - A6), caused a decrease in almost every rating. The assessment on attractiveness and perceived interior quality scored significantly worse (p<0,05), while perceived safety and alertness had highly significant (p<0,01) differences.

Adding accents (A6 - A1) caused a highly significant decrease in attractiveness and quality impression, while causing distracting reflections in the windshield (p<0,01).

Summarising, a low level luminance induced many advantages in comparison with no lighting at all in the interior. By increasing the brightness, an optimum in many criteria was reached (scenario A8) and then the scores decreased rapidly, in particular in the attractiveness, perceived quality, and perceived safety criteria.

Space perception and functionality were not too much influenced by variation in brightness of ambient lighting. Attractiveness, perceived quality and perceived safety were clearly influenced and showed an optimum area.

These results can be seen also in the answers to the question *I really liked/I really disliked*, where scenarios A8 and then A7 obtained the best results. Both scenarios were also judged as having an optimal brightness (question 5), while scenarios A6 and A1 were assessed as excessively bright and scenario A5 as too dark.

The comparison between the scenario without ambient lighting and that with the centre console illumination (scenarios A5 – A11, the results are displayed in Figure 3.10) 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 a dark interior.

Two comparisons were employed for the evaluation of luminance variations on single lighting elements: *doors bright – doors low level* (A3 – A4) and *foot space bright – foot space low level* (A9 – A10). The results of these two comparisons are plotted respectively in Figure 3.10 and Figure 3.11. This variation produced no significant differences in the answer distribution, apart from the brightness assessment in the doors' comparison, and the impression of space in the foot space one.

Effects of Colour

Scenarios A7 and A12 provided similar luminance levels and same light positions, but different colours: orange and blue. Their comparison offered several significant differences. 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. An overview of these scores is given in Figure 3.13.

Effects of Position

Three different lighting positions were evaluated: *doors, centre console* and *foot space* (scenarios A4 – A9 – A11). Although the differences between these three scenarios were quite small, several significant differences were found. The foot space lighting obtained slightly lower assessments than the other two illumination places. Compared to doors lighting, foot space lighting (scenarios A4 – A9) allowed a worse perception of the whole car interior, complicated the concentration ($p<0,05$) and was found to be cheaper, less comfortable, and pleasant ($p<0,01$).

Compared to centre console lighting, doors lighting (comparison A4 – A11) was assessed to be brighter ($p<0,01$), allowed a better perception of the car interior, looked more luxurious, and had an activating effect while complicating the finding of controls ($p<0,05$).

The overview of this comparison is given in Figure 3.14.

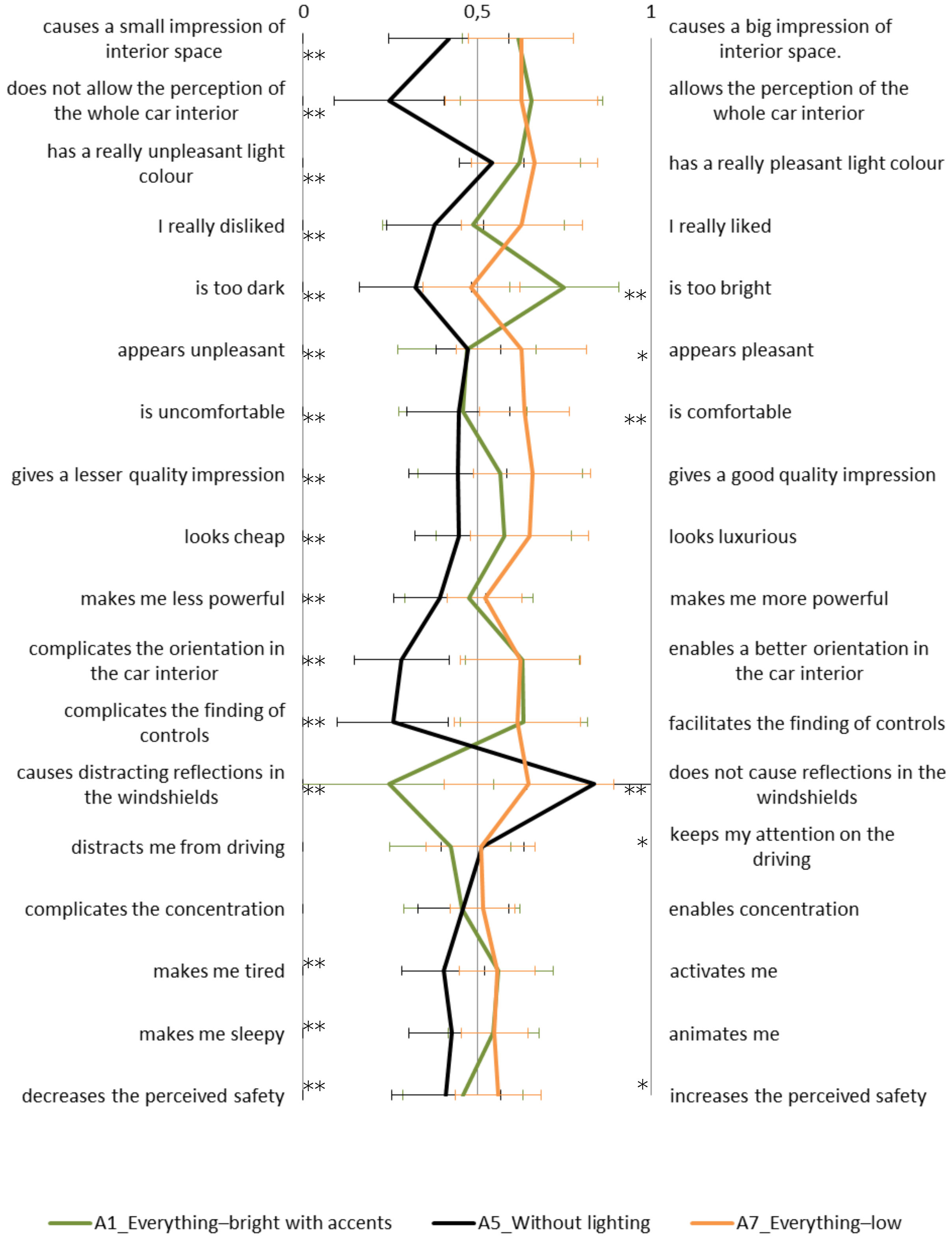


Figure 3.8 Results of the questionnaire on the subjective perception in study A. The comparison on the brightness of the whole vehicle is provided. For each question the mean value and the standard deviation of the answers are represented. Highly significant (p<0,01) (**) and significant (p<0,05) (*) differences are indicated, on the left side regarding the comparison A5-A7, on the right side for A7-A1.

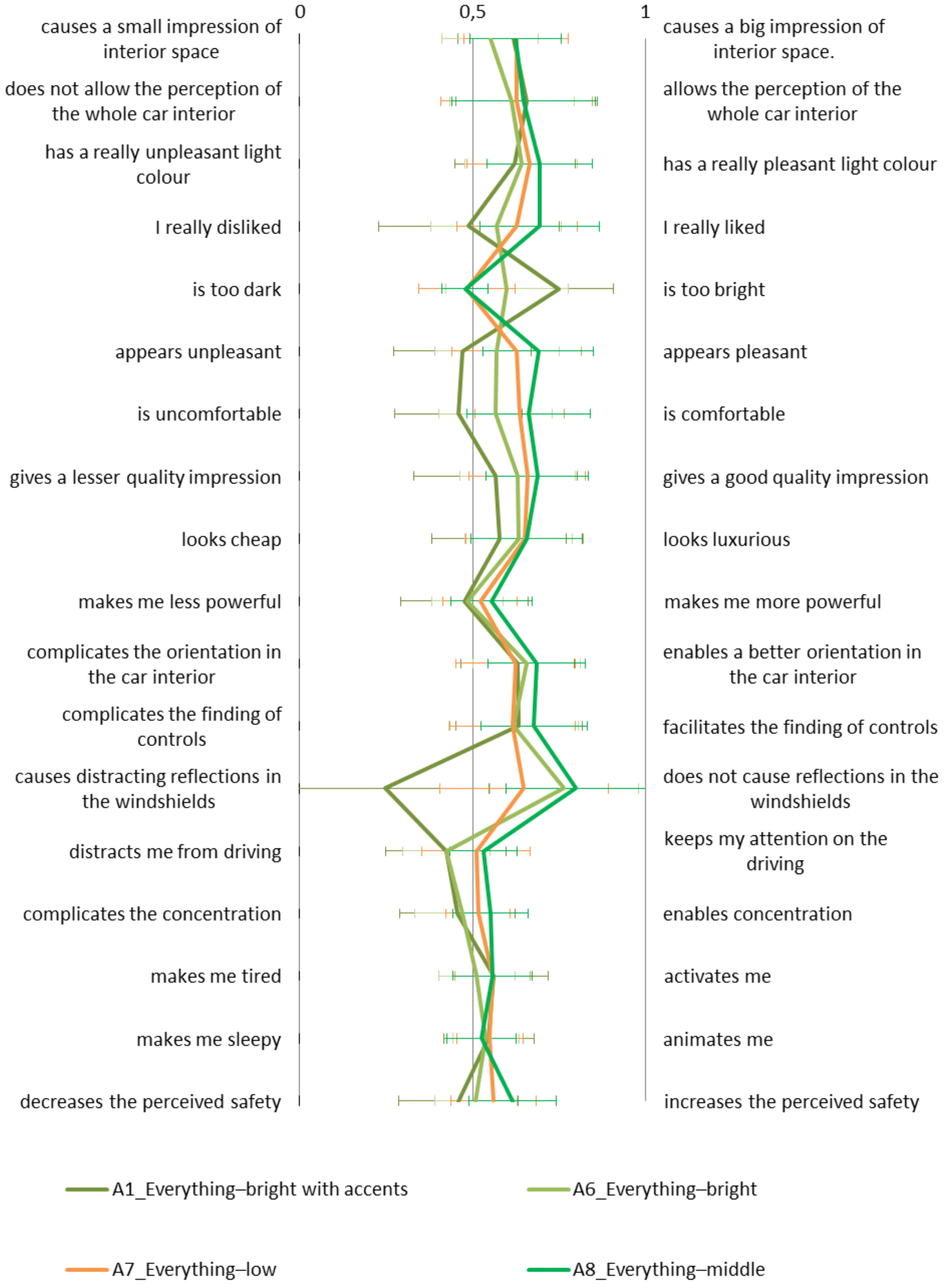


Figure 3.9 Results of the questionnaire on the subjective perception in study A. The comparison between the different brightness levels in the whole car interior is provided (from dark to bright: A7-A8-A6-A1). For each question the mean value and the standard deviation of the answers are represented.

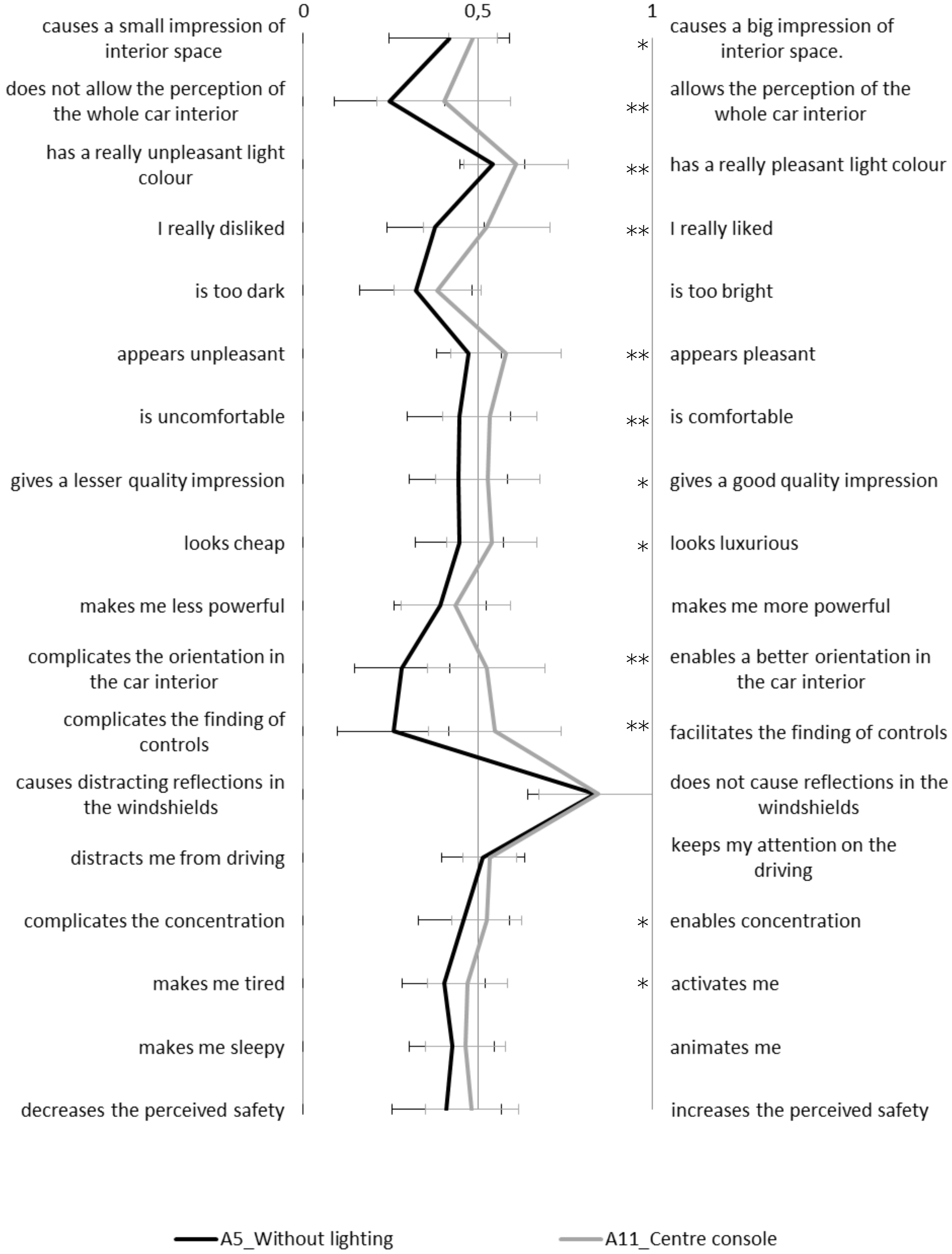


Figure 3.10 Results of the questionnaire on the subjective perception in study A. The comparison between the two scenarios *without lighting* and *centre console lighting* is provided. For each question the mean value and the standard deviation of the answers are represented. Highly significant (p<0,01) (**) and significant (p<0,05) (*) differences are indicated.

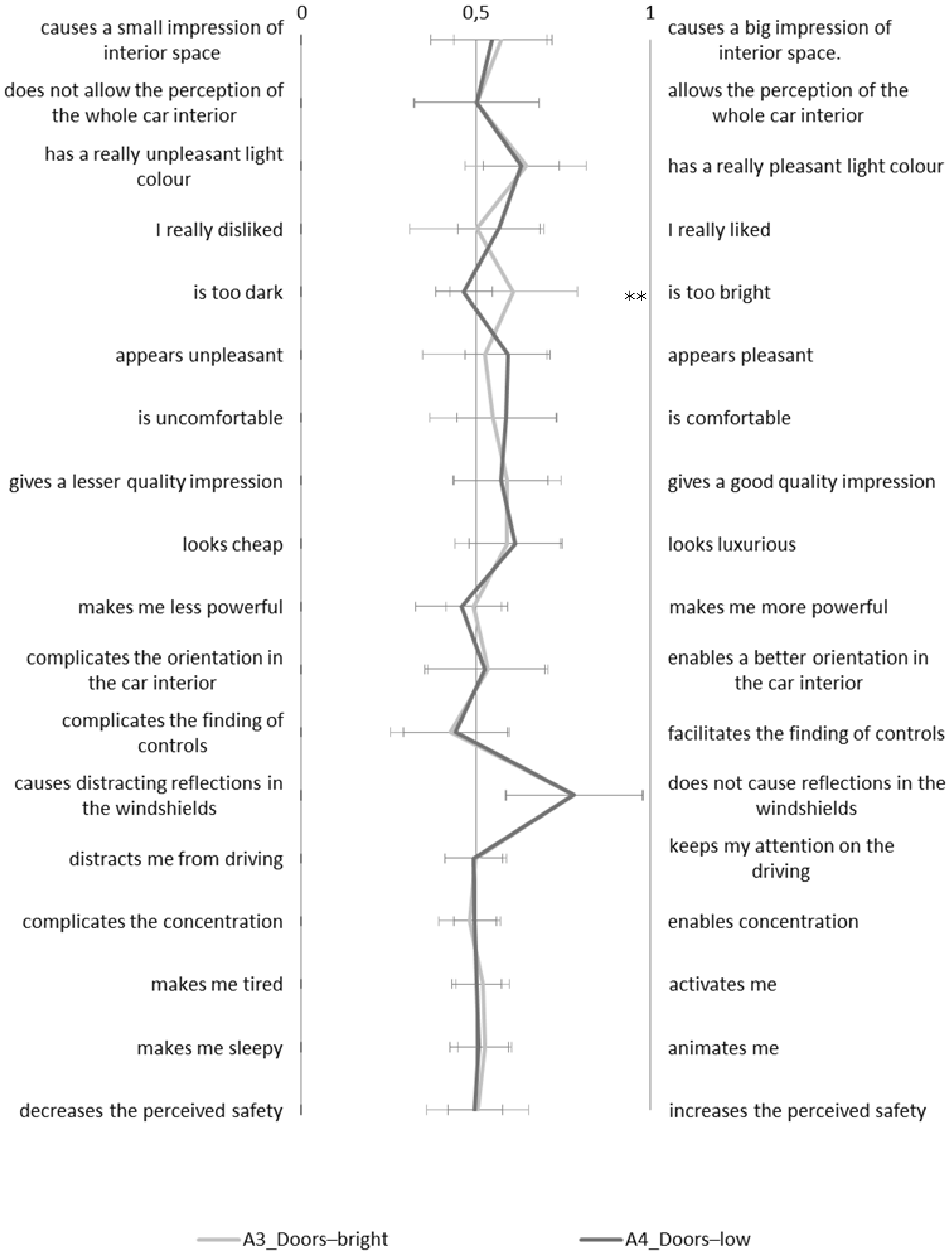


Figure 3.11 Results for the questionnaire on the subjective perception in study A. The comparison between the two different brightness levels of the door trims is provided. For each question the mean value and the standard deviation of the answers are represented. Highly significant (p<0,01) (**) and significant (p<0,05) (*) differences are indicated.

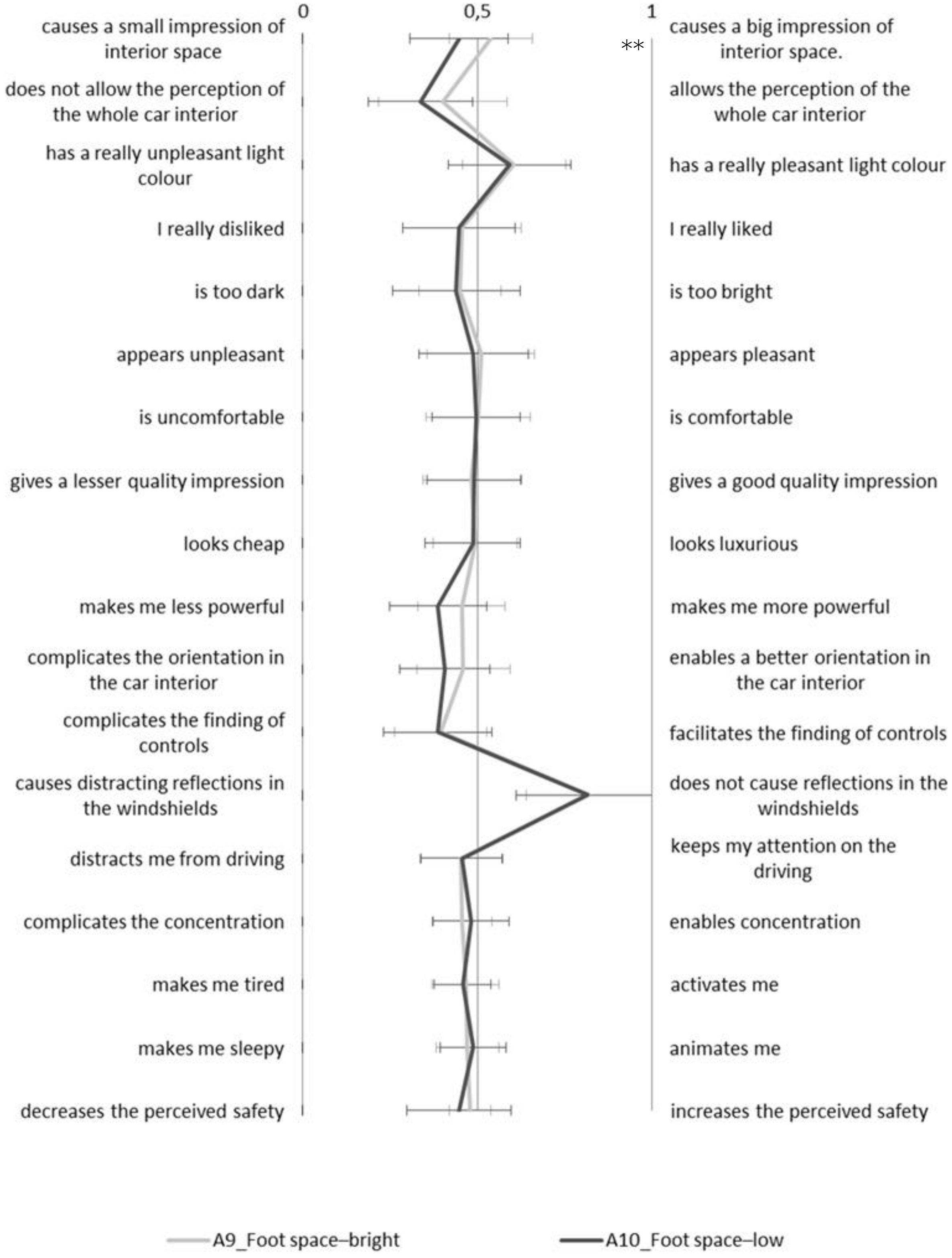


Figure 3.12 Results for the questionnaire on the subjective perception in study A.. The comparison between the two different brightness levels of the foot space is provided. For each question the mean value and the standard deviation of the answers are represented. Highly significant (p<0,01) (**) and significant (p<0,05) (*) differences are indicated.

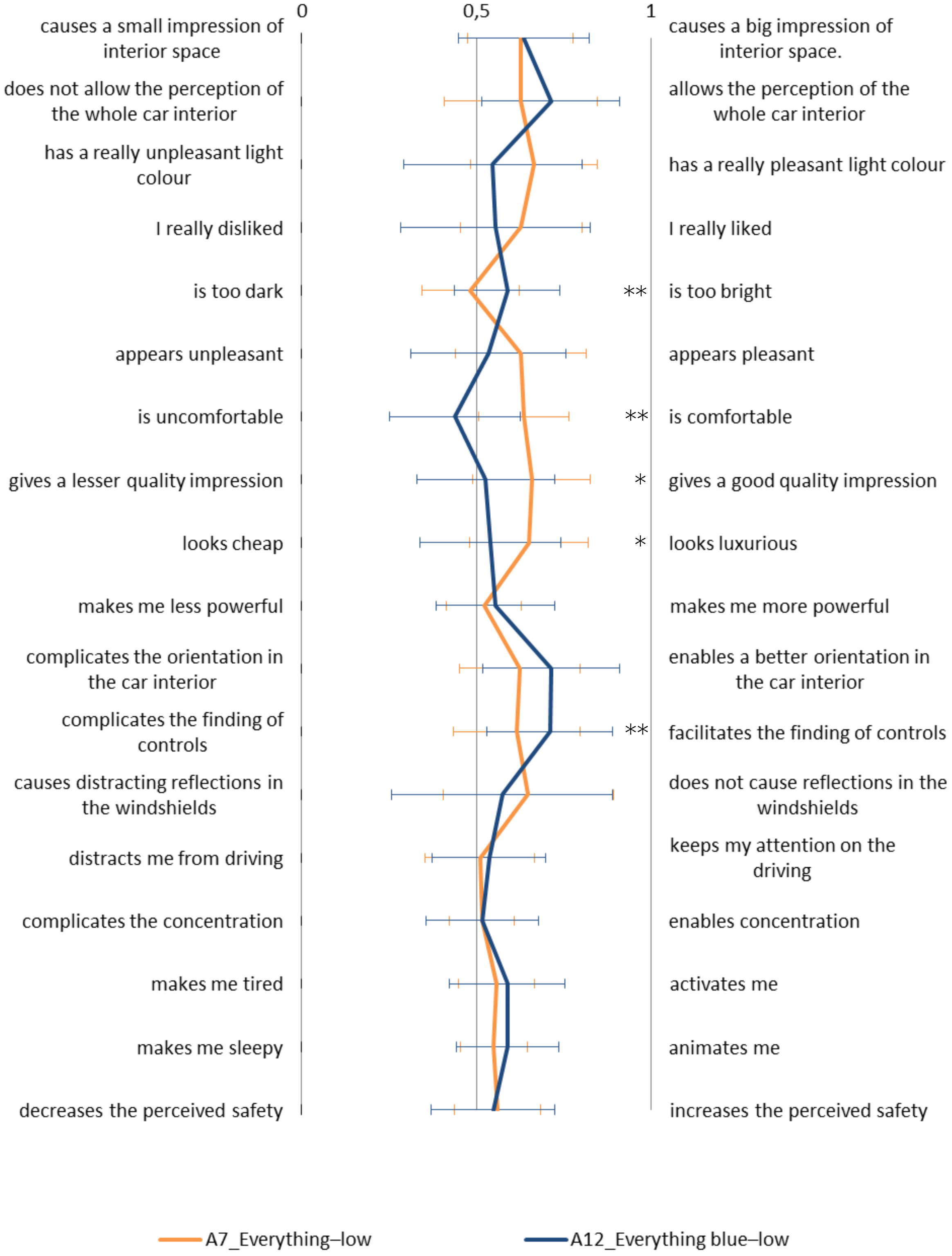


Figure 3.13 Results for the questionnaire on the subjective perception in study A. The comparison between orange and blue lighting in the whole car interior is provided. For each question the mean value and the standard deviation of the answers are represented. Highly significant (p<0,01) (**) and significant (p<0,05) (*) differences are indicated.

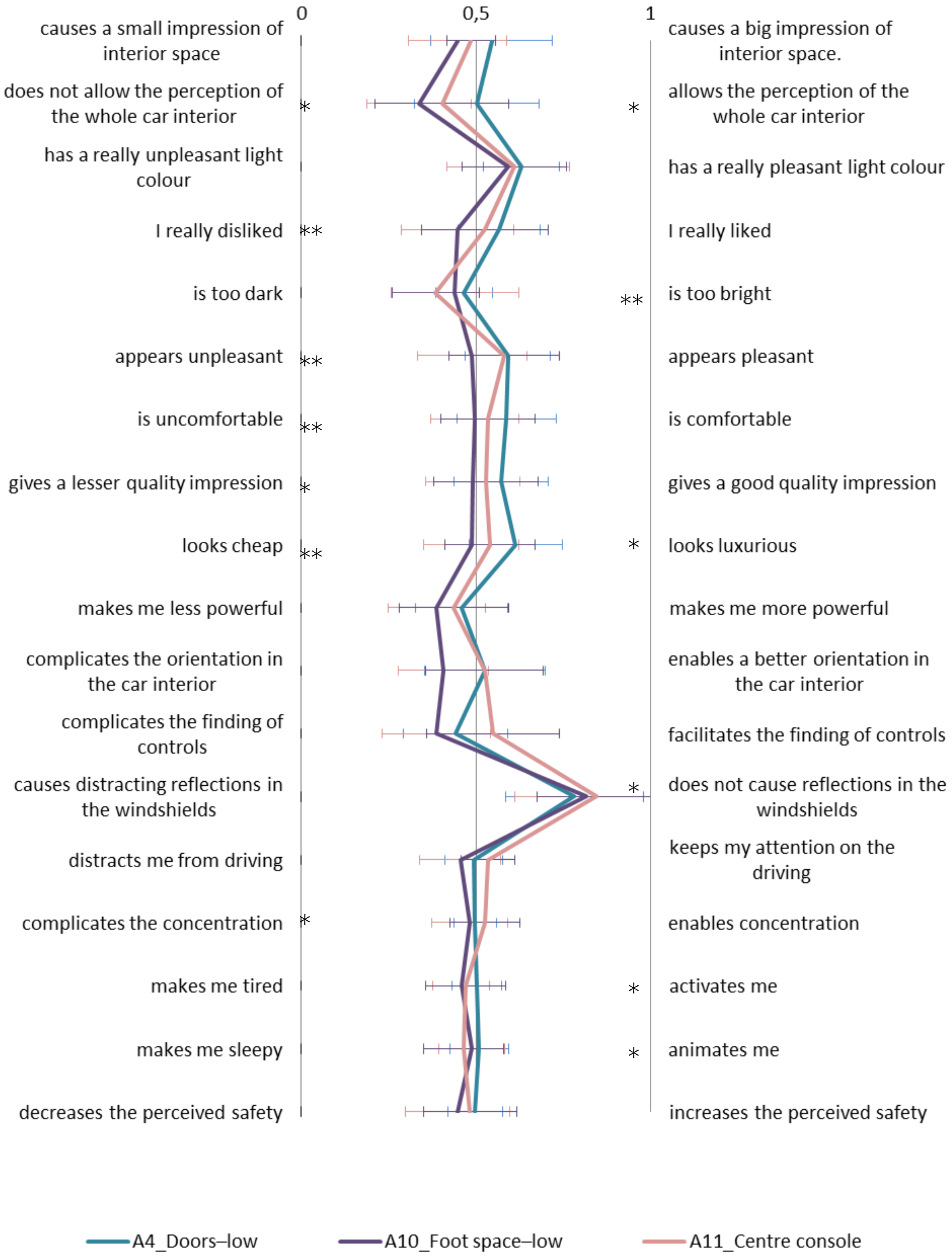


Figure 3.14 Results for the questionnaire on the subjective perception in study A. The comparison between the three different lighting position doors, foot space and centre console is provided. For each question the mean value and the standard deviation of the answers are represented. Highly significant (p<0,01) (**) and significant (p<0,05) (*) differences are indicated, on the right side regarding the comparison A4-A11, on the left side A4-A9.

3.3.5 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 is probably due to the different sensations and feelings which animated the different participants independently of the test and the tested scenarios. On the other side the answers on the dominance axis concentrated more on the middle point, this effect is 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 ($\Delta P = P - P_0$; $\Delta A = A - A_0$; $\Delta D = D - D_0$, where P_0, A_0, D_0 are the values gathered at the beginning of the test).

The difference distributions are displayed in Figure 3.15, Figure 3.16 and Figure 3.17 in form of Boxplot graphs. In these graphs the lower and higher edges of the box display respectively the first and third quartiles of the answer distribution. The solid line inside the box indicates the median, while the two whiskers above and underneath the box display maximum and minimum values. The additional hollow dots indicate outliers while the asterisks represent extreme outliers.

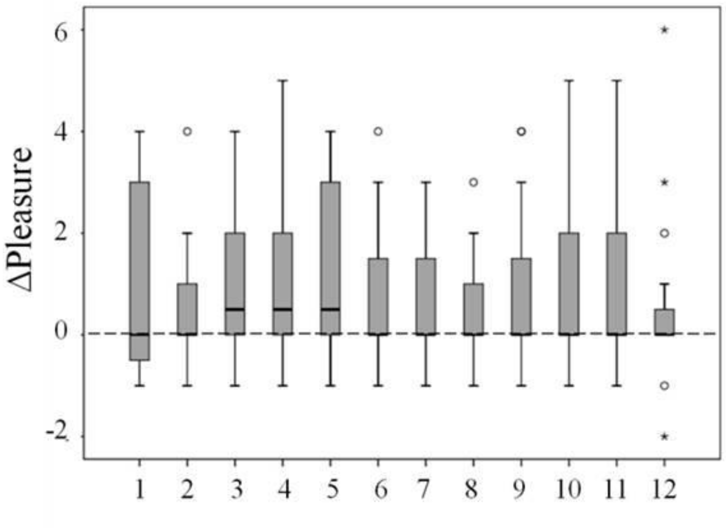


Figure 3.15 Boxplot graph of the distribution of the difference in the pleasure rating between each scenario and the answer at the beginning of the experiment.

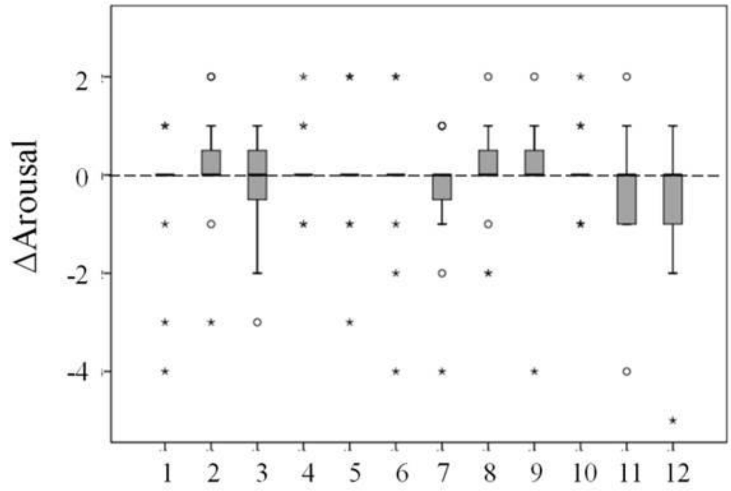


Figure 3.16 Boxplot graph of the distribution of the difference in the arousal rating between each scenario and the answer at the beginning of the experiment.

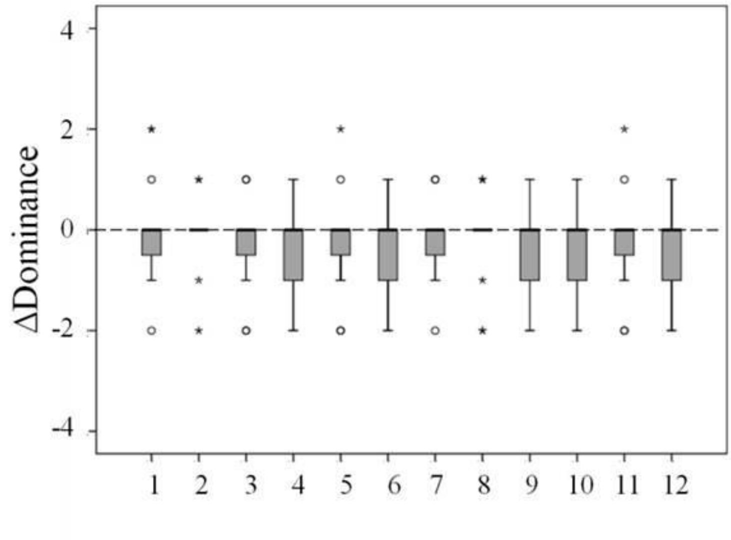


Figure 3.17 Boxplot graph of the distribution of the difference in the dominance rating between each scenario and the answer at the beginning of the experiment.

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/m^2) and mostly peripheral position.

3.3.6 Effects on driver's performance

For each participant and each experimental run the standard deviation to the street lane $\sigma(D_e)$ was considered as a measure of his driving performance.

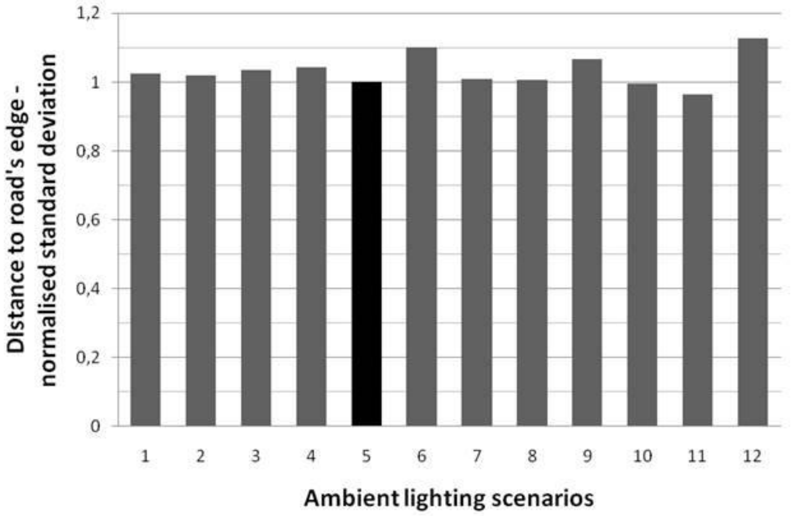


Figure 3.18 Values of $\overline{\sigma}(D_e)$ in relation to lighting scenarios. With number 5 is highlighted the scenario without ambient lighting, which value is normalised to 1.

This data, shown in Figure 3.18, was normalised: for each participant $\sigma(D_e)$ of scenario A5 was considered 1. Then it was 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 ($F= 0{,}435$ $\alpha=0{,}939$).

However, since this measure was not the primary goal of the research, it is difficult to assess its importance. Certainly, the driver's performance was not significantly influenced either way by the lighting scenarios. On one hand, it cannot be said that ambient lighting improves the driving performance; on the other hand, no significant decrease in the performance could be detected either, although some scenarios were judged clearly uncomfortable, causing discomfort glare. It might be possible to get a significant result for this measure by extending the duration of each experimental run. However, it is realistic to believe that driver fatigue would have a larger influence than ambient lighting on such a measurement.

3.3.7 Conscious perception of the single lighting elements

After each experimental run it was always asked to the participants which lighting elements they had noticed being on during the drive. The answers, given orally, were noted by the experimenter on his protocol. This research was intended to state if there was a difference between conscious perception (the effective noticing of each light source) and unconscious influences (the questionnaire about subjective perception) of ambient lighting elements.

The results are displayed in Figure 3.19. The percentage indicates how often a lighting element was perceived on when it really was on. Almost no false hits (elements perceived on although they were not) were recorded.

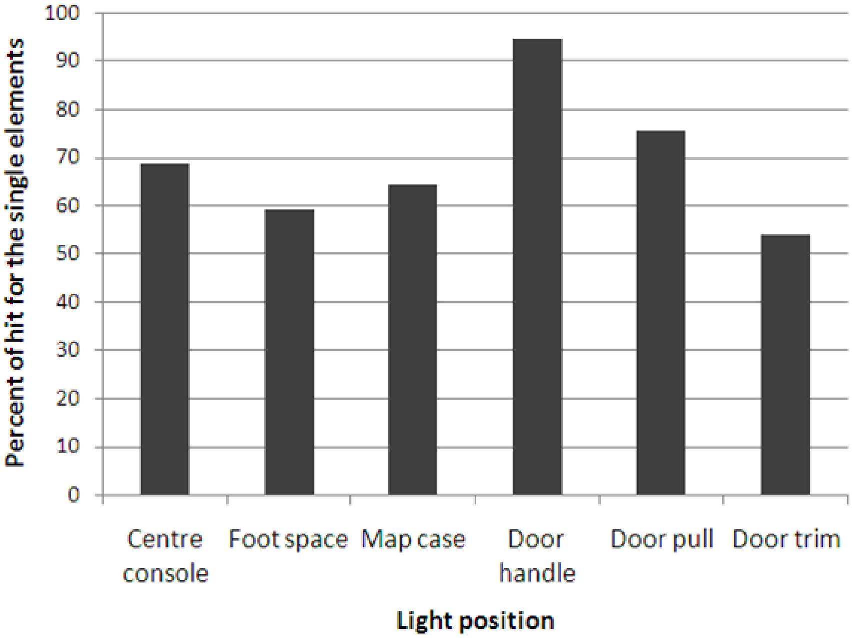


Figure 3.19 Percentage of perceived single lighting elements. 100% means that they were always consciously perceived when turned on.

Mostly punctual lighting sources like door handles and door pulls were identified (when turned on) in respectively 94% and 76% of the cases. On the other hand, light sources which featured a more diffuse lighting area (centre console, foot space, map case and door trims) were perceived more seldom, down to the minimum of 55% in case of the door trims. Nevertheless, these elements influenced significantly the subjective perception, as collected in the questionnaire, although not being always noticed during the experimental run.

Generalising, for a better subjective impression, it is not important to consciously see the lighting elements, or perceive clearly where the illuminated areas are, but to let them have an unconscious effect on the driver.

3.3.8 Favourite brightness

At the end of the experiment, the participants were asked to choose their favourite brightness level in the car. The experimenter proposed twelve scenes, in which all the lighting elements in the vehicle were turned on in a harmonised fashion and in orange colour. The twelve scenes proceeded from no lighting at all to the maximum reachable brightness level. They were presented once in growing luminance order and then in a decreasing luminance order. The test persons were asked to stop the presentation when they felt they were comfortable and they could drive well with this light level.

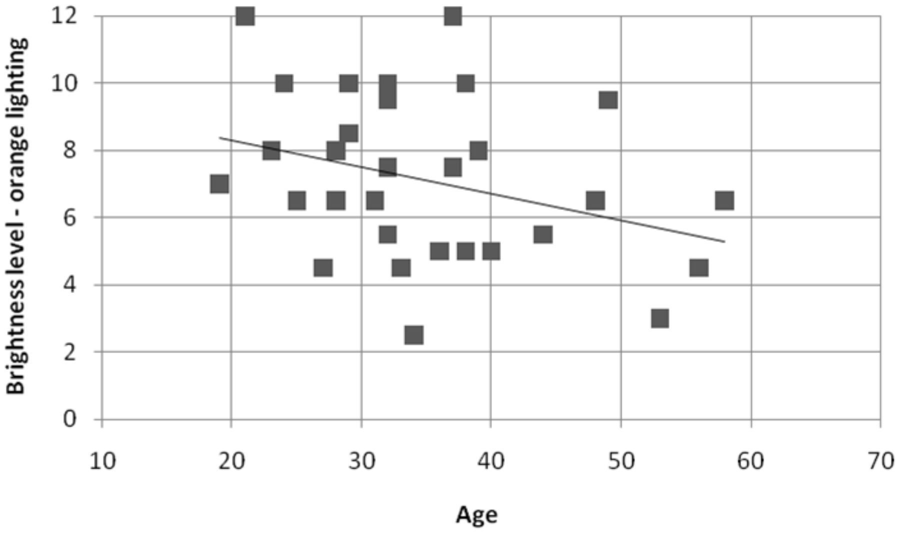


Figure 3.20 Favourite brightness level chosen by the 31 test persons plotted against their age. Each point refers to the mean value that each participant chose (in both order, with growing and decreasing brightness). The lighting colour was orange (605 nm). The line represents the minimum mean square error line, although the present correlation ($R^2=0,103$) is not significant ($p=0,07$).

No significant differences were originated by the order of the presentation (growing or decreasing brightness). The results are displayed in Figure 3.20, plotted against the age of the test persons. It can be seen a decreasing not significant trend of the brightness with the age. No participant chose the completely dark scenario. Moreover, it can be noticed how the preferred brightness ranges from relatively low to extremely high. This can be taken as an hint, to provide ambient lighting at an optimal luminance level, but still leave the customer the possibility to regulate his own favourite brightness.

3.4 Experimental study B: colours effect on a MINI

3.4.1 Test subjects

The investigation took place with 30 participants, 12 women and 18 men, between 22 and 53 years-old (mean age 34 years). 13 of them had already experienced ambient lighting while driving, 16 wore glasses or contact lenses. For each participant the experiment lasted 1,5 hours.

3.4.2 Ambient lighting scenarios

In this study, ten different ambient lighting scenarios were presented to each participant. A scene without ambient lighting was employed as a reference. The lighting colours red (dominant wavelength: 617 nm), green (528 nm) and blue (470 nm) were presented in two brightness levels: *series* and *bright*. The illumination elements are displayed in Figure 3.21.

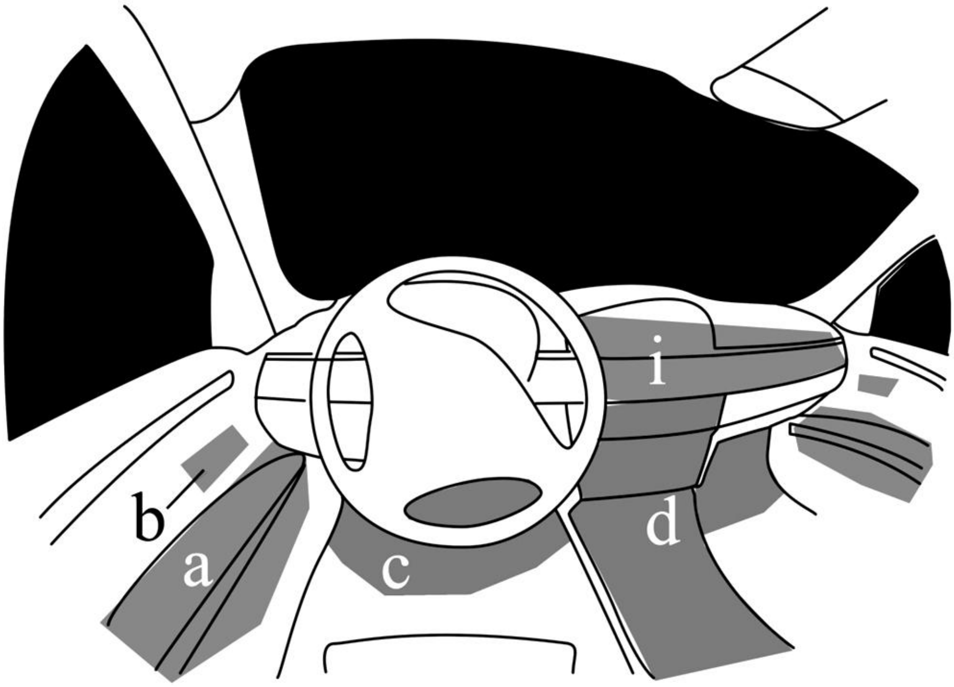


Figure 3.21 Illuminated zones in the experimental vehicle in study B: a. Door trims, b. Door handles, c. Foot space, d. Centre console (illuminated from above and backlit), i. Instrument panel.

Table 3.4 Overview of the ambient lighting scenarios presented in the study B

Scenario	Colour	Brightness level
B1	-	No lighting
B2	Red	Series
B3	Blue	Series
B4	Green	Series
B5	Turquoise	Bright
B6	Red	Bright
B7	White	Bright
B8	Green	Bright
B9	Blue	Bright
B10	Blue	Brightest

In the *series* scenario the centre console, door trims, door handles, and b-pillar illuminations were turned on. In the *bright* scene the following lighting elements were added: centre console retro-illumination, foot space lighting and instrumentation panel lighting. The spectral distribution of the employed LEDs is displayed in Figure A.4 in the appendix.

At *bright* level two more colours were presented: turquoise and white, which were originated by mixing respectively green plus blue, and green plus red plus blue. For the blue lighting colour, besides the *series* and *bright* scenario, a third scenario was proposed, in which the brightness of all the light sources was turned at its maximum, in a similar extent to the scenario A1 in study A.

Since the test vehicle was a prototype realised as a design study, it featured several innovative aspects[18]. Besides the extensive application of ambient lighting elements, the geometry of the cockpit was slightly different than the series production MINI cockpit. The materials used for the interior consisted of red textile and black plastics. This fact was decisive for the choice of the lighting colours to present in the study. Indeed, as ambient lighting is perceived almost only through the reflection on the interior materials, their perceived colours are changed by the lighting colour. So, it is easy to imagine how the red textile under a blue lighting looked almost black, although with somehow bright reflections, while under red lighting the materials glowed like they would be on fire. This difference in aspect was balanced through a proper control of the lighting levels of the LEDs, which realised constant photopic luminance levels on each illuminated part.

Another aspect emerged when mixing LED colours, originated by their small spectral bandwidth. For instance, yellow is obtained by turning on red and green together: on the red textile only the red component was reflected properly, while the black plastics happened to reflect more green. As a result, the car interior looked as lit by two different colours. Since the research of this phenomenon did not constitute the aim of this experimental study, it was

avoided as much as possible, by using the mix-colours turquoise and white, which did not originate such effect. To a certain extent, a specific control on each RGB LED element could balance this effect. Though, when combined with the control for balancing the luminance levels within a scenario and between the scenarios, this control was not satisfying enough to guarantee homogeneous lighting impression (in series development, this could even constitute an interesting feature, for exciting show effects).
An overview of the presented scenarios is provided in Table 3.4.

3.4.3 Execution of the experiment

The experimental setup was the same as the one employed in study A and described in section 3.2.1, apart from the vehicle employed. In this case too, the main task of the driver was to follow a vehicle. Given a different steering-feel of the whole system compared to reality, this task was enough to focus the driver on the street like in a real situation.
A difference to the setup in study A consisted in the possibility of the system to read two toggle pad buttons placed on the steering wheel. These controlled dynamic lighting scenarios, making it possible to change colour and brightness of the ambient lighting in a continuous fashion. This control possibility was used in a secondary research, when the participants were asked to choose their favourite ambient lighting colour and brightness. During the main research this control mode was shut down and the displayed scenarios were static.

3.4.4 Questionnaire: subjective perception of the lighting

The employed questionnaire was similar to the one used in study A, as described in section 3.3.3. It featured two parts, the first dealing with the subjective impressions of the vehicle interior, the second with the emotional state of each participant. The latter remained the same as in study A and consisted in a Self-Assessment Manikin, as explained in section 3.2.3
The subjective impression part was constituted by questions in the form of differential pairs. In this section, several improvements were introduced.
A seven step scale was used (as in Figure 3.22), instead of a continuous scale, in order to make the understanding of the scale and the decision by the test persons easier and faster [35]. The consistency with the scale used in the study A and its results were verified through different statistical tests.
Moreover, several questions were deleted. On one hand the questions which were double (e.g., the light situation *looks luxurious*, ... *gives a good quality impression*), which in study A proved to be answered consistently by the participants, and showed high correlation coefficients

(Pearson > 0,85) (cf. Table A.5 in the appendix). On the other hand, some questions were impossible to answer to, since the prototype did not feature the necessary fixtures. The controls in the cockpit were minimalistic, so the question on finding the controls was neglected. No side windshield was present and therefore no reflection was possible, so also the question on the reflections was left aside. In this fashion, the questions were only twelve, thus making the test a bit faster.

Table 3.5 Semantic differential pairs proposed in the questionnaire. The ratings were given between the two extremes 0 and 1, proportionally to the point where the test persons crossed on the 7-step scale. *The displayed light situation...*

Question number	**Element (0)**	**Element (1)**
1	causes a small impression of interior space	causes a big impression of interior space
2	does not allow the perception of the whole car interior	allows the perception of the whole car interior
3	complicates the orientation in the car interior	enables a better orientation in the car interior
4	is too dark	is too bright
5	has a really unpleasant light colour	has a really pleasant light colour
6	I really disliked	I really liked
7	appears unpleasant	appears pleasant
8	gives a lesser quality impression	gives a good quality impression
9	distracts me from driving	keeps my attention on the driving
10	relaxes me	activates me
11	decreases the perceived safety.	increases the perceived safety
12	is glaring me	is not glaring me

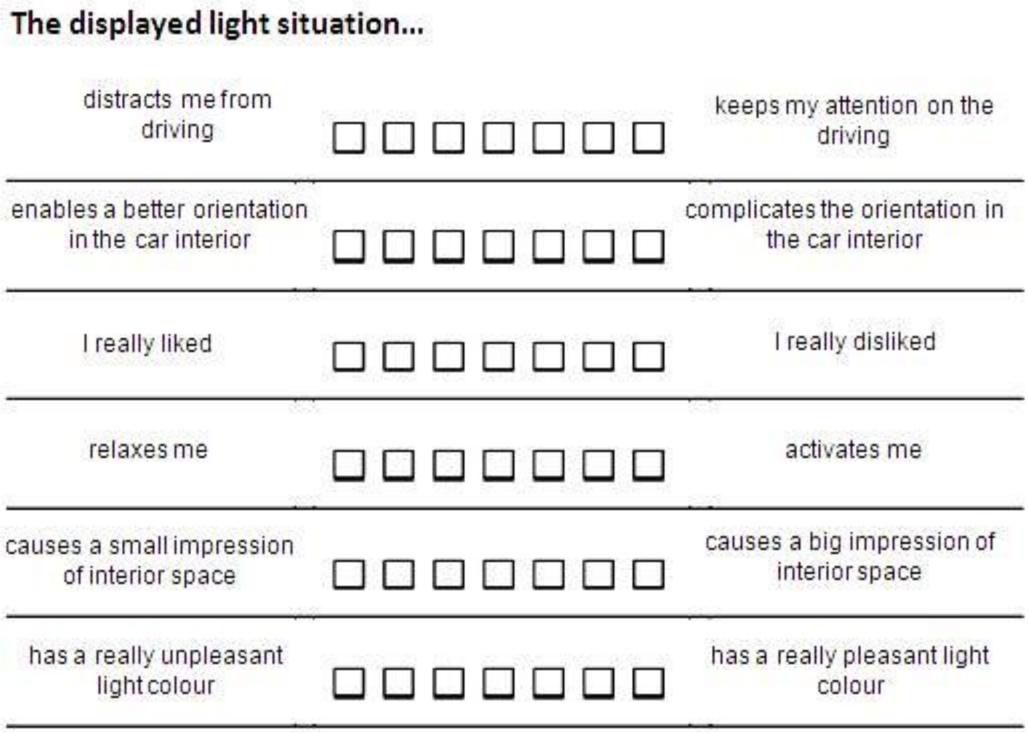
These modifications were made because some participants in study A complained about its excessive length (sometimes up to 2 hours), few breaking the test in the last two scenarios. Although this fact wasn’t statistically significant, since the presented scenarios were properly randomised, the recommendations were seriously taken into account.
The questions, listed in Table 3.5, were grouped in the following criteria:

The displayed light situation...

- *(Space perception and orientation)* ...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; ...enables a better orientation in the car interior / complicates the orientation in the car interior; ...is too dark / is too bright.

- *(Interior attractiveness and perceived quality)* ...has a really unpleasant light colour / has a really pleasant light colour;...appears pleasant / appears unpleasant; ...I really liked / I really disliked; ...gives a lesser quality impression / gives a good quality impression.
- *(Perceived safety)* ...increases the perceived safety / decreases the perceived safety; ...is glaring me / is not glaring at all.
- *(Alertness)* ...distracts me from driving / keeps my attention on the driving; ...relaxes me / activates me;

The grouping was slightly different then in the study A, since it was drawn from the categories obtained in the factor analysis described in section 4.1.



The displayed light situation...

distracts me from driving	☐ ☐ ☐ ☐ ☐ ☐ ☐	keeps my attention on the driving
enables a better orientation in the car interior	☐ ☐ ☐ ☐ ☐ ☐ ☐	complicates the orientation in the car interior
I really liked	☐ ☐ ☐ ☐ ☐ ☐ ☐	I really disliked
relaxes me	☐ ☐ ☐ ☐ ☐ ☐ ☐	activates me
causes a small impression of interior space	☐ ☐ ☐ ☐ ☐ ☐ ☐	causes a big impression of interior space
has a really unpleasant light colour	☐ ☐ ☐ ☐ ☐ ☐ ☐	has a really pleasant light colour

Figure 3.22 Example of the proposed questionnaire in study B.

3.4.5 Effects on driver's subjective perception

The effects of different ambient lighting scenarios on the driver's perception were investigated by comparing the results of the different test runs between them and testing their significance with a Wilcoxon signed-rank test. At the beginning every scenario was tested against the one *without lighting* (B1), which acted as reference scenario. Then the scenarios with same luminance level (*series* and *bright*) were compared. The comparison between scenarios with same lighting colours (*red, green,* and *blue*) but different luminance levels was also carried out, providing an insight on the effect of luminance.

The ratings were normalised in a scale going from 0 to 1. Only in one case the optimum was in the middle of the scale, namely the question *is too dark/is too bright*.

The mean values and standard deviation of the answers distribution for each scenario and each question are listed in Table A.11 in the appendix.

In an overview, the scenario *without lighting* and the scenarios with *series* luminance level were judged as too dark, the scenarios red, blue, white and turquoise *bright* were assessed as having an optimal brightness, while the scenario B10 was assessed too bright. The most liked scenarios were blue, white and red bright, though the answers were widely distributed, due to personal colour preferences. Scenario B10 (blue *brightest*) was judged as the most glaring. All the other scenarios were rated as not glaring.

Comparison of the reference scenarios in Study A and Study B

The two scenarios *without lighting*, which represented the reference situation for both study A and B, were compared, in order to understand which differences in the subjective assessment originated from the variation of the car in which the driver had experienced ambient lighting. It is useful to remember that the test persons who took part in the study A were not the same who participated to study B. In this context only the mean assessments of the questions common to the two experiments can be compared, as shown in Figure 3.23 The scenario B1 was assessed with lower ratings then scenario A5. This is probably due on one hand to the different geometry of the two car interiors, and to the fact that car B had much less instrumentation and controls and therefore was much darker in the scenario *without lighting*. On the other hand, the method using 7-steps scales in the semantic differential favoured a wider distribution of the assessments, while the continuous scale employed in study A favoured more centred assessments. Nevertheless, the comparison shows how similar the two scenario ratings are.

The discrepancies must not lead to confute the used assessment method, since only differences between scenarios are considered in the analysis and not absolute values. In this perspective, different assessments of the basic scenarios can be seen as different offsets to the other evaluations. Nevertheless, the internal consistency of the studies is preserved.

Comparisons to the reference scenario without ambient lighting

All the ambient lighting scenarios were compared with the scenario *without ambient lighting*.

In these comparisons emerged that each ambient lighting scenario scored better than the *without ambient lighting* situation by highly significant ($p<0,01$) differences in each category. Exceptions were the questions in the alertness group (*distracts me from driving / keeps my atten-*

tion on the driving, relaxes me / activates me) in which no significant variation was found. This can be considered as a positive result, since no significant diminution of the attention on the street caused by ambient lighting was detected.

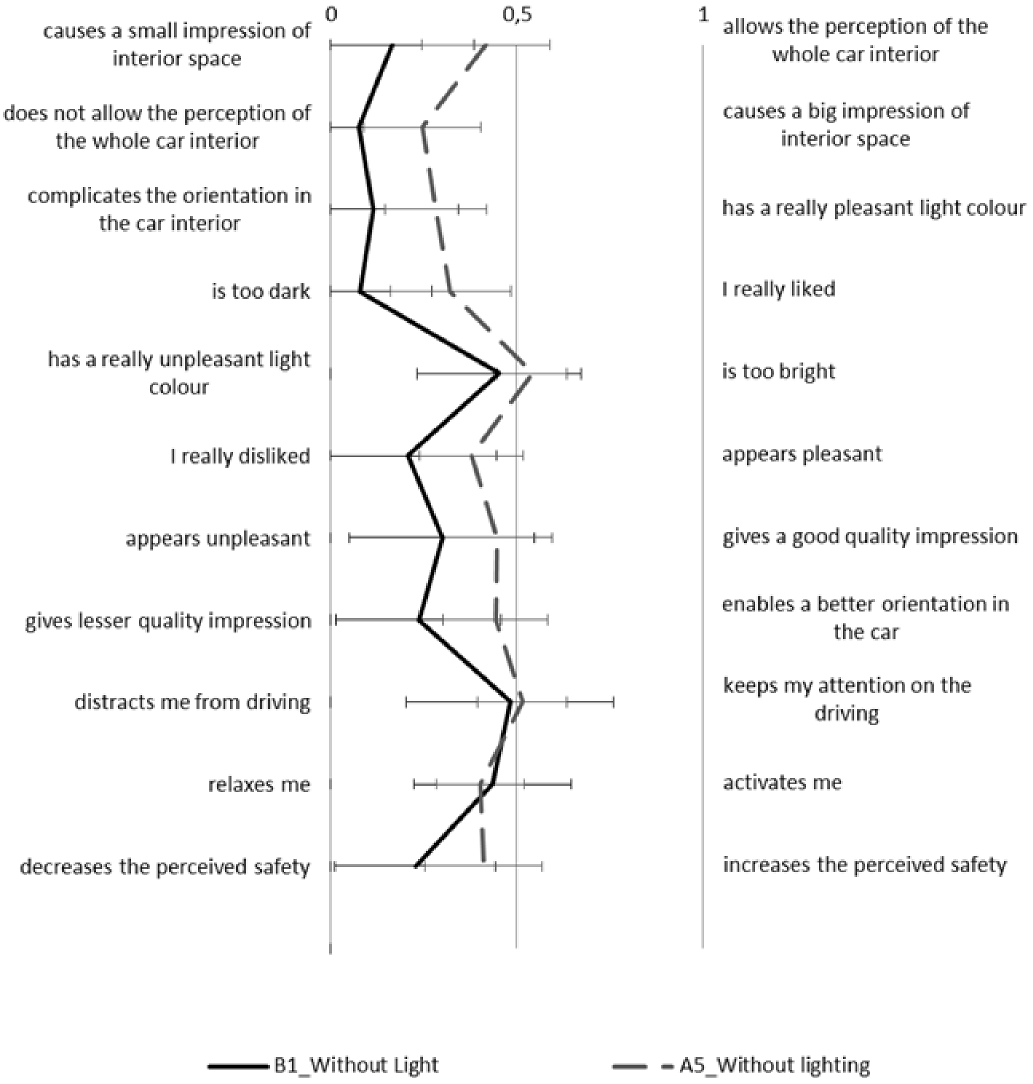


Figure 3.23 Comparison of the results between the two scenarios *without lighting* in study A and study B. Here the mean assessments for the shared questions and their standard deviation are plotted. Only the common questions are shown.

Moreover, on the question *is glaring me / is not glaring at all* the scenarios on a *bright* level were highly significantly (p<0,01) and the *blue series* significantly (p<0,05) more glaring than from the reference scenario. In spite of these significant differences, the assessments were mostly in the direction of *no glaring*. Only in the case of the brightest blue scenario (B10) the mean evaluation was in the middle of the scale, with 50% of the persons judging it glaring. Blue and turquoise bright scenarios (B9 and B5) were not rated glaring, but their assessment in this criterion was still significantly poorer than the assessment of the scenario *without lighting*.

Effects of different colours

The different ambient lighting colours were compared at the same luminance level. For the *series* level, red, blue, and green (scenarios B2, B3, B4), for the *bright* level, red, blue, green, turquoise, and white (scenarios B5, B6, B7, B8, B9) ambient lighting were compared.

At the *series* luminance level, the blue scenario was rated significantly and highly significantly better than the other two in the *space perception and orientation* criterion (Figure 3.24). In comparison with green, blue was also rated brighter ($p<0{,}05$), more attractive, and increased the perceived safety ($p<0{,}01$), although being rated more glaring ($p<0{,}05$). Between red and green scenario no significant differences were observed. Blue scored significantly better than red in space perception and pleasantness ($p<0{,}05$). The significance of the comparisons between the different scenarios regarding the whole study B are listed in Table A.13 through Table A.16 in the appendix.

Table 3.6 Comparison of the *bright* scenarios. Each scenario was compared with the others through a Wilcoxon signed-rank test. The light grey cells represent significant differences ($p<0{,}05$) while the dark grey represent the highly significant differences ($p<0{,}01$). The letters in each cell indicate which scenario was given the higher score. The questions are listed in Table 3.5.

Compared scenarios		1	2	3	4	5	6	7	8	9	10	11	12
Red bright – R	Turquoise bright -T			T									R
Red bright – R	White bright - W	W	W	W									
Red bright – R	Green bright - G				R		R	R	R				
Red bright – R	Blue bright - B	B			B								R
Green bright – G	Blue bright - B	B	B		B		B	B	B				
White bright – W	Green bright - G	W	W	W	W	W	W	W	W				
Turquoise bright –T	Green bright - G	T	T	T	T		T		T		G		G
Turquoise bright –T	Blue bright - B						B	B			B		
White bright – W	Blue bright - B			W									
Turquoise bright –T	White bright - W			W									

At the *bright* luminance level, five lighting colours were compared: red, blue, green, white, and turquoise. The results are displayed in Figure 3.25. The significance of the comparisons between the different scenarios can be seen in Table 3.6. White colour received better assessments than the other colours, in *space perception and orientation* and *attractiveness and perceived quality* criteria, scoring highly significantly better than green in almost every question, highly significantly better than red in the *space perception and orientation* criterion, significantly better than blue and turquoise in the orientation question. Green scored significantly worse than red regarding *attractiveness and perceived quality* criterion and orientation.

Regarding the assessment of glare, it resulted that red glared significantly less than blue and turquoise, and green significantly less than turquoise.

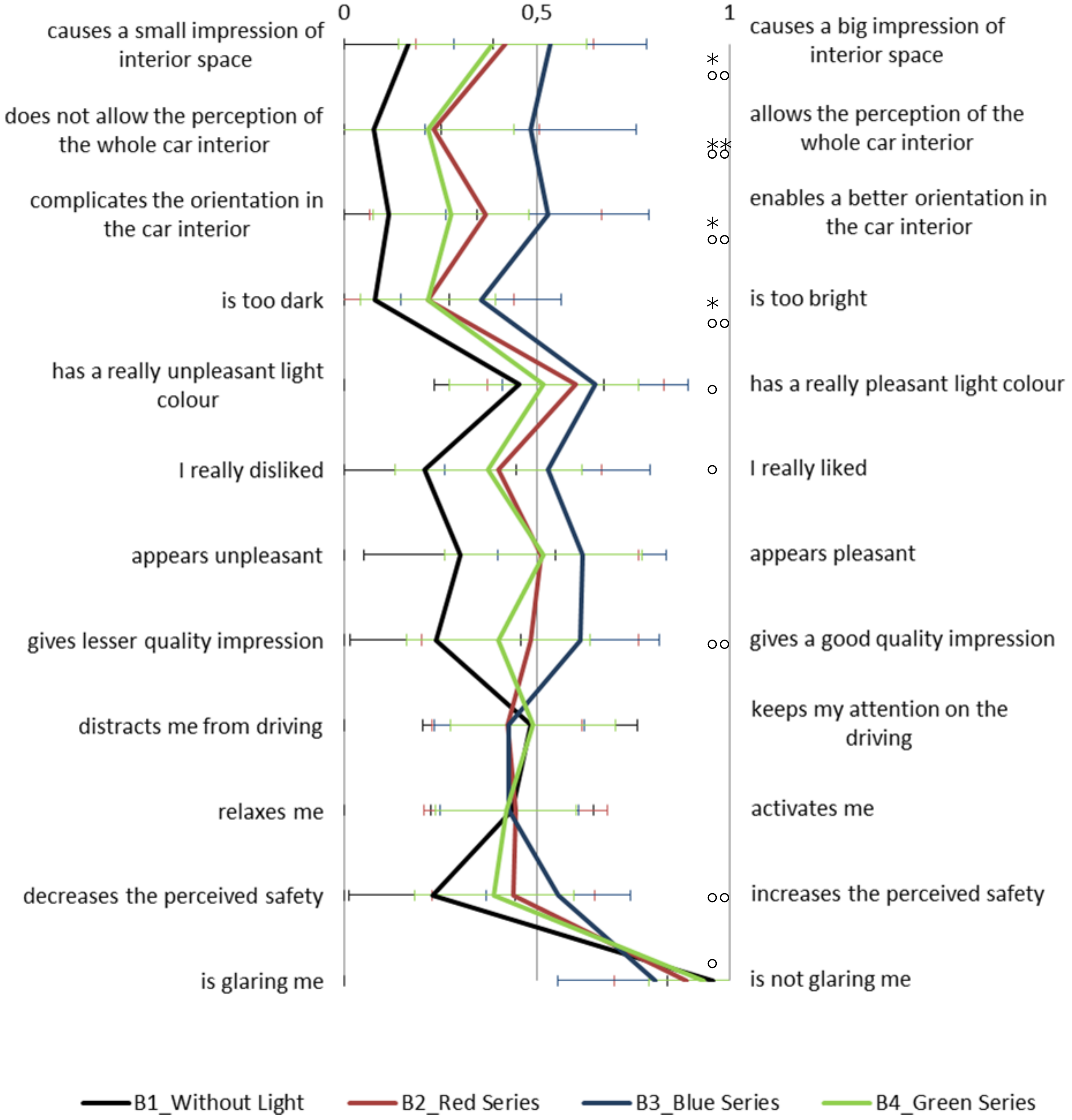


Figure 3.24 Results of the questionnaire of study B. The *series* scenarios, red, blue and green, are compared with the scenario *without ambient lighting*. For each question the mean value and the standard deviation of the answers are represented. Each scenario was compared with the other two through a Wilcoxon signed-rank test. The * refers to the comparison between scenarios B2 and B3 (red and blue series); ° to the comparison between B3 and B4 (blue and green series). Between B2 and B4 (red and green) no significant differences were found. The symbols * and ° represent significant differences (p<0,05) while the symbols ** and °° represent the highly significant differences (p<0,01).

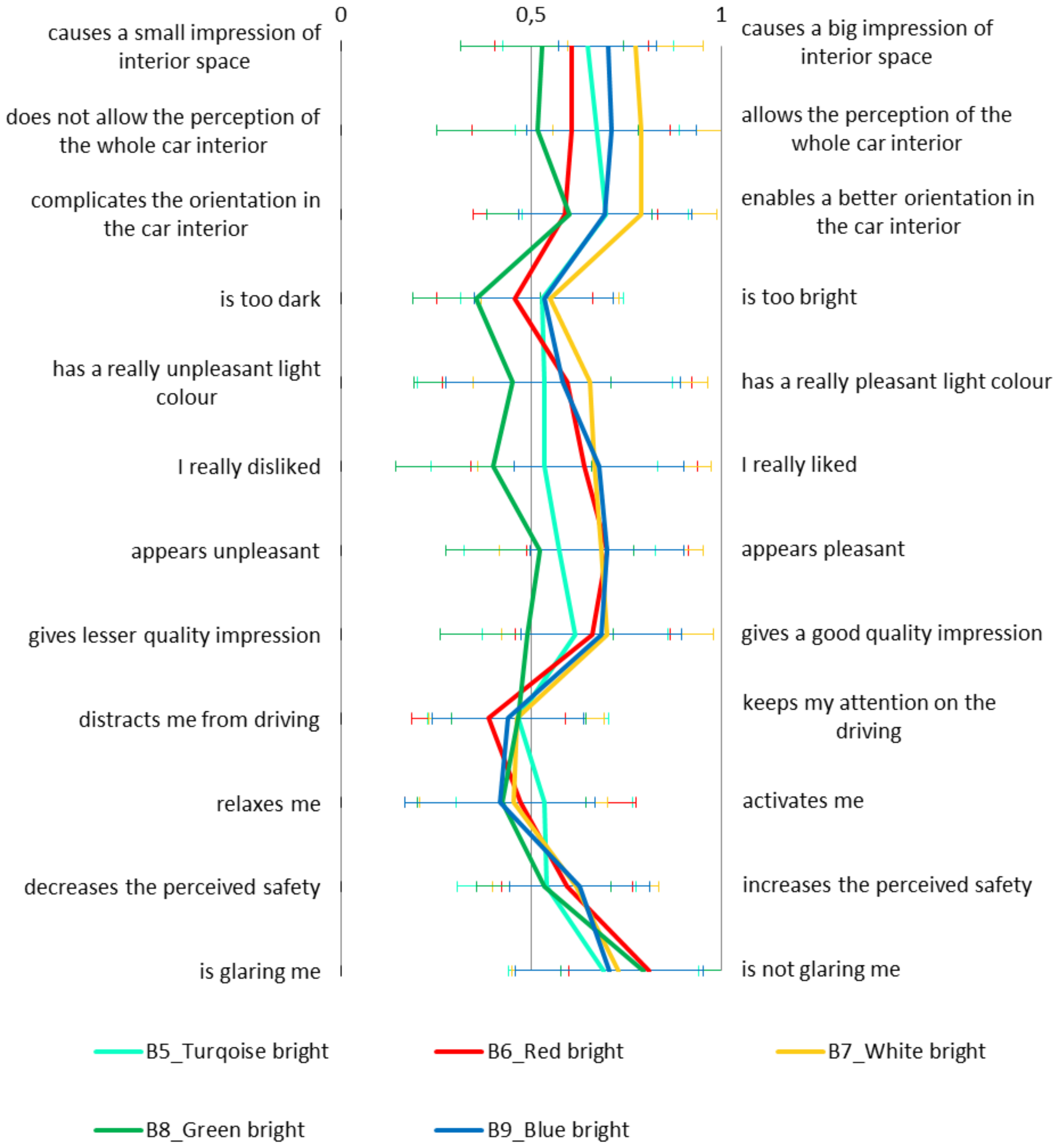


Figure 3.25 Results of the questionnaire of study B. The *bright* scenarios, red, green, blue, white and turquoise, are compared. For each question the mean value and the standard deviation of the answers are represented. The list of significant differences between the evaluations is displayed in Table 3.6.

Figure 3.26 Results of the questionnaire of study B. The red scenarios *series* and *bright* are compared. For each question the mean value and the standard deviation of the answers are represented. * indicates a significant difference between the two results (p<0,05); ** indicates an high significant difference (p<0,01).

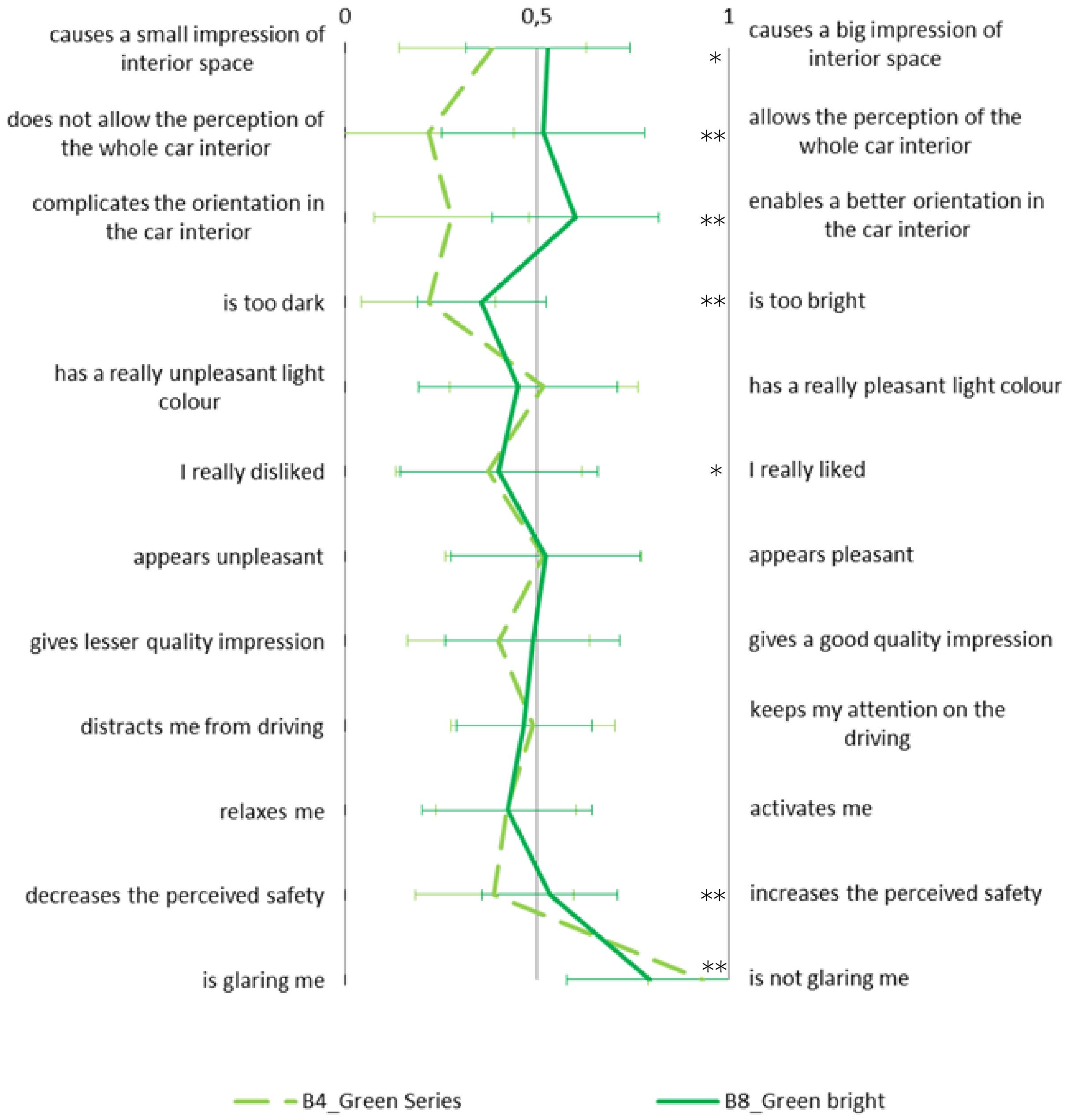


Figure 3.27 Results of the questionnaire of study B. The green scenarios *series* and *bright* are compared. For each question the mean value and the standard deviation of the answers are represented. * indicates a significant difference between the two results (p<0,05); ** indicates an high significant difference (p<0,01).

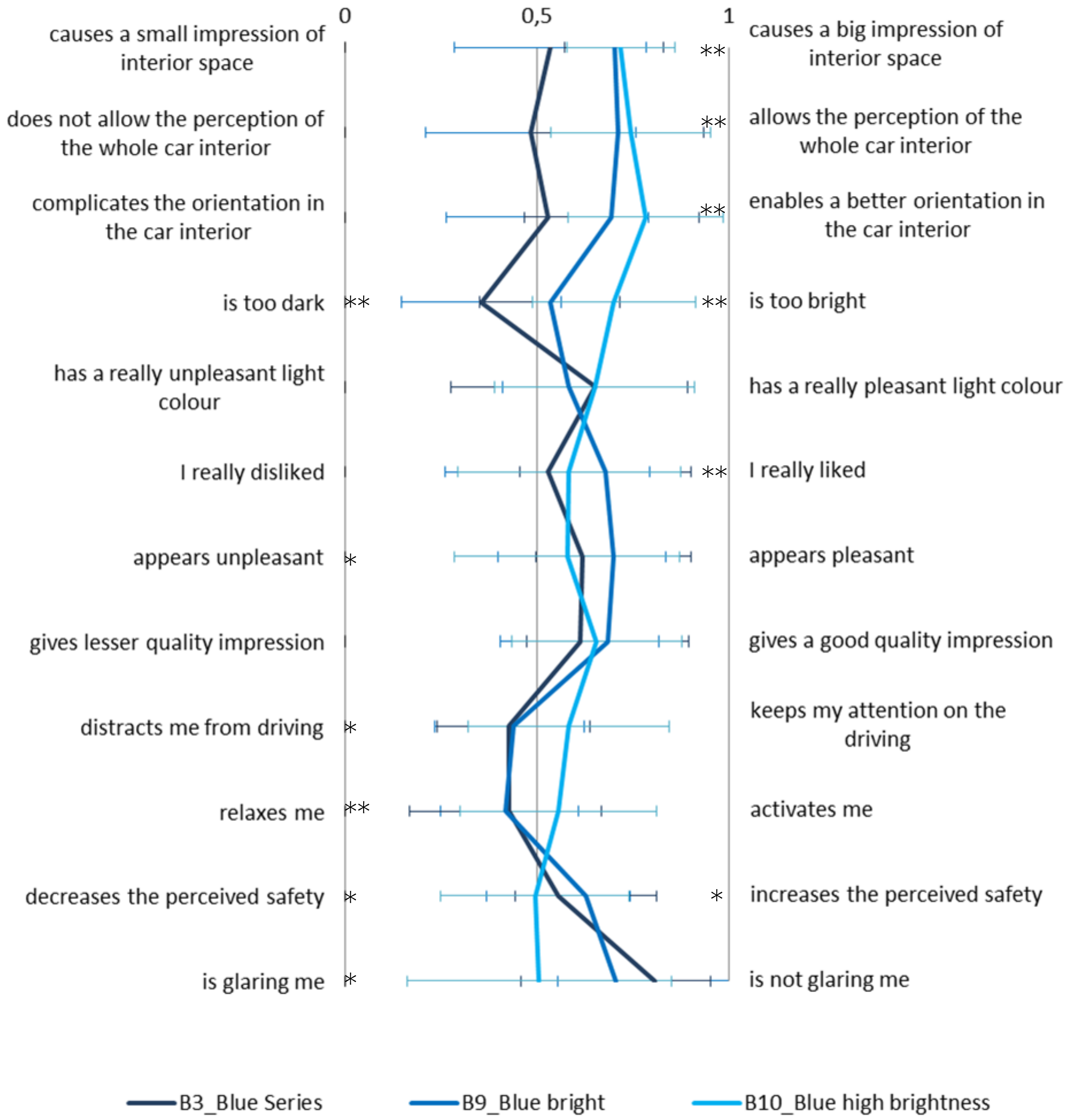


Figure 3.28 Results of the questionnaire of study B. The blue scenarios *series bright* and *brightest* are compared. For each question the mean value and the standard deviation of the answers are represented. * indicates a significant difference between the two results (p<0,05); ** indicates an high significant difference (p<0,01). On the left side are indicated the significance levels for the comparison B9-B10, on the right side the ones for the comparison B3-B9.

Effects of different brightness levels

Regarding the brightness variations, the *series* scenarios and the *bright* scenarios of a lighting colour were compared.

The red scenarios B2 (*series*) and B6 (*bright*) were analysed. The bright scenario was rated highly significantly better (p<0,01) than the series scenario, apart from the questions *has a pleasant light colour, activates me, keeps my attention on driving,* in which both scenes were assessed similarly, and regarding the glare, where the series scenario was rated significantly better (Figure 3.26).

Green scenarios B4 (*series*) and B8 (*bright*) were compared as well. The bright scenario was assessed better regarding the *space perception and orientation* criterion and the perceived safety (p<0,01), and similarly to the series scenario in terms of *attractiveness and perceived quality.* The series scenario glared less than the bright one (p<0,01) (Figure 3.27).

Regarding blue colour, the *series* (B3), *bright* (B9), and *brightest* (B10) scenarios were assessed. Increasing the luminance from series to bright level brought an increased *space perception and orientation* (p<0,05), but no improvement in any other criteria, apart from the question *I really liked.* The brightest scenario appeared unpleasant, decreased the perceived safety and increased the glare (all significant differences) in comparison with the bright one. On the other hand, it provided a higher activation (p<0,01) and kept the attention of the driver on the driving (p<0,05). The latter effect could be explained by the fact that if the driver felt glared he tended to concentrate more on the driving, in order to contrast the visual impairment (Figure 3.28).

3.4.6 Effects on driver’s emotional state

The results obtained from the Self-Assessment Manikin test were quite similar to the ones obtained in study A, especially regarding the difficulty of the answer to the dominance question.

Each scenario rating was compared to the answer given at the beginning of the experiment by each test participant. The difference between these two ratings gave a dimension of the emotional change caused by the scenario ($\Delta P = P - P_0$; $\Delta A = A - A_0$; $\Delta D = D - D_0$, where P_0, A_0, D_0 are the values gathered at the beginning of the test for each person).

The differences distributions are displayed in Figure 3.29 to Figure 3.31 in form of Boxplot graphs.

No significant results were obtained regarding dominance and arousal. Though, few significant differences indicated that green and turquoise colour had negative influences on the pleasure ratings.

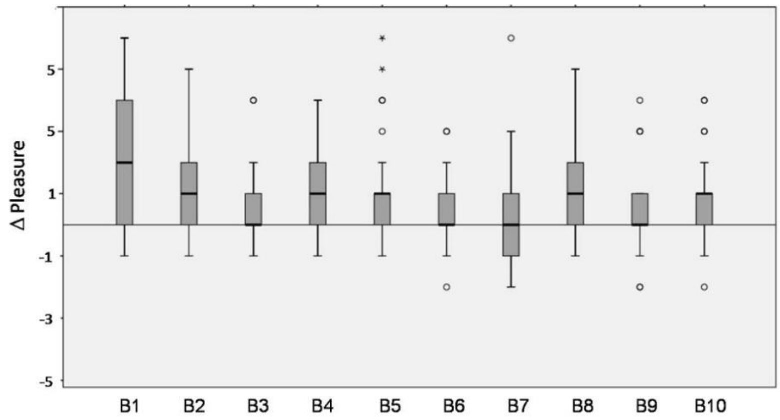


Figure 3.29 Boxplot graph of the distribution of the difference in the pleasure rating between each scenario and the answer at the beginning of the experiment.

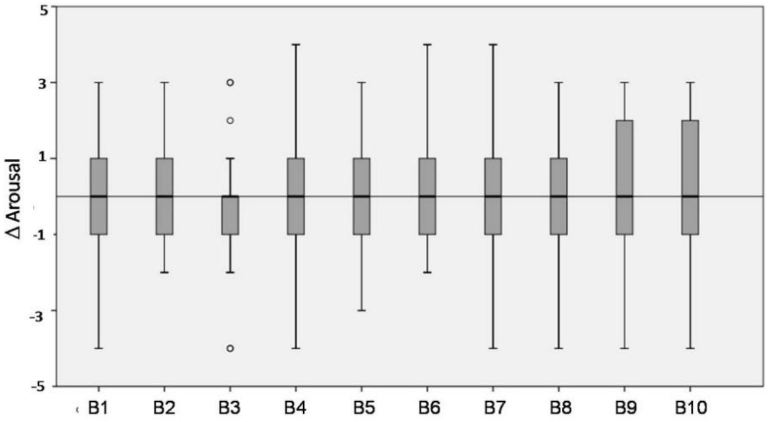


Figure 3.30 Boxplot graph of the distribution of the difference in the arousal rating between each scenario and the answer at the beginning of the experiment.

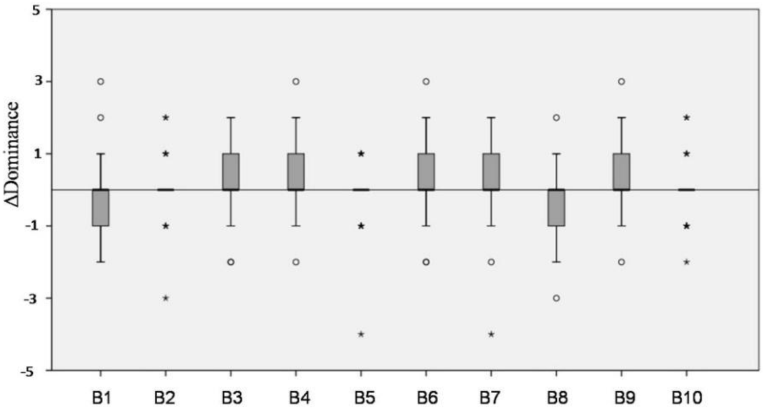


Figure 3.31 Boxplot graph of the distribution of the difference in the dominance rating between each scenario and the answer at the beginning of the experiment.

3.4.7 Effects on driver's performance

Like in study A (cf. Section 3.2.4), the position of the car on the virtual highway was tracked and analysed. The distance to the side lane was constantly measured during each test run. The standard deviation of this measure during the whole experimental run was considered a driving performance measure. For each test person the standard deviation was normalised, so that the scenario without ambient lighting (scenario B1) had a value of 1. The mean values of the normalised standard deviations are shown in Figure 3.32.

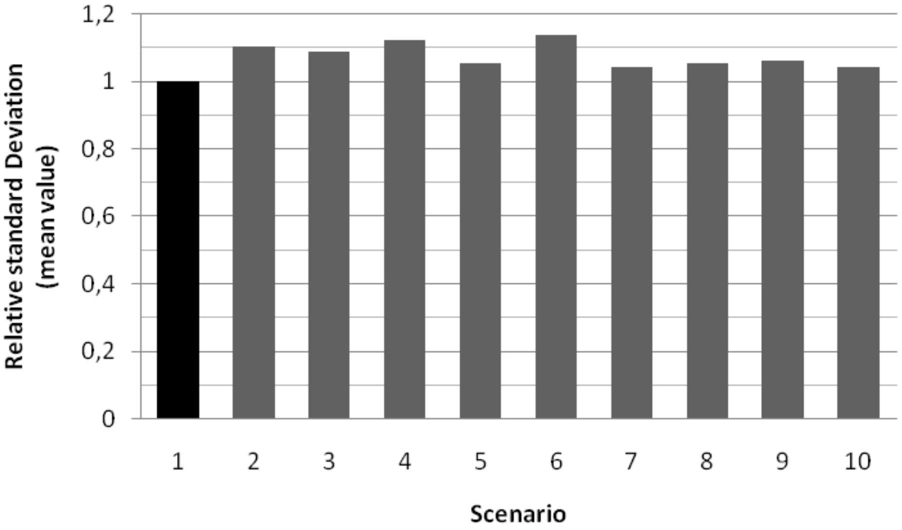


Figure 3.32 Driver's performance in the 10 scenarios of the MINI study. Standard deviation of the distance to the right lane: mean values for each scenario. The values were normalized so that the first scenario (without ambient lighting) was considered 1 for each test person. A bigger value implies a worse performance.

In order to evaluate the effect of ambient lighting on the driver's performance, an ANOVA on the performance data was carried out, giving no significant result (F=0,883, α=0,541). It could not be proven that the ambient lighting improved or decreased the driver's performance in the task of following the road.

3.4.8 Favourite luminance

Beside the main research study, two more surveys were performed, focusing on favourite luminance and colour for the ambient lighting. The participants were asked to find their favourite luminance level for the colours red, green and blue. By using special buttons placed on the steering wheel, the participants could set the ambient luminance level in order to find a configuration which they would feel comfortable driving with.

The choices are displayed in the Figure 3.33 in form of a Boxplot graph. The luminance scale indicates the mean luminance of the areas illuminated by ambient lighting.

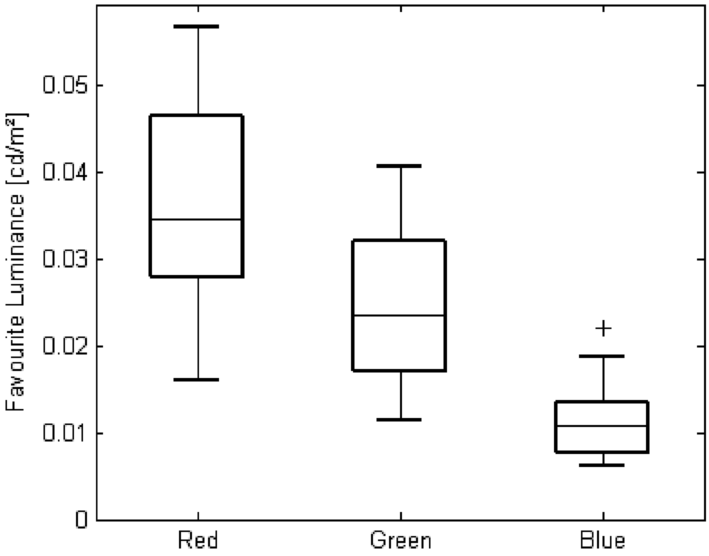


Figure 3.33 Favourite luminances of the three tested colours. The Boxplot graphs represent the answers distribution. The luminance on the vertical axis are the mean values calculated for the areas lit by ambient lighting in the whole cockpit from the driver point of view.

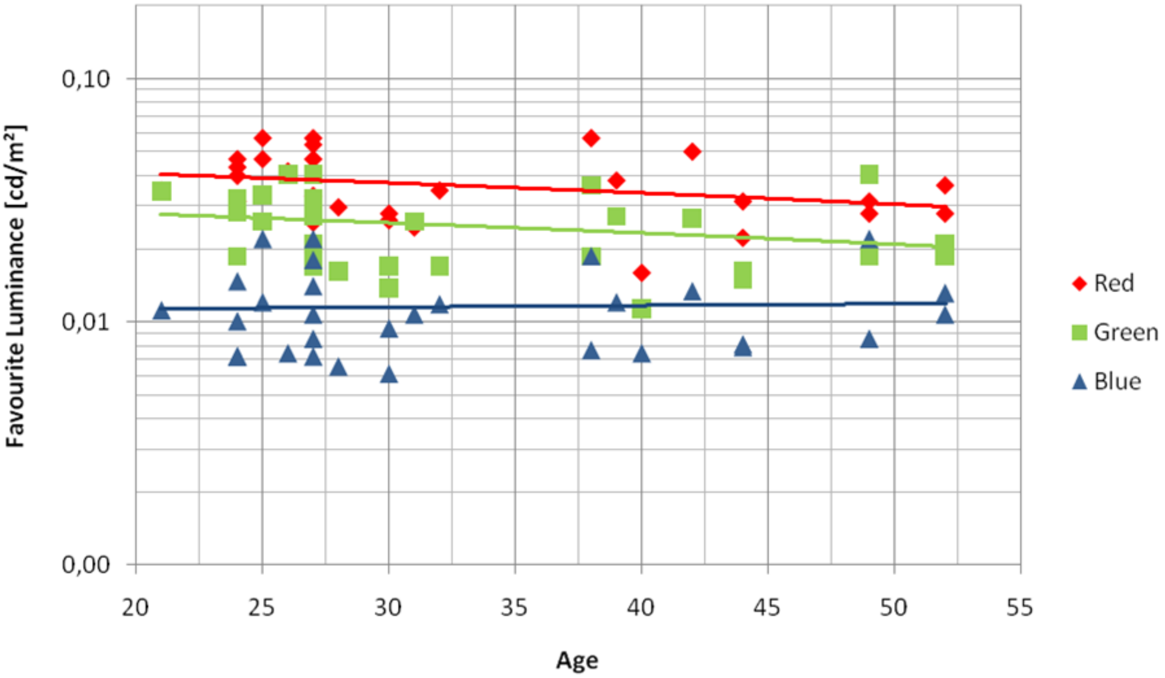


Figure 3.34 Distribution of the chosen luminances depending on the age of the participants. The lines in the graph represent the minimum mean square error line for each colour. There is no significant correlation between age and favourite luminance ($R^2<0,1$ and $p>0,5$ for each colour).

It can be noticed how blue colour must be set at a lower luminance level than green and red. This choice can be due to the fact that in a mesopic environment the blue is perceived brighter than in photopic conditions (Purkinje effect). Moreover, rods and blue cones are more dense in the peripheral regions of the retina, causing the blue to be perceived even brighter in the visual field periphery [64] [129] [11], where ambient lighting is usually perceived.

In Figure 3.34 it was attempted to put the chosen luminance level in correlation with the age of the test person, since it is known that colour vision and the perception of colours change with age [124], as well as the perception of brightness [1] [107] and glare sensitivity [109] [73].

No significant correlation was found between the luminance values and the age of the participants.

3.4.9 Favourite colour

In a similar way, the participants were asked to find their favourite colour in the range of the RGB spectrum featured by the LEDs installed in the vehicle. These LEDs featured on their red, green and blue chips dominant wavelengths of 617 nm, 528 nm, and 470 nm respectively. The colours to choose from were obtained by interpolating in turn two of the three basic colours. These colours are represented in Figure 3.35 in the CIE 1931 colour space.

The answers showed quite distributed preferences for each colour, which can be explained on the basis of personal tastes. Green constituted an exception, being almost rejected. This can be explained with the dominant orange colour of most of the interior textiles, which when illuminated with green light originated a black-brown impression, similar to the one of the black plastics parts. Blue lighting originated a similar colour impression, although with different shades. This probably led to a better acceptance.

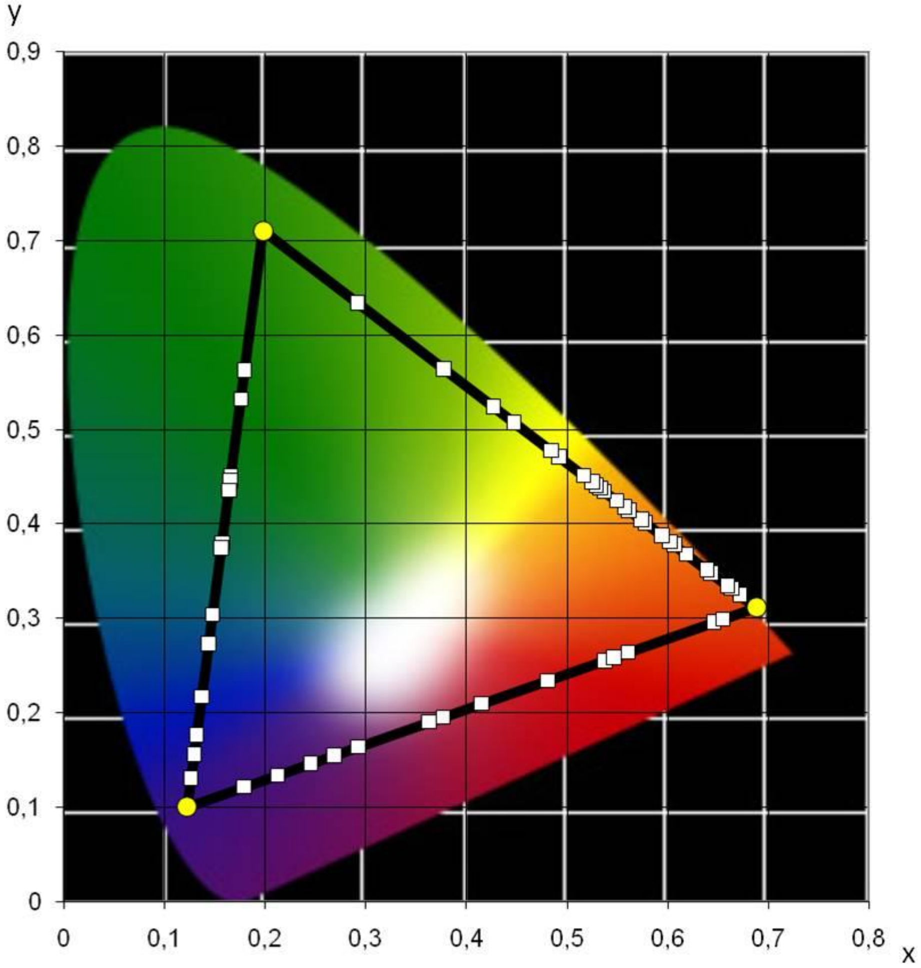


Figure 3.35 Favourite ambient lighting colours, displayed on a CIE 1931 colour space. The black triangle represents the colours which could be selected by the test persons. The three circles are in fact the measured position of the three chips on the employed LEDs. The white squares represent the choices of the test persons. Multiple choices of the same colour are not displayed. Their distribution on the triangle is quite uniform, apart from the absence of choices in the green area and a higher density of them in the red-orange area.

3.5 Experimental study C: field research study

In order to verify the results obtained in the simulator research studies A and B and to prove their effectiveness in real situations, a field research study was carried out.

3.5.1 Experimental design

The study consisted in a shortened “on the road” version of the simulator study A.
The vehicle employed in the study was the same BMW 3 Series provided with enhanced ambient lighting features employed in study A (cf. Section 3.3.2). Four selected ambient lighting scenarios were presented to 15 test persons (10 men and 5 women) who were asked to assess them while driving. One scenario was presented two times, once while driving on a country road without any street-lighting and once while driving on a city street provided with street lighting. Six participants took part in both street and simulator studies.
The tests were carried out on a country road in the north of Munich, Germany. The employed route was about 8 km long; its plan is displayed in Figure A.7 in the appendix. This choice guaranteed a similar lighting environment to the laboratory research study. In that case there was no representation of street lighting in the scene, since the simulation displayed a highway driving scene. Therefore, also in this study it was planned to drive on country road devoid of any street lighting. Apart from two traffic lights, there was no fixed lighting on the employed route. On the other hand, the lighting of incoming and preceding cars constituted a peculiar, though random, environmental condition. This kind of environmental lighting, which illuminates for few seconds the car interior and causes an attention shifting of the driver or even glare, was not taken into account in the drive simulation in the laboratory research study.
In the last test run, an ambient lighting scenario was displayed while driving on a city street: in this case fixed street lighting was present, as well as three traffic lights and oncoming traffic. The driven route (about 2 km long) is showed in Figure A.8 in the appendix. This test was made in order to state if there was a shift in the evaluation of the ambient interior lighting due exclusively to the environmental illumination.

3.5.2 Execution of the test

The test took place between the 27th of October and the 5th of November 2009 in the northern periphery of Munich, starting from the *Forschungs- und Innovationszentrum* of the BMW Group. Each session took place between 18:30 and 23:00, always after the astronomical twilight, guaranteeing in this way the same atmospheric illumination conditions.

At the rendezvous point the participants filled out a general questionnaire and the aims and procedure of the experiment were explained. The test began with a ten minute drive, in order to reach the planned route and to get the participants acquainted with the driving of the car. After reaching the defined start, the actual experiment started. Each ambient scenario was displayed for three minutes, while driving. After three minutes, the participants were asked to stop the car on the side lane or in a specific parking slot beside the road and to fill the questionnaire assessing the ambient lighting. The questionnaire was exactly the same as in study A. Its first part dealt with the subjective perception of the interior, and employed differential pair questions. The second part of the questionnaire dealt with the emotional state of the participants and was constituted by a SAM-Manikin (cf. Section 3.2.3). Since each person had their own driving style, and the traffic conditions were not always the same, the length driven in each run changed slightly for every participant.

After four scenarios were displayed in a country road environment, the fifth scenario was displayed while driving in a city street.

Because of the safety implications, secondary tasks were avoided in this study. Instead the participants were asked to use the controls and gear in the car interior as they would normally do, in order to make them feel comfortable.

The test lasted approximately one hour, including the preparation, the driving towards the circuit, and coming back.

3.5.3 Presented scenarios

The four ambient lighting scenarios were selected from the scenarios employed in the drive simulation in study A. These were presented to the participants in random order. An overview is given in Table 3.7.

These particular four scenes represented the whole spectrum of ambient lighting possibilities in that vehicle. The *without ambient lighting* scenario was considered the reference condition also in this case. The scenario *everything bright with accents* (A1) was assessed in the first study as annoying, if not glaring. Between these two extremes, the *series* scenario (A2) was chosen, in order to provide a comparison with the series production vehicle. The scenario which scored best in the drive simulation study (*everything on – middle level,* A8) was chosen as well. The latter was chosen for the experimental run under street lighting too. Ambient lighting colour was orange for all scenarios. The main varying dimension between the scenarios was therefore luminance.

Table 3.7 Ambient lighting scenarios employed in the field study. The identification numbers of the scenarios in both experiments A and C are provided.

Scenario	**Number (street)**	**Number (drive simulator)**
Without ambient lighting	C1	A5
Series	C2	A2
Everything on – middle level	C3	A8
Everything on – bright level with accents	C4	A1
Everything on – middle level - with street lighting	C5	A8

3.5.4 Environmental conditions

The lighting conditions of the roads in which the experimental study was carried out were measured. An illuminance meter (Pocket Lux, LMT, Berlin, Germany) was placed faced upwards on the centre of the dashboard of the car, in order to collect the illuminance due to street lighting and oncoming traffic. Also the illuminance on the eye of the driver was measured.

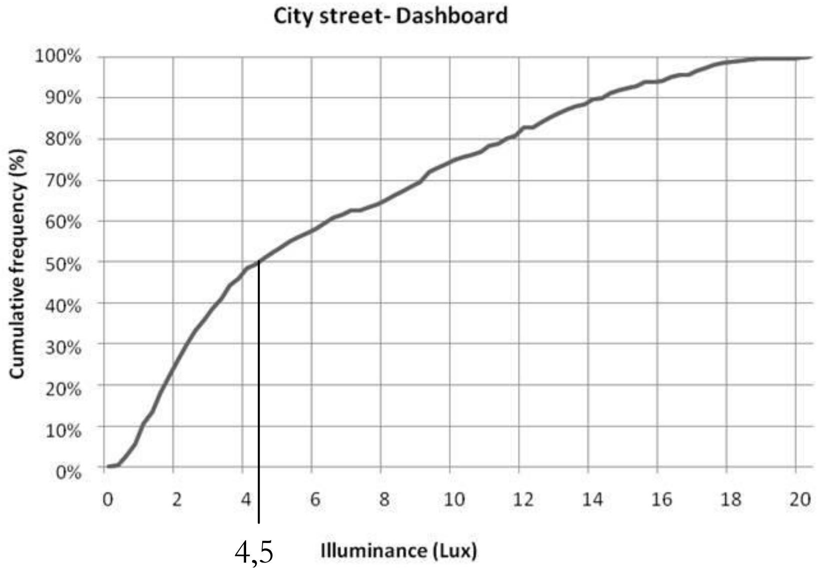


Figure 3.36 Cumulative frequency of the illuminance measured on the dashboard of the test vehicle during the scenario C5, while driving on a city street. The median value is displayed.

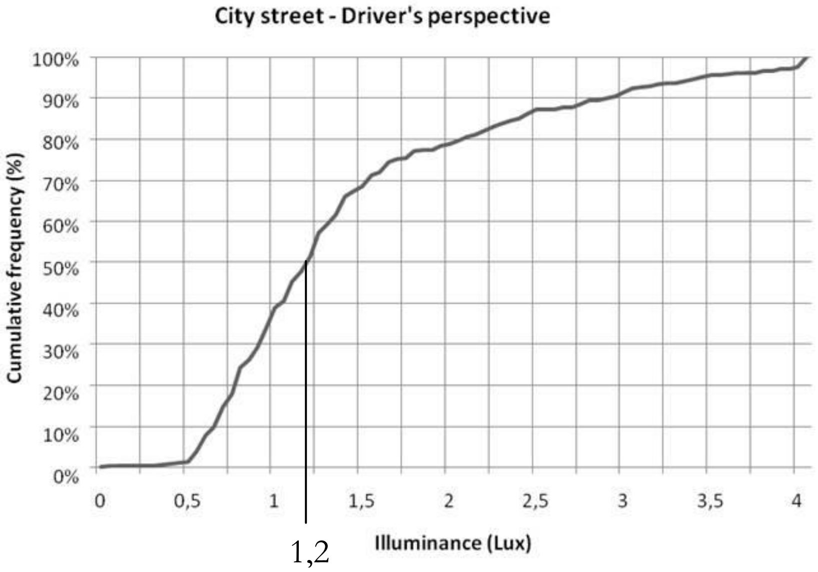


Figure 3.37 Cumulative frequency of the illuminance measured at the eye of the driver during the scenario C5, while driving on a city street. The median value is displayed.

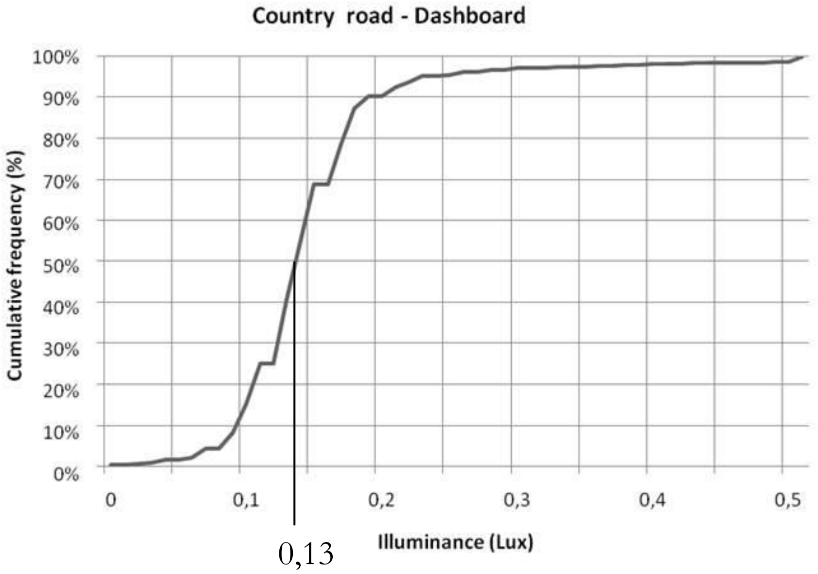


Figure 3.38 Cumulative frequency of the illuminance measured on the dashboard of the test vehicle during the scenarios C1 to C4, while driving on a country road. The median value is displayed.

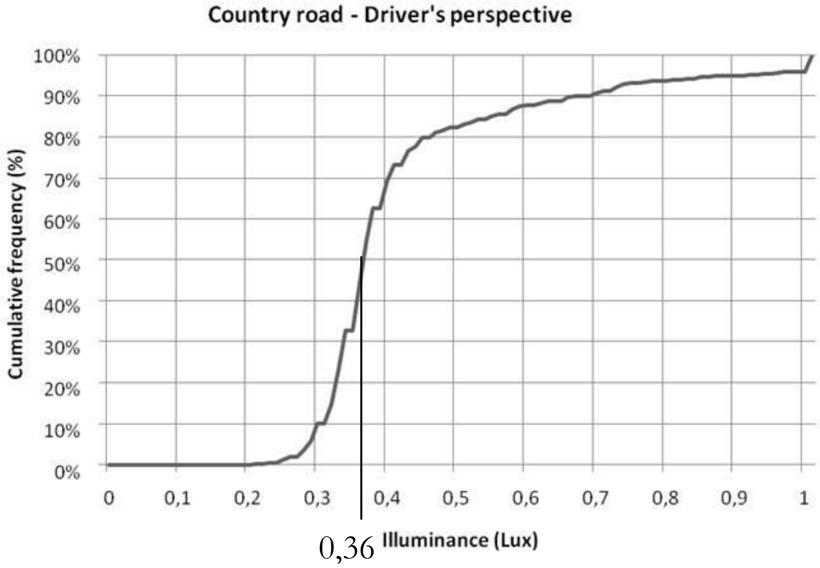


Figure 3.39 Cumulative frequency of the illuminance measured at the eye of the driver during the scenarios C1 to C4, while driving on a country road. The median value is displayed.

The cumulative frequency of the measured values is displayed in Figure 3.36 to Figure 3.39. On the dashboard shone a median illuminance of 0,13 lx on the country road and 4,5 lx in the city (ratio 34:1), while at eye level the measured median illuminances were respectively 0,36 lx and 1,2 lx (ratio 3,33:1). The former position gives a measure of the light level provided by the street lighting, while the latter is influenced also by the oncoming traffic.

3.5.5 Effects on the subjective perception

Similarly to study A, the answer distributions for different scenarios were compared with each other by means of a Wilcoxon signed-rank test. The comparisons provided significant and highly significant results. The detailed results to each question for each scenario are listed in Table A.17 and displayed in Figure A.9 in the appendix.

A comparison between the results of the simulator study and the field research is shown in Table 3.8. Here four relevant comparisons are displayed and for each comparison the results of a 2-tailed Wilcoxon signed-rank test. The highlighted cells indicate significant and highly significant differences. The symbols in the highlighted cells give the direction in which the differences are significant.

Table 3.8 Comparison of the significant results obtained in the laboratory study A (columns A) and in the field study C (columns C). The significant results (p<0,05) are highlighted in light grey, while highly significant results (p<0,01) are highlighted in dark grey. The symbols in each cell indicate which scenario obtained a higher score in the specific question. The scenario numbers refer to Table 3.7

	Comparison	**C1 (¤) – C2(Δ)**		**C2 (¤) – C3 (Δ)**		**C2 (¤) – C4(Δ)**		**C3 (¤) – C4 (Δ)**	
	Question	**A**	**C**	**A**	**C**	**A**	**C**	**A**	**C**
1	Impression of space	Δ	Δ						
2	Perception of the whole interior	Δ	Δ			Δ			
3	Comfortable light colour	Δ	Δ					¤	
4	I like it	Δ	Δ			¤		¤	
5	To bright – too dark	Δ			Δ	Δ	Δ	Δ	Δ
6	Looks pleasant	Δ	Δ			¤	¤	¤	¤
7	Is comfortable	Δ	Δ		¤	¤	¤	¤	¤
8	Perceived value	Δ	Δ			¤		¤	
9	Luxurious	Δ	Δ			¤			
10	Makes me powerful	Δ	Δ						
11	Enhances orientation	Δ	Δ						
12	Finding of control elements	Δ	Δ	Δ				¤	¤
13	Disturbing reflections					¤	¤	¤	¤
14	Keep□ my attention on driving	Δ		¤		¤	¤	¤	¤
15	Enables concentration	Δ				¤			
16	Activates me	Δ	Δ				Δ		Δ
17	Animates me	Δ					Δ		Δ
18	Perceived safety	Δ	Δ			¤		¤	

This comparison leads to several considerations.

- The field research provided fewer significant results. On one hand, this is due to the number of participants involved: 15 against 31. On the other hand, external unknown factors were added to the experiment. Therefore, a decrease of significance was expected.
- Not each significant result in the laboratory study was confirmed in the field research. Few significant results in the field research had not appeared in the laboratory study before. Apart from these small incongruences, the two studies match completely, most meaningfully for the directions of the significant differences.
- This matching is a validation of the simulator experience. The evaluation of vehicle interior ambient lighting in such environmental conditions was carried out for the first time in this context. The results obtained in the simulator environment were confirmed by the field study.

Table 3.9 Comparison of the mean values obtained in the simulator study A and in the field study C for similar ambient lighting scenarios. Scenarios are described in Table 3.7. The questions numbers and items of the differential pairs are listed in Table 3.3. On these results an unpaired t-test was carried out: * indicates a significant difference between the two results (p<0,05); ** indicates an high significant difference (p<0,01).

Question Number	A5	C1		A2	C2		A8	C3		A1	C4	
1	0,42	0,40		0,61	0,59		0,62	0,61		0,62	0,63	
2	0,25	0,19		0,56	0,54		0,65	0,70		0,66	0,72	
3	0,54	0,45	**	0,68	0,77	*	0,69	0,74		0,62	0,69	
4	0,38	0,34		0,67	0,63		0,69	0,60		0,49	0,49	
5	0,32	0,26		0,44	0,38		0,48	0,49		0,75	0,73	
6	0,47	0,42		0,66	0,72		0,69	0,67		0,47	0,46	
7	0,45	0,44		0,67	0,75		0,66	0,64		0,46	0,42	
8	0,44	0,41		0,68	0,68		0,69	0,63		0,57	0,56	
9	0,45	0,42		0,67	0,68		0,66	0,61		0,58	0,56	
10	0,39	0,39		0,52	0,48		0,55	0,52		0,48	0,49	
11	0,28	0,33		0,63	0,64		0,69	0,72		0,63	0,61	
12	0,26	0,29		0,58	0,61		0,68	0,74		0,63	0,57	
13	0,84	0,92		0,84	0,94	*	0,80	0,95	**	0,25	0,17	
14	0,51	0,60	*	0,57	0,58		0,53	0,55		0,42	0,34	
15	0,46	0,56	*	0,54	0,56		0,55	0,49		0,46	0,42	
16	0,40	0,44		0,52	0,49		0,56	0,53		0,56	0,63	
17	0,43	0,44		0,52	0,50		0,53	0,54		0,55	0,70	**
18	0,41	0,41		0,57	0,54		0,62	0,56		0,46	0,46	

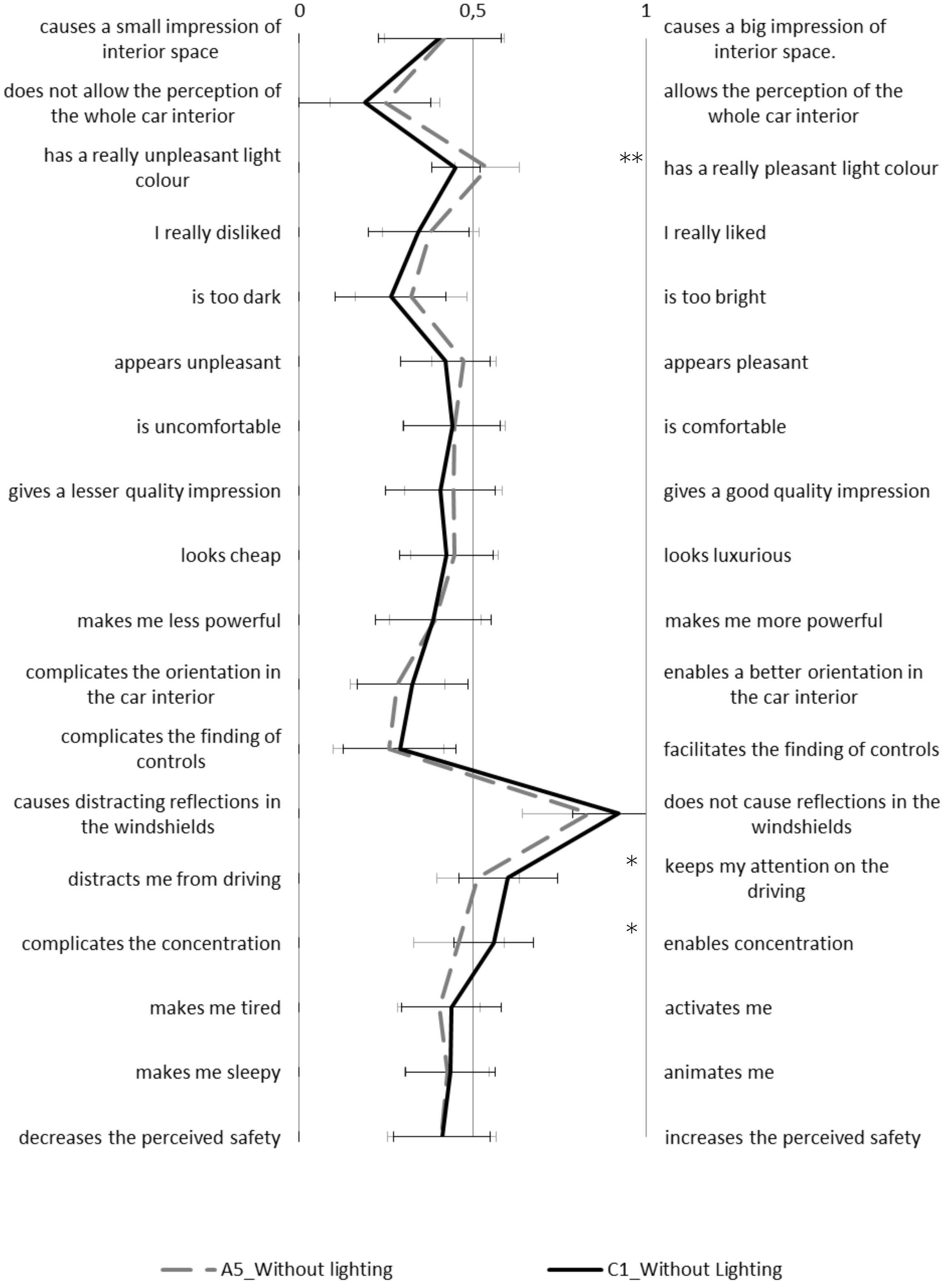


Figure 3.40 Results of the comparison between studies A and C. The scenarios *without lighting* are compared. For each question the mean value and the standard deviation of the answers are represented. * indicates a significant difference between the two results (p<0,05); ** indicates an high significant difference (p<0,01).

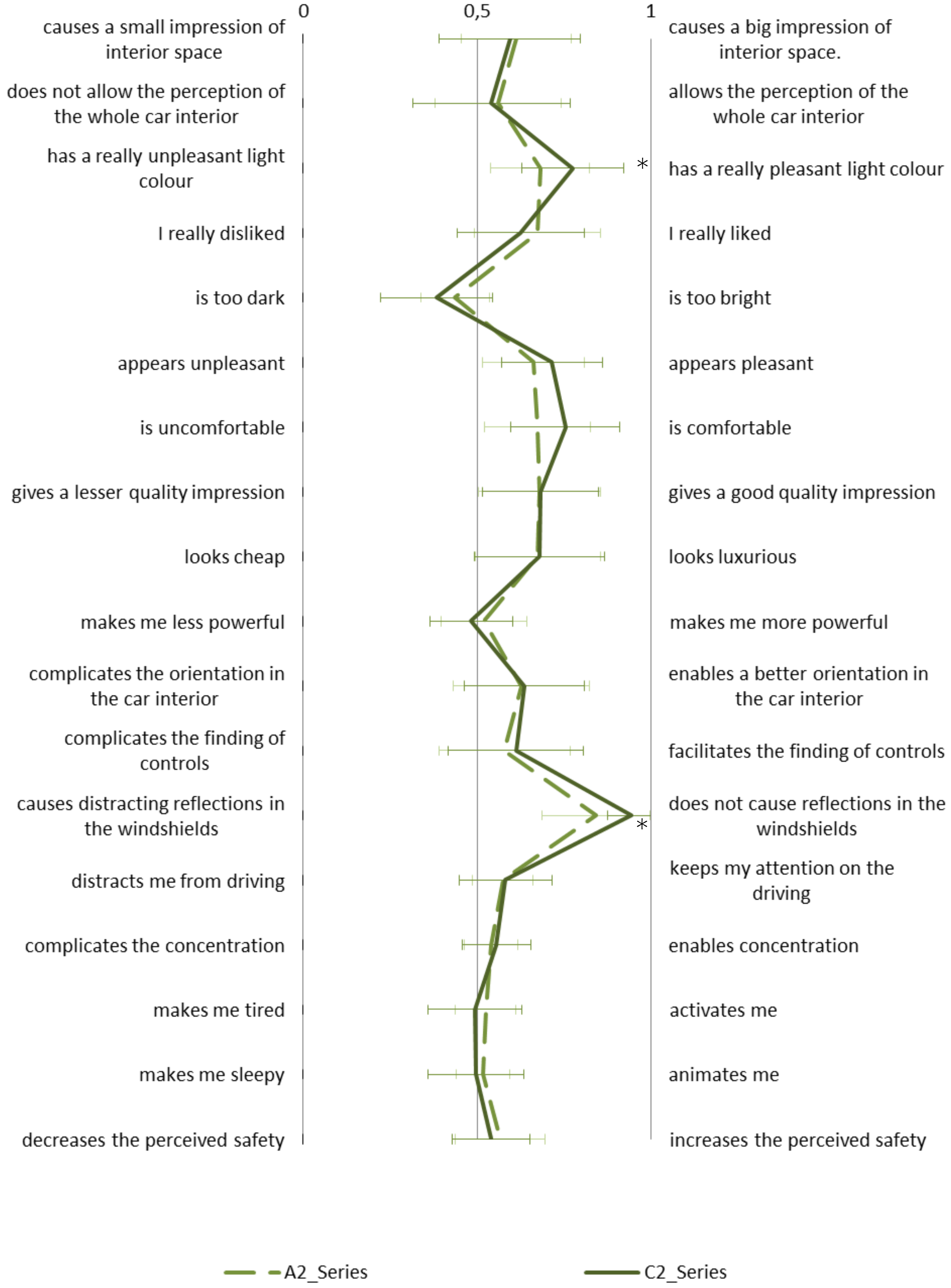


Figure 3.41 Results of the comparison between studies A and C. The *series* scenarios are compared. For each question the mean value and the standard deviation of the answers are represented. * indicates a significant difference between the two results (p<0,05); ** indicates an high significant difference (p<0,01).

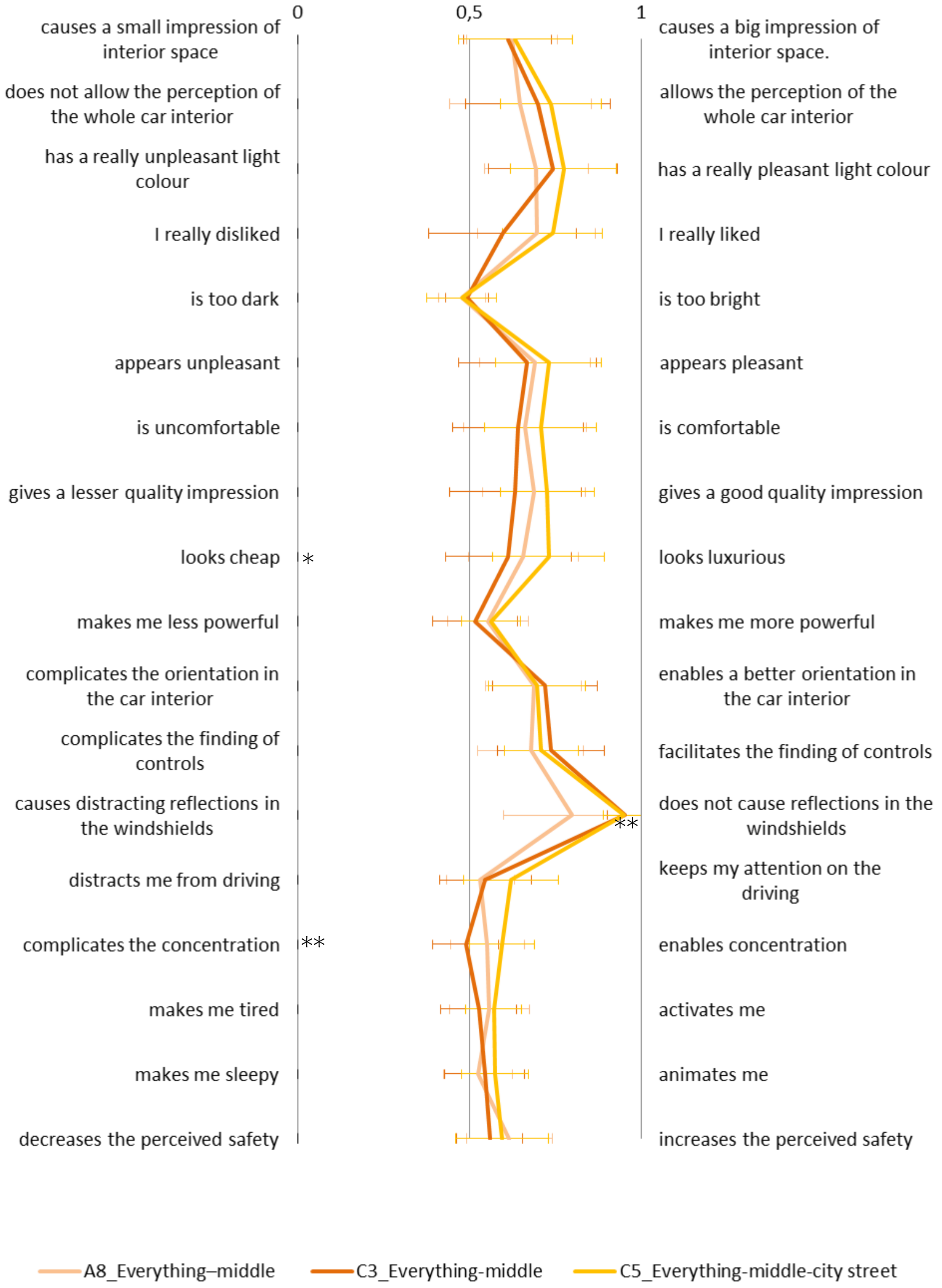


Figure 3.42 Results of the comparison between studies A and C. The *everything on - middle* scenarios are compared. For each question the mean value and the standard deviation of the answers are represented. * indicates a significant difference between the two results (p<0,05); ** indicates an high significant difference (p<0,01). Here also the scenarios with and without street lighting are compared. On the right side of the graph the significance level for the comparison A8-C3 is displayed, on the left side for the comparison C5-C3.

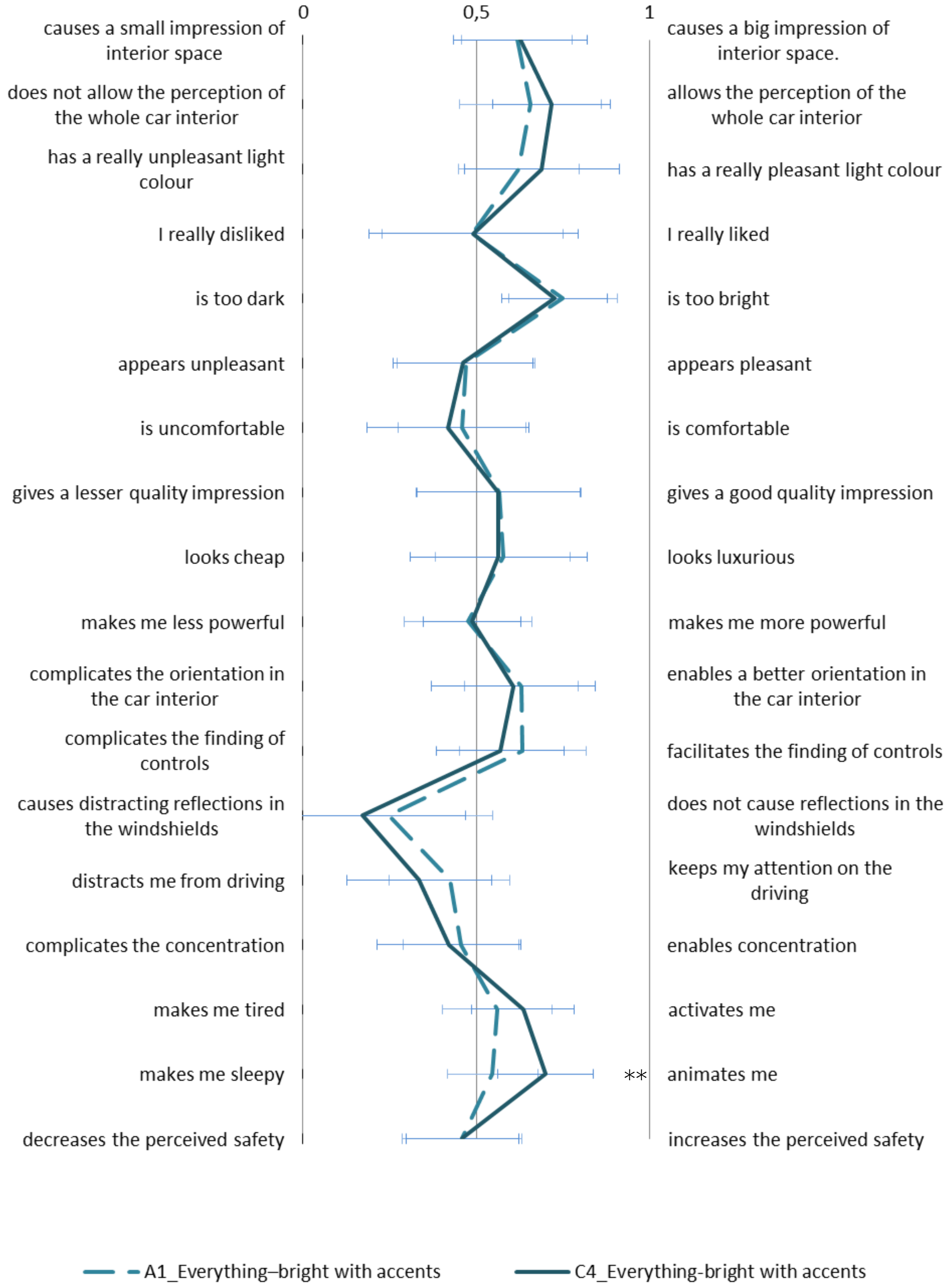


Figure 3.43 Results of the comparison between study A and C. The scenarios *everything on – bright with accents* are compared. For each question the mean value and the standard deviation of the answers are represented. * indicates a significant difference between the two results (p<0,05); ** indicates an high significant difference (p<0,01).

The results of the two studies were also compared on an absolute level, employing an unpaired t-test, as displayed in Table 3.9 and in Figure 3.40 to Figure 3.43. Significant differences were found only in the assessment of distracting reflections (in the comparisons of the scenarios *series* A2 – C2 and *everything on – middle level* A8 – C3), pleasantness of colour (comparisons *without lighting* A5 – C1 and A2 – C2) and attention and concentration (A5 – C1). The results show how similar are the assessments provided on the street and in the simulator. This is a further confirmation to the reliability of the results obtained in the simulator.

For each question i and each scenario j the mean value of the evaluations given by all the test persons were calculated: $\overline{A_{ij}}$ for the laboratory experiment and $\overline{C_{ij}}$ for the field study. The difference between these values is the difference between the evaluations in both environmental conditions: $d_{ij} = \overline{A_{ij}} - \overline{C_{ij}}$. The mean absolute difference is $\overline{|d_{ij}|} = 0{,}041$. The evaluation scale spanned between 0 and 1, so the resultant mean discrepancy between the evaluations on the two experiments can be considered about 4% in respect to the whole interval.

A Quantile-Quantile (Q-Q) plot of the difference values against a normal distribution (Figure 3.44) shows that, apart from the extreme values, their distribution is normal. This result is confirmed by the same analysis carried out on data limited to the answers of the participants of both studies. Moreover, the median of the differences distribution is 0, indicating that these are equally distributed between positive and negative values.

This fact indicates the consistency of the evaluation in the two different environments: although the different conditions and different participants, similar evaluations were given to the same scenarios. Moreover, these results show that the outcomes of the studies carried out in the simulator are realistic and can be used as sensible and faithful data for further developments. In fact, the same scenes in simulator and on the street were evaluated in the same way.

Another consideration can be drawn for the comparison between the same scenario experienced under street lighting and under no lighting (C3-C5) (Figure 3.42). This comparison provided no significant outcomes apart from questions *looks luxurious / looks cheaper* ($p<0{,}05$) and *complicates the concentration / enables concentration* ($p<0{,}01$). Here the same scenario displayed under street lighting obtained a better score than when displayed without street lighting. A similar not significant trend is present in many other questions. Since there are not almost any significant results, it is inferred that a similar assessment was given despite the external conditions. Though, the situation with street lighting was slightly preferred. This fact hints that a harmonisation of the visual light levels between car interior and outside view is perceived and assessed pleasing and comfortable.

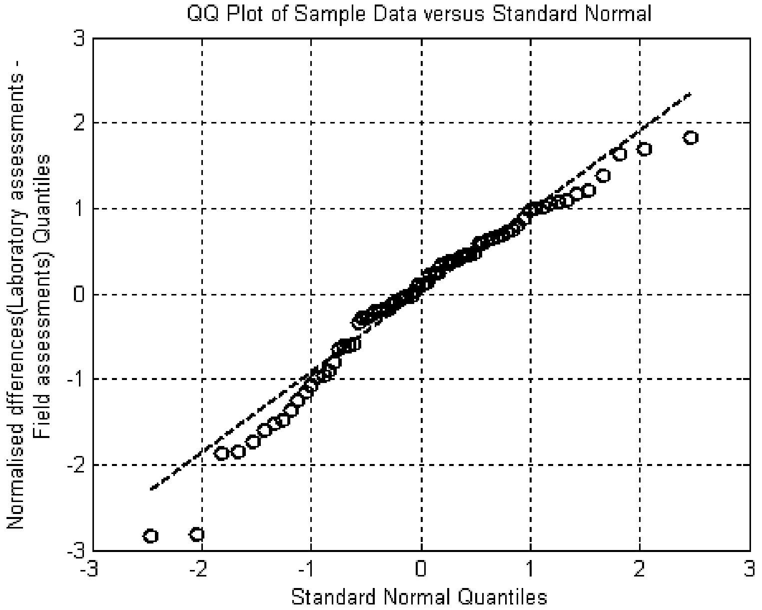


Figure 3.44 Quantile-Quantile Plot of the differences in assessment between the field and laboratory study, plotted against a normal Gaussian distribution. The differences, represented on the vertical axis, are normalised to their standard deviation. The extreme values are outliers. Since the values follow a straight line, it is assumed that the distribution of the differences is normal. The median value is also 0, meaning that the differences are equally distributed in both positive and negative direction.

A wider research study, focused on the effects of the external conditions on the perception of the interior, would give more specific indications in this topic. In fact, similar conclusions are already applied in the study of vehicle instrumentation lighting and displays. In both fields an adaptation to the external light level is compulsory to obtain more comfortable and functional driving conditions [115].

4 Analysis of the experimental data

4.1 Analysis of the results on subjective perception

The answers provided in studies A and B were run through a factor analysis. This technique is employed in the psychological and social studies in order to understand which are the basic independent dimensions behind a data structure. Thereby, the real issues and motivations which drive the test persons to give determinate assessments are researched [5]. In order to complete the picture, correlation tests between the various answers distributions in the two studies were carried out (Table A.5 and Table A.12 in the appendix, respectively for study A and study B).

Table 4.1 Factor analysis of the answers distributions in study A. The factor loadings λ for four factors are listed. The loadings λ>0,5 are represented in bold. The factors are named after their most important qualities. Only the positive side of the question is listed.

	Attractiveness and perceived quality	**Space perception and orientation**	**Perceived safety and attention**	**Activation**
causes a big impression of interior space	0,28	**0,56**	0,10	0,16
allows the perception of the whole car interior	0,29	**0,79**	0,23	0,11
enables a better orientation in the car interior	0,32	**0,77**	0,31	0,14
facilitates the finding of controls	0,24	**0,78**	0,26	0,14
is too bright	-0,02	**0,57**	-0,27	0,20
has a really pleasant light colour	**0,66**	0,06	0,16	0,09
I really liked	**0,73**	0,26	0,42	0,16
appears pleasant	**0,70**	0,14	0,45	0,07
is comfortable	**0,70**	0,08	0,33	0,11
gives a good quality impression	**0,86**	0,24	0,23	0,16
looks luxurious	**0,88**	0,21	0,16	0,15
makes me more powerful	0,29	0,35	**0,56**	0,33
increases the perceived safety	0,38	0,30	**0,59**	0,06
keeps my attention on the driving	0,25	-0,03	**0,72**	0,10
enables concentration	0,23	0,01	**0,74**	0,24
animates me	0,28	0,38	0,40	**0,60**
activates me	0,19	0,32	0,23	**0,86**
does not cause reflections in the windshields	0,20	-0,40	0,13	-0,06

Table 4.2. Factor analysis of the answers in study B. The factor loadings λ for four factors are listed. The loadings λ>0,5 are represented in bold. The factors are named after their most important qualities. Only the positive side of the question is listed.

	Space perception and orientation	**Attractiveness and perceived value**	**Perceived safety and attention**	**Absence of glare**
causes a big impression of interior space	**0,73**	0,45	-0,01	-0,12
allows the perception of the whole car interior	**0,91**	0,17	-0,02	-0,12
enables a better orientation in the car interior	**0,85**	0,17	0,06	-0,10
is too bright	**0,71**	0,20	-0,32	-0,36
has a really pleasant light colour	0,05	**0,58**	0,20	0,00
I really liked	0,46	**0,71**	0,23	0,03
appears pleasant	0,35	**0,69**	0,48	0,09
gives a good quality impression	**0,50**	**0,70**	0,14	0,01
keeps my attention on the driving	-0,03	0,32	**0,63**	0,23
activates me	-0,10	0,13	**0,59**	0,14
increases the perceived safety	**0,53**	0,33	**0,58**	-0,02
it's not glaring at all	-0,32	0,07	0,39	**0,81**

The results of the factor analysis are listed in Table 4.1 and Table 4.2 for study A and B respectively. In the two tables the factor loadings λ are displayed. Four factors are needed to describe the majority of the variance in the answers distributions. The obtained factors have been named after their most important components. Their distribution gives an insight of the way in which the test persons assessed the lighting scenarios and how the subjective perception is structured. The results of the two studies differ slightly from each other, due to the different sets of questions, as explained in section 3.4.4.

In both studies, the assessment on *space perception and orientation* is independent from the assessment on *attractiveness and quality impression*. Only in study B the answer on the *quality impression* is related to both factors. The third factor *perceived safety and attention* relates to the actual task of driving: the driver feels safe in the cockpit, while concentrating on the street and focusing his attention to his task. The fourth factor is different in the two studies. In study A, it is called *activation* while in study B it is the *absence of glare*. This difference is purely caused by the different sets of questions used in the studies.

This analysis shows that the attractiveness and comfort is not directly related to the absence of glaring nor to space perception.

The similarity between the two factor analysis (study A and B) underlines that, although in two different vehicles and under different lighting conditions, different test persons answered the questions with similar, if not the same, logic and motivations. In both studies, the majority of questions can be grouped in the two categories *space perception and orientation* and *attractiveness and perceived value.*

Table 4.3 Factor analysis for the data of the studies A, B and C. Only the common questions have been considered. The factor loadings λ for four factors are listed. The loadings λ>0,5 are represented in bold.

	Space perception and orientation	**Attractiveness and perceived quality**	**Perceived safety**	
causes a big impression of interior space	**0,69**	0,38	0,14	-0,05
allows the perception of the whole car interior	**0,84**	0,22	0,22	0,13
is too bright	**0,69**	0,09	-0,18	0,13
enables a better orientation in the car interior	**0,79**	0,22	0,32	0,06
has a really pleasant light colour	0,12	**0,60**	0,12	-0,27
I really liked	0,29	**0,82**	0,38	0,32
appears pleasant	0,21	**0,69**	**0,52**	-0,16
gives a good quality impression	0,41	**0,69**	0,28	0,00
increases the perceived safety	0,37	0,34	**0,64**	-0,04
keeps my attention on the driving	0,12	-0,05	-0,12	0,18
activates me	0,00	0,19	0,48	-0,11

By performing the same analysis on the complete data set of the three studies A, B, and C, the results listed in Table 4.3 are provided. Only the questions common to the three studies have been considered in this analysis. Regarding the two main factors *space perception* and *attractiveness*, the results are very similar to the previous two factor analyses. In this case, the third factor is embodied only by the *perceived safety*. This difference is probably due to the different number of questions considered (11 instead of 18 and 12 respectively).

The whole analysis suggests that three independent main criteria have to be considered in the assessment of ambient lighting, as represented in Figure 4.1. The illumination settings which maximises the three main criteria defines the optimal layout for ambient lighting.

In order to provide this assertion with more understanding, the factor values for the scenarios of studies A and B were calculated. In this way, the evaluations obtained by the different answer distributions can be concentrated in just four values, instead of 18 (for study A) and 12 (for study B).

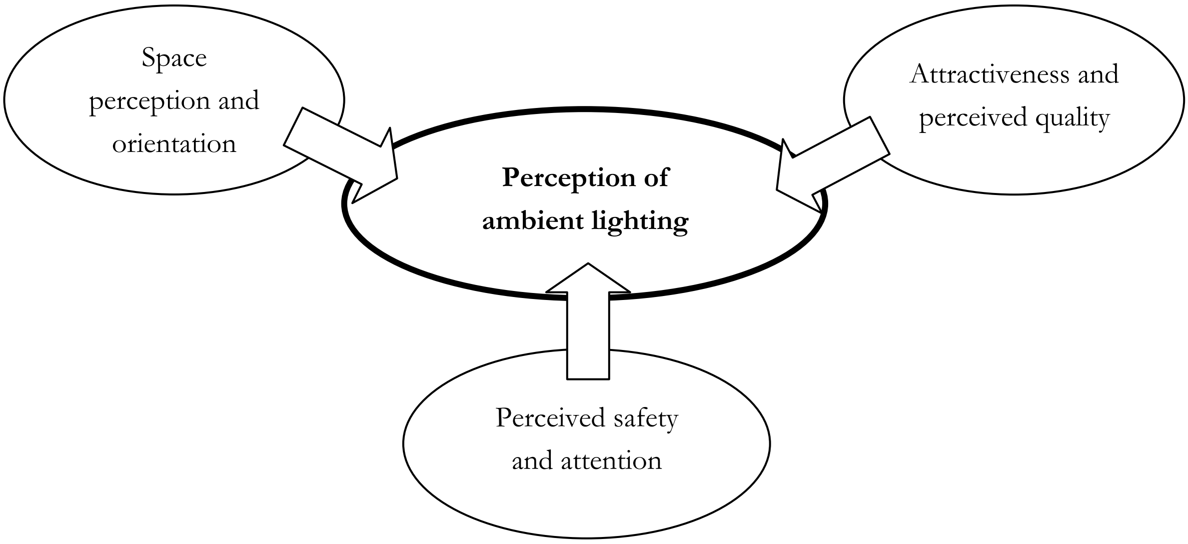


Figure 4.1 Main independent factors contributing to the perception of ambient lighting in vehicle interior.

The factor values F for each scenario are obtained as follows:

$$A - A_m = \lambda F + \varepsilon \qquad (3.2)$$

where A is the answers matrix, A_m is the vector of the mean values for each question, λ is the matrix of the factor loadings, F is the matrix of factor values and ε a random error. λ was obtained by the above mentioned factor analysis; A is composed by the mean answers of all the test persons for each scenario and each question; A_m is composed by all the mean answers (of all the test persons and scenarios) for each question. Therefore, F can be calculated.

F provides the values of the four factors for each scenario. It is supposed that the variations of the answers matrix A can be explained by a linear combination of the factor values and their respective factor loadings. The values of F describe the perception of the lighting scenarios through the four independent criteria obtained in the factor analysis.

The factor values F for the two studies A and B are displayed respectively in Table 4.4 and Table 4.5 and in Figure 4.2 and Figure 4.3. These ratings give an immediate insight on the evaluation of the scenarios. Their interpretation is clearly faster and easier than the interpretation of the statistical analysis in sections 3.3.4 and 0.

Table 4.4 Values of the four factors for each scenario of study A.

		Attractiveness and perceived quality	Space perception and orientation	Perceived safety and attention	Activation
A1	Everything on – bright with accents	-0,078	0,269	-0,103	0,017
A2	Series	0,124	-0,013	0,053	-0,048
A3	Doors – bright	0,028	-0,039	-0,041	0,058
A4	Doors – low	0,050	-0,075	-0,022	0,019
A5	Without lighting	-0,088	-0,313	0,022	0,033
A6	Everything on – bright	0,055	0,095	-0,076	-0,009
A7	Everything on – low	0,071	0,080	0,012	-0,017
A8	Everything on – middle	0,103	0,091	0,066	-0,074
A9	Foot space – bright	-0,048	-0,119	-0,024	0,025
A10	Foot space – low	-0,048	-0,187	-0,037	0,065
A11	Centre console	-0,025	-0,100	0,058	-0,040
A12	Everything on blue – low	-0,145	0,241	0,092	-0,010

Table 4.5 Values of the four factors for each scenario of study B.

		Space perception and orientation	Attractiveness and perceived value	Perceived safety and attention	Absence of glare
B1	Without Lighting	-0,354	-0,150	0,053	0,037
B2	Red series	-0,246	0,045	0,023	0,014
B3	Blue series	-0,044	0,081	0,041	-0,022
B4	Green series	-0,251	-0,006	0,009	0,060
B5	Turquoise bright	0,211	-0,051	-0,029	-0,008
B6	Red bright	0,080	0,091	0,020	0,058
B7	White bright	0,301	0,053	-0,017	0,047
B8	Green bright	0,086	-0,215	0,113	0,025
B9	Blue bright	0,195	0,033	0,060	-0,047
B10	Blue brightest	0,197	0,061	-0,188	-0,203

The three main factors are independent from each other. Therefore, some scenarios maximize only one factor, while minimizing the others (e.g. the scenario A1, *everything bright with accents*, which offers a high *space perception and orientation* but poor *attractiveness and perceived quality* and *safety impression*). A well perceived scenario must fulfil the three main criteria equally, without privileging only one.

Scenario A8 maximised all three main criteria, resulting also the best perceived one. Other scenarios provided enhancements only to one aspect, but failed to improve the other two. For example, scenario A2 guaranteed the higher attractiveness but could not provide an adequate space perception. On the other end, scenario A12 with its blue light offered an extremely high space perception but was assessed uncomfortable.

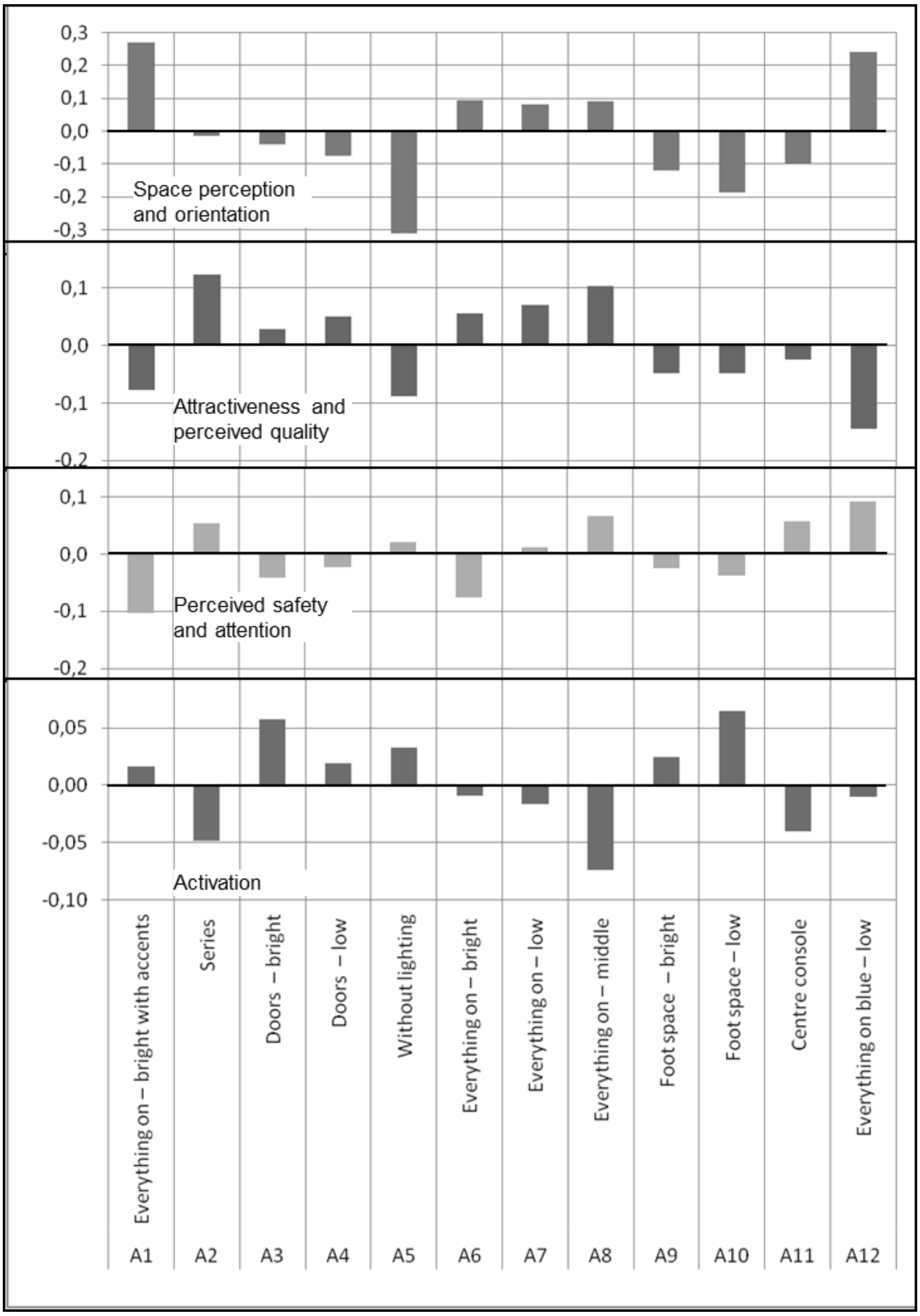


Figure 4.2 Plot of the factor values for each scenario in study A.

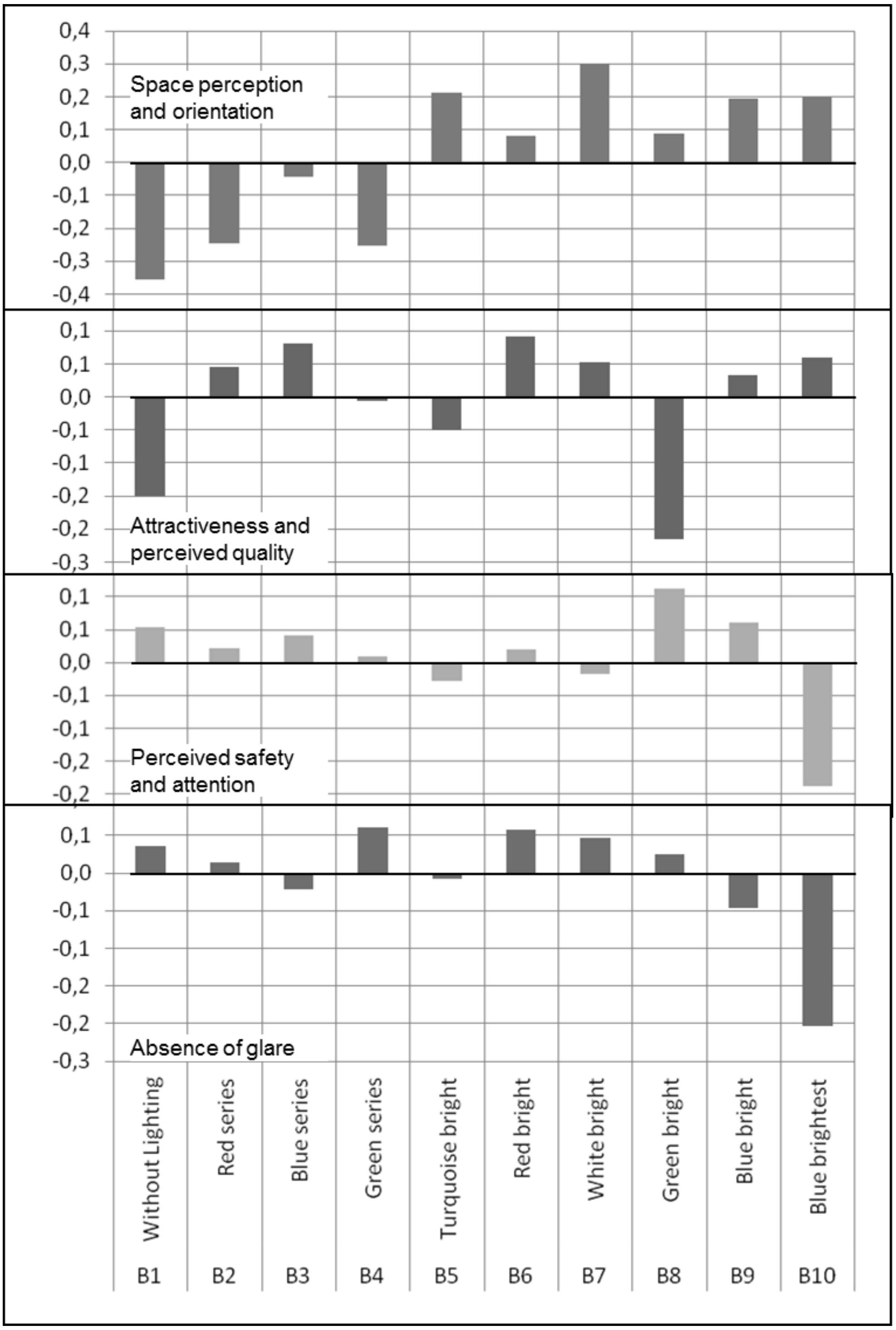


Figure 4.3 Plot of the factor values for each scenario in study B.

4.2 Influences of luminance and position of the light sources

4.2.1 Luminance measurements of ambient lighting

A fish-eye luminance measurement from the driver's point of view gave a helpful overview on the ambient lighting distribution in the car cockpit (Figure 4.4).

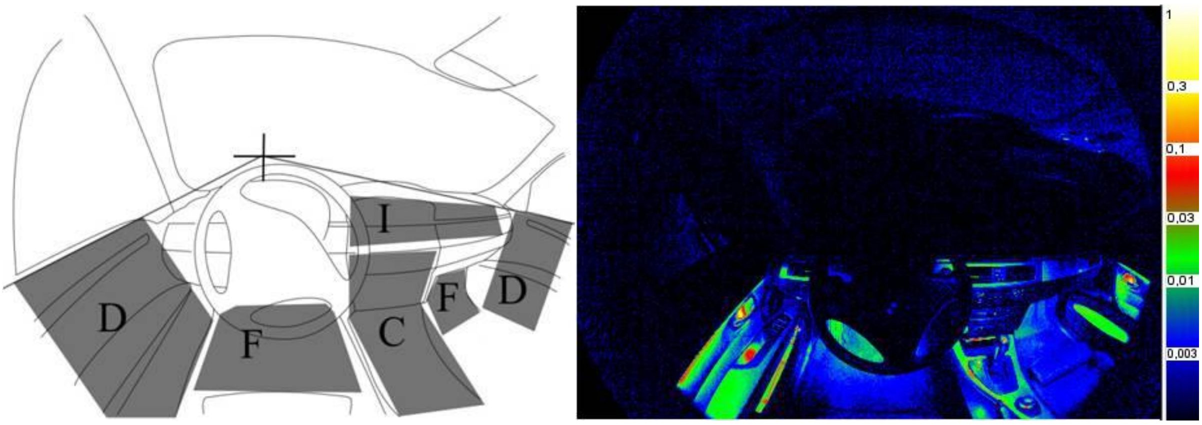


Figure 4.4: Example of luminance measurement of ambient lighting in car interior. Left – Luminance measurement zones. D: doors, F: foot space, C: centre console, I: instrument panel. Right – false colour representation with fish-eye optic. The luminance is indicated in cd/m².

The luminance of the illuminated zones in the experimental vehicles was measured using a luminance camera provided with a fish-eye optic (luminance camera LMK Mobile Advanced, TechnoTeam, Ilmenau / Germany). In this way, the luminance in the whole field of view was measured from the driver's perspective. The visual field was divided into different zones (Figure 4.4 left), which represent the illuminated areas of the interior: *D* the door trims, *C* the centre console, *F* the foot space, and *I* the instrument panel. In these zones, only the measured points with a photopic luminance between 0,002 cd/m² and 0,3 cd/m² were considered. These points were considered illuminated by ambient lighting. Luminances below the 0,002 cd/m² were considered dark, while those above the 0,3 cd/m² were considered symbol lighting. Therefore measure points beyond these thresholds were not measured together with ambient lighting. Cockpit lighting as well as backlit symbols was not considered in the measurements.

For each measure point, the luminance L_i and the solid angle Ω_i under which the driver sees it were considered.

An evaluation of a mean luminance is not sufficient for describing how bright a surface is. Also the solid angle under which the illuminated areas (between 0,002 cd/m² and

0,3 cd/m²)are seen by the driver shall be considered too, since it varies widely, depending on the luminance level of the light source.

For each zone an Index W was calculated, which represents the brightness of the considered zone.

$$W = 5 + log_{10}\left(\sum_i \Omega_i L_i\right) \tag{4.1}$$

In this formula, L_i and $\mathbf{\Omega}_i$ represent respectively the luminance and the solid angle of each measured pixel i in the evaluation image. In the sum only the points with luminance between 0,002 and 0,3 cd/m² are considered. The constant 5 is given, so that W has positive values by illuminances higher than 0,00001 lx. This formula is similar to the UGR-formula (Unified Glare Rating) [13] [103]. Though, in the UGR-formula the luminance is calculated to the power of 2, and the adaptation luminance is also considered. A similar formula was obtained by GRIMM [45], which described ambient lighting in relation with the discomfort glare caused by it.

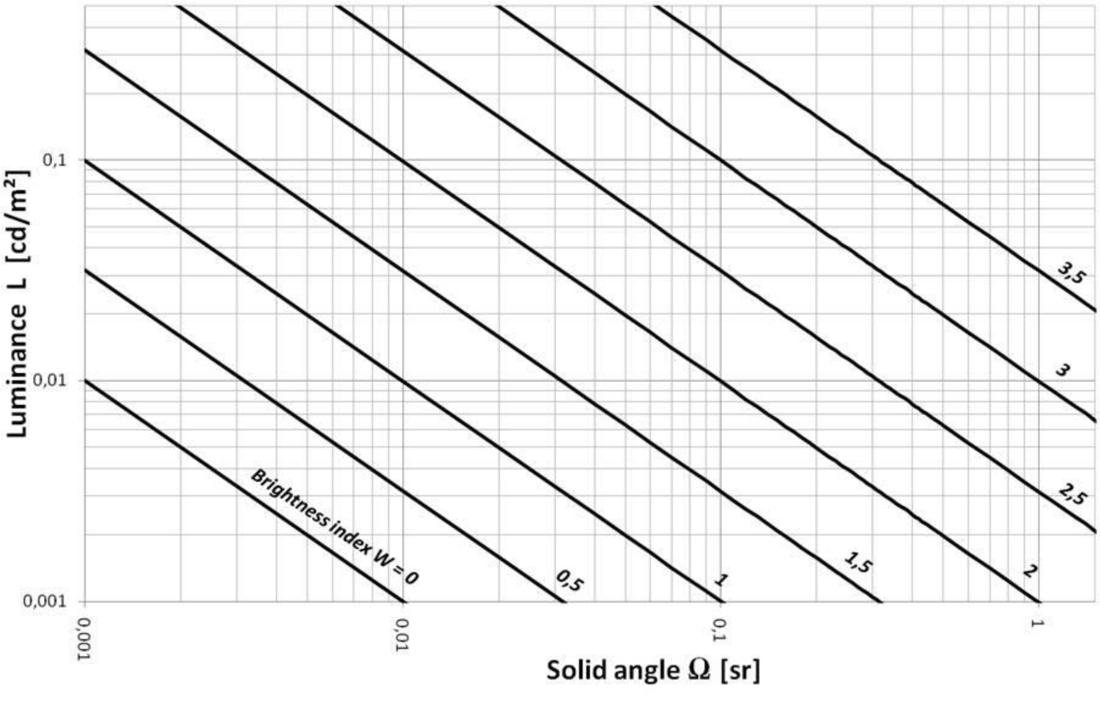


Figure 4.5 Representation of the brightness indexes W in relation to solid angle and mean luminance of the measured area.

The product $L_i\mathbf{\Omega}_i$ embodies the spherical illuminance measured at the driver eye, caused by the single pixel i. Therefore, it can be reasonably used for describing the brightness impression. Moreover, the value W can be practically collected in two different ways: by considering each point like in the analytic formula, or by considering the mean luminance value for each considered region L_r and its solid angle Ω_r. The latter way is easier and quicker when using presently commercial available evaluation software.

Another possible measurement method is to collect directly the spherical illuminance at the eye of the driver by means of a illuminance meter. The value W can be as well easily obtained from it. Though, by using this technique two major impairments are provided: spatial information is not present(therefore more measures are necessary in order to assess more light elements instead of just one photo); the upper threshold of 0,3 cd/m² for ambient lighting cannot be used; in this way, small bright lighting elements are included in the measurement and can provide similar values to the ones of wide dim areas.

In Figure 4.5, the magnitude of the index W is plotted against the mean luminance L of the measured area and the solid angle Ω under which the area is seen by the driver. Such a graph can be used as a basis representation, on which both measurement values and goal values of the illumination can be represented. Mean luminances higher than 0,25 cd/m² are generally not recommended [45] for ambient lighting, since they can cause discomfort glare. Therefore, the upper limit of the graph is 0,5 cd/m².

Measurements of the brightness of the interior ambient lighting using this method are listed in the appendix in Table A.2 for the scenarios employed in study A, in Table A.3 for the ones used in the favourite luminance choice for orange, in Table A.9 for the scenarios presented in study B and in Table A.10 for the choices of favourite luminances for red, green and blue.

4.2.2 Correlation between brightness indexes and subjective factors

The aim of the above described technique is to provide objective measurements of ambient lighting which possibly relate to its subjective impression. Therefore, in this section a connection between the results obtained in the studies of the subjective perception and the measured values of the interior brightness is researched. This is a first step in the direction of providing objective guidelines for the layout of ambient lighting.

The brightness indexes measured for each scenario and for each single lighting position were put in relation to the factors obtained by the factor analysis.

Using the results of study A, which was explicitly devoted to different settings in luminance and position, a correlation between the measured brightness indexes and the subjective factors was drawn.

The values of each factor were plotted against the brightness indexes of the whole interior and of the three measurement areas doors (D), foot space (F), and centre console (C) in Figure 4.6 to Figure 4.9. A covariance analysis on this data was also performed (Table 4.6).

Table 4.6 Extract of the covariance matrix, relating the subjective factors to the brightness indexes W of the single elements, their squares and mixed products. With D are indicated the doors, with C the centre console, with F the foot space.

	W_D	W_C	W_F	W_D^2	W_C^2	W_F^2	W_DW_C	W_CW_F	W_FW_D
Attractiveness and perceived quality	0,067	0,018	-0,009	**0,476**	0,147	-0,084	0,336	0,019	0,120
Space perception and orientation	0,195	0,076	0,146	**1,466**	0,627	**0,914**	**1,115**	**0,896**	**1,257**
Perceived safety and attention	-0,030	0,004	-0,043	-0,230	0,031	-0,290	-0,119	-0,189	-0,254
Activation	-0,015	-0,022	-0,002	-0,108	-0,176	-0,008	-0,142	-0,072	-0,095

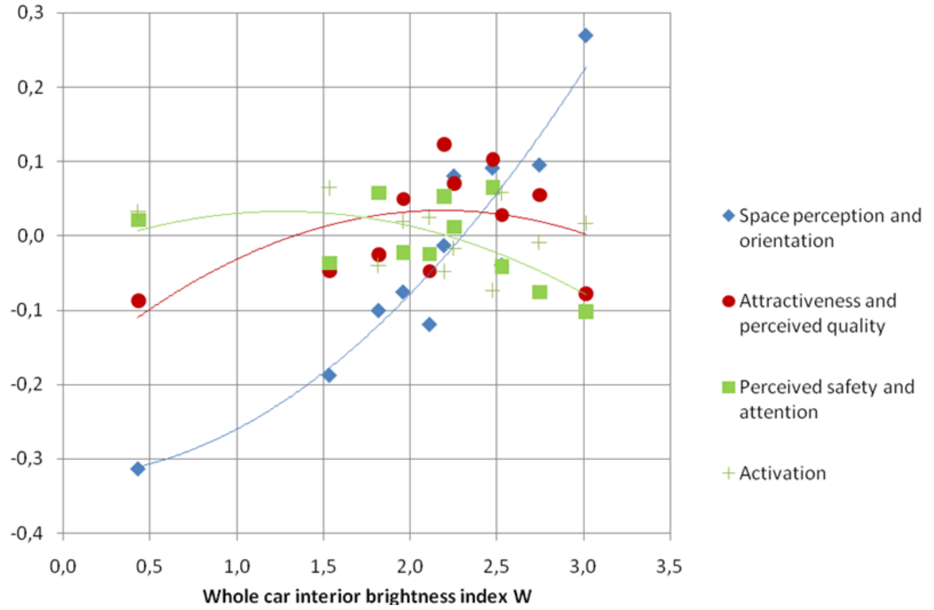


Figure 4.6 Factor values for the 11 orange scenarios in study A plotted against the brightness index W of each scenario, measured for the whole vehicle interior. The binomial approximations for the factors *attractiveness*, *space perception* and *perceived safety* are also displayed.

The covariance analysis showed the following results.

Foot space brightness had an impact on *space perception and orientation*, but neither on *attractiveness* nor on *perceived safety*. Doors brightness had a positive influence on all the criteria apart from *perceived safety*. The brightness of the centre console illumination supported positively each criterion. The criterion *Space perception and orientation* was influenced more than the other factors by the brightness of the light elements.

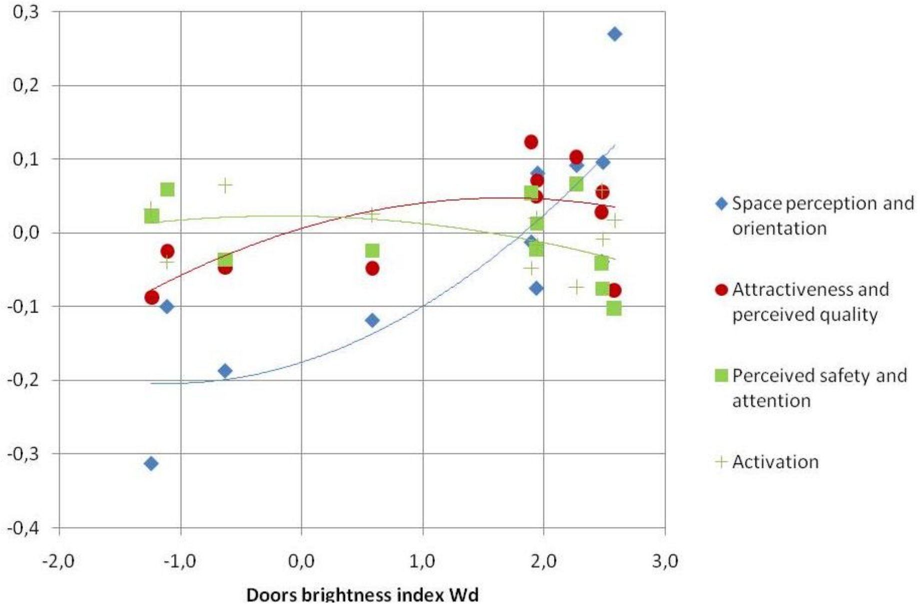


Figure 4.7 Factor values for the 11 orange scenarios in study A plotted against the doors brightness index W_D for each scenario. The binomial approximations for the factors *attractiveness*, *space perception* and *perceived safety* are also displayed.

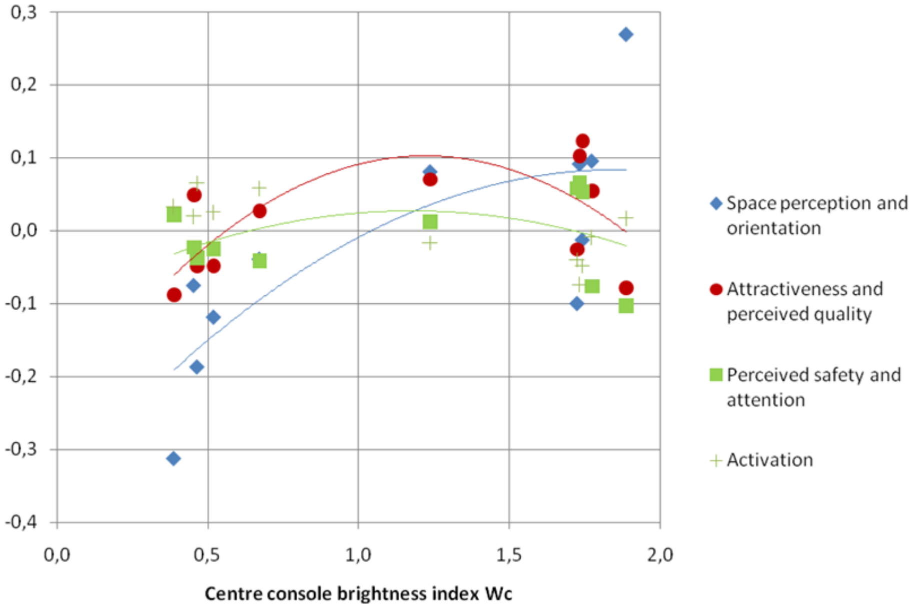


Figure 4.8 Factor values for the 11 orange scenarios in study A plotted against the centre console brightness index W_C for each scenario. The binomial approximations for the factors *attractiveness*, *space perception* and *perceived safety* are also displayed.

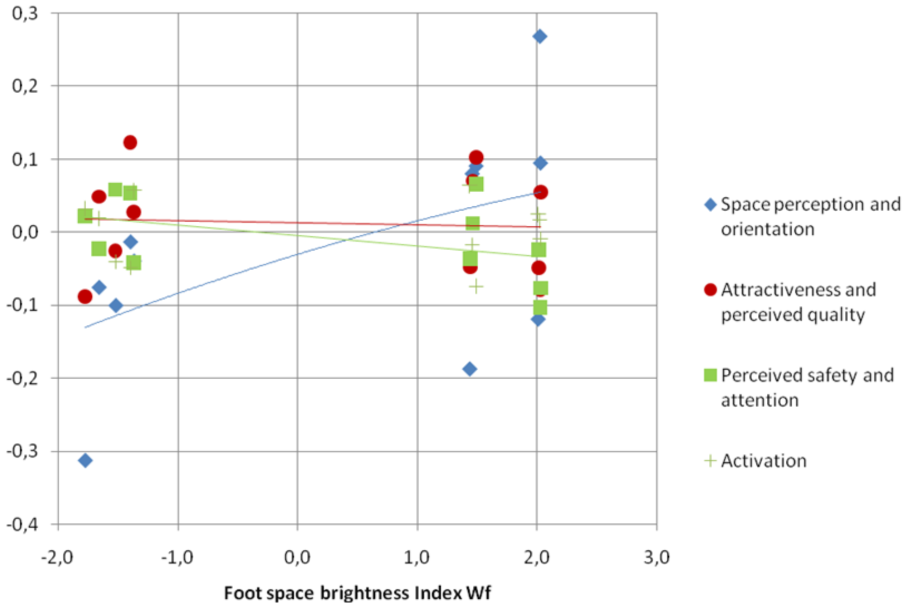


Figure 4.9 Factor values for the 11 orange scenarios in study A plotted against the foot space brightness index W_F for each scenario. The linear approximations for the factors *attractiveness*, *space perception* and *perceived safety* are also displayed.

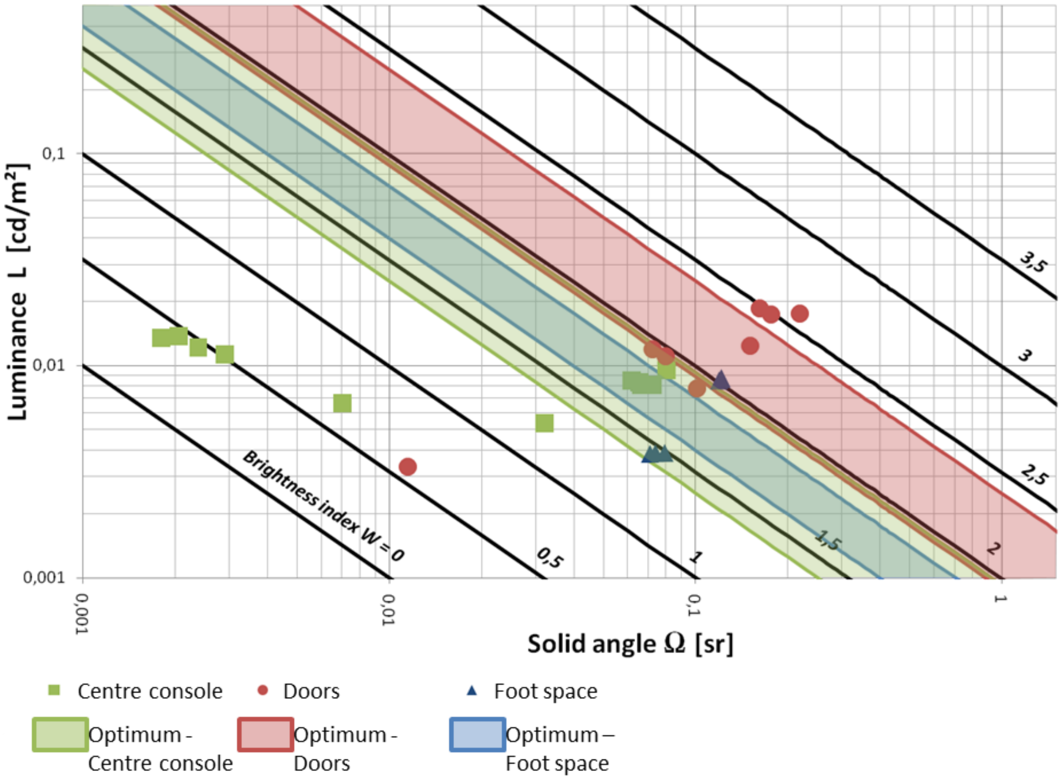


Figure 4.10 Plot of the brightness levels of the different measure zones for the scenarios in study A. In the graph are also indicated the optimal ranges for each zone.

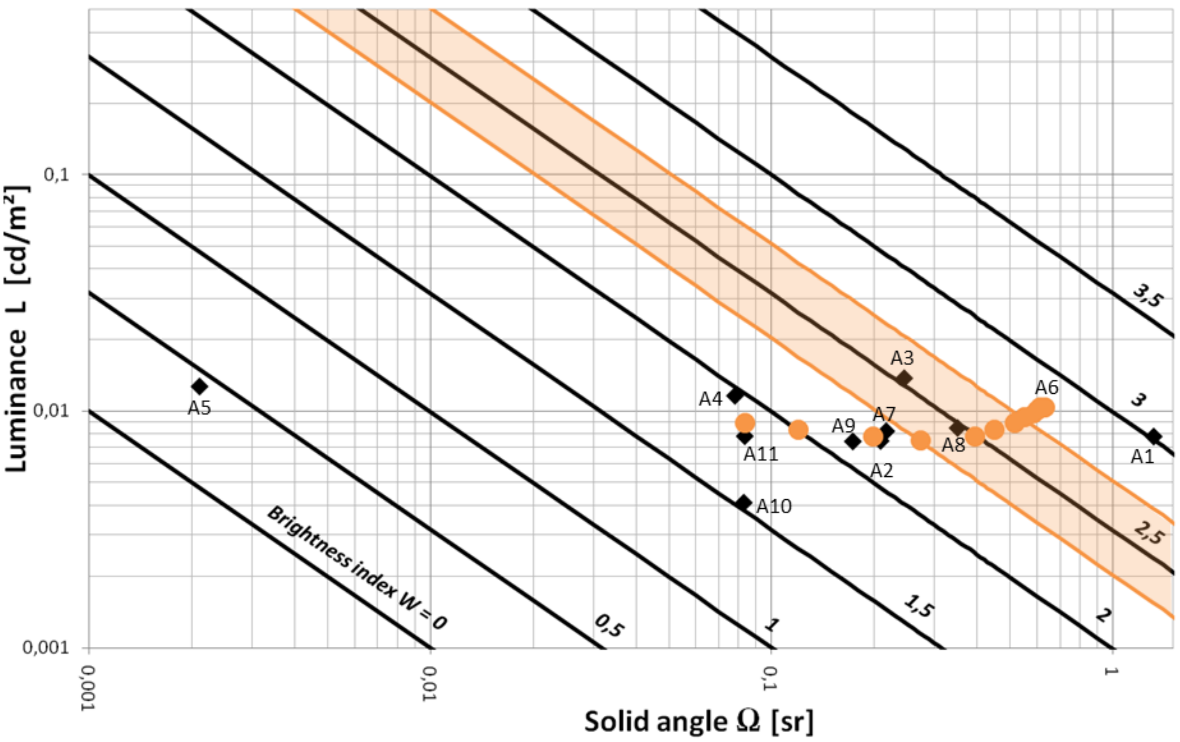


Figure 4.11 Plot of the brightness levels W of the scenarios used in study A for the whole vehicle interior. The orange dots represent the scenarios used for the choice of the favourite brightness. The two orange lines and the light orange area indicate the optimal area. The black dots indicate the scenarios A1 to A11 employed in the subjective study A.

Optimal brightness ranges for each lighting element were obtained from the graphs, by looking in which range the three criteria (activation was not considered, due to its small variations) had maximum values. These optimal ranges are plotted, together with the measured values, in Figure 4.10.

Similarly, the values *W* for the whole interior are displayed in Figure 4.11. In this diagram, the values obtained by the scenarios of study A (black dots) are compared to the scenarios used for the choice of the favourite luminance (orange dots). The orange lines define the range in which 70% of the test persons chose their favourite brightness level.

Notably, the two scenarios (black dots) which fall in this range were also the two which received best ratings in the subjective research.

The measurement values *W* are displayed in Table A.2 and Table A.3.

4.3 Influences of colour

The influence of colour on the subjective perception and emotional state of the driver was researched in study A (orange and blue) and B (red, blue, green, white, turquoise), which results were discussed in sections 3.3.4 and 0.

It was observed, especially in study B, that the perceived brightness of different lighting colours differed from the measured photopic luminance. Moreover, not only the brightness but also the subjective perception of space is strongly influenced by the colour.

These effects are correlated to the characteristics of mesopic vision (cf. section 2.1.3).

It is difficult to correlate the wavelength to the magnitude of the impression. Therefore, it is difficult to attach the parameter *colour* to the above-displayed formulas. Nevertheless, an overview of the subjective impressions due to the colours is provided. The colours blue and turquoise enhanced the *space perception and orientation*. The reason is probably that the blue cones and the rods, which are responsible for perceiving blue light in mesopic conditions, are placed mostly in the periphery of the eye. Warm colours like orange and red provided a better *attractiveness and perceived quality*. This could be connected to cultural reasons.

The colour white reunited the qualities of both long and short wavelength colours, by offering high values on both subjective criteria. Green scored poor ratings in all criteria.

Table 4.7 Subjective effects of different ambient lighting colours. With a plus are indicated the subjective advantages for the light colour, with a minus its subjective drawbacks. Also favourite luminances and brightness indexes are indicated. The dominant wavelengths of the LEDs which composed white and turquoise light are indicated as their dominant wavelength.

Colour	Dominant wavelength	Attractiveness and perceived quality	Space perception and orientation	Favourite mean luminance	Favourite brightness index W
Red	617 nm	+	-	0,035	2,9 – 3,05
Orange	605 nm	+			2,3 – 2,7
Green	528 nm	-	-	0,015	2,6 – 2,8
Turquoise	528+470 nm		+		
Blue	470 nm		+	0,012	2,05 – 2,24
White	617 + 528 + 470 nm	+	+		

The favourite luminance and brightness range for each tested colour is listed in Table 4.7, along with its main qualities and drawbacks. Perceived safety is not listed, since the differences in this criterion were not as significant as for the other two.

In Figure 4.12 the brightness *W* of the different scenarios tested in the MINI for study B are displayed. The brightness of the scenarios used for the choice of the favourite luminance for the three different colours, red green and blue are represented with coloured dots. The black dots represent the scenarios used in the study of the subjective impression. The scenarios *without lighting* and *series* were perceived as too dark in the subjective studies and lie in the darkest part of the graph (the four dots with *W*<2). The brightest scenario, B10, lies over the preferred brightness for blue. The other scenarios, which were rated rather positively (apart from green) lie all in the areas of the favourite brightness for each colour. (For the values *W*, cf. Table A.9 and Table A.10 in the appendix)

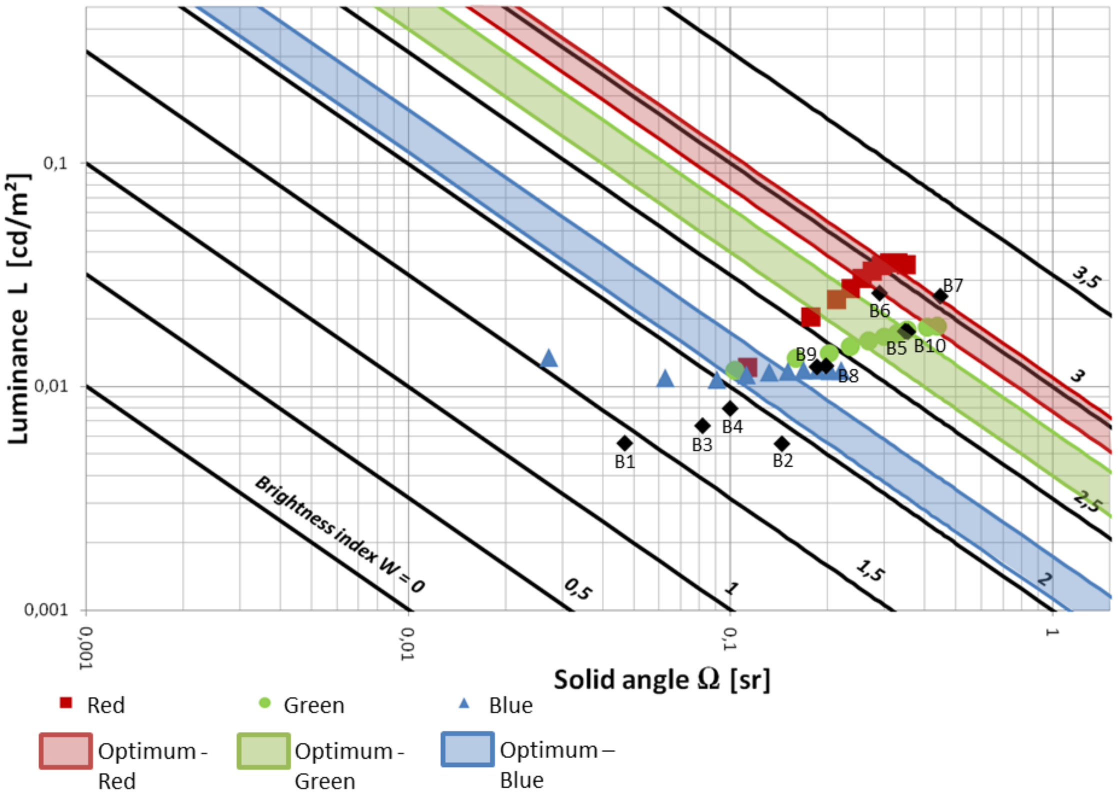


Figure 4.12 Plot of the brightness indexes W for the whole interior. The red, green and blue dots represent respectively the scenarios used for the choice of the favourite luminance in the respective colour. The coloured lines indicate the indexes relative to the favourite zones (minimum and maximum each), as listed in Table 4.7. The black dots indicate the brightness of the whole interior in the scenarios B1 to B10, used for the subjective study. The measurement values are listed in Table A.9 and in Table A.10 in the annexes.

5 Evaluation of single ambient lighting components

A necessary step for the integration of the obtained results in the vehicle development process is the passage from the context of the whole car impression to the single component level.

The specifications for the lighting output and distribution for each component are defined in the early stage of the development and then consequently controlled in order to monitor the quality of the finished parts. The values obtained in the subjective research studies can be a sound basis for the definition of the goal values in these specifications, provided a reliable connection between the two contexts is established.

With this aim, a measurement fixture was realised. The goal was to have a fixture with which it was possible to measure the light output and distribution of as many ambient lighting elements as possible. The mounting conditions were also kept as similar as possible to the ones in the car. Particular attention was given to the reflection of the light on trim elements rather than to the direct light, as ambient lighting is mostly perceived as reflected light.

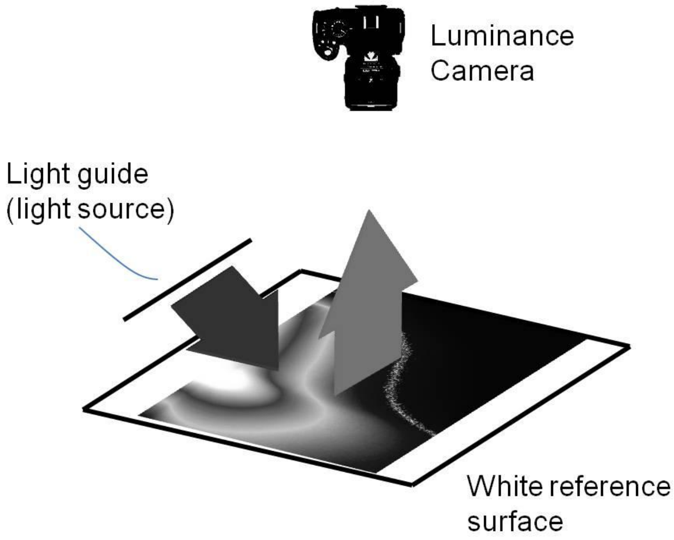


Figure 5.1 Functional scheme of the luminance measurements on single components: the light source (normally a module composed by a LED and a light guide or a single LED) illuminates the white reference plane. The reflection is then measured by the luminance camera positioned on top of it.

The light source (a linear light guide or a LED) can be fixed on an arm of the fixture. This arm can be moved in order to reach various positions and simulate the different geometries which are present in the car interior. The light source illuminates a white plain surface of 1x1 m. The reflected light is then measured by a luminance camera placed on the top of the fixture, as presented in Figure 5.1.

The reflective surface is white and plain in order to act as a reference and provide generality to the measurement. The assessment of illumination homogeneity can be carried out on such white surface. A similar homogeneity is perceived on the materials employed in the car interior, such as plastics or leather. The value of the absolute luminance measured on the reference surface has to be corrected with the reflection coefficient of the single materials and of the single light colour. In Table 2.3 several examples of such coefficients are provided as an example of materials and lighting colours employed in vehicle interiors.

Alternatively, series parts can be laid on the fixture and illuminated as well.

A measurement process based on this fixture was worked out and included in the standard specifications of the BMW Group regarding light guides for ambient lighting. This standard acts as help in the development process, by giving objective measurements to developers and suppliers, which can rely on that for the assessment of the lighting properties of an light source and not only on their subjective judgement.

Though this is a reliable and replicable procedure, there are several downsides which should be overcome in the future.

Firstly, no absolute luminances are involved in the measure, since the real luminance in the car is strongly influenced by the geometry and the reflection coefficient of the surface on which is reflected. Therefore, no reliable connections between the measured value and the goal value in the real vehicle interior can be drawn.

Moreover, the evaluation of the homogeneity should be also taken as a advice, since in some cases no clear criterion could be obtained, which defines exactly between accepted and rejected homogeneity. Depending on the geometry of the part, some irregularities in the light output can be even perceived as pleasant.

Nevertheless, such a measurement method constitutes a solid basis on which problems in the distribution of lighting output of the single sources can be easily recognised and objectively communicated. This alone can save a lot of effort and time in the development process.

6 Discussion

6.1 Conclusions

The analysis of the perception of vehicle ambient lighting while driving brought many findings. The explained method allowed having a deep insight on how ambient lighting is perceived by the driver. The three independent perception categories *space perception and orientation*, *attractiveness and perceived quality* and *perceived safety and attention* were confirmed in all three studies and can be used in the assessment of many types of vehicles, independently from the characteristics of their interior.

Also, the reliability of the proposed investigation method was validated by the consistent results given by different test persons under different environmental conditions.

After the feedback of the participants, the test could have been shorter than the planned three minutes for each experimental run. Indeed, many participants said they already had an idea of their subjective assessment after a shorter time. On the other hand, the evaluation of the emotional state would have needed more time in order to be estimated.

In fact, influences on the emotional state were verified only in some comparison between lighting colours only in the pleasure dimension. Other parameters did not have such influence, and the two dimensions arousal and dominance were not significantly affected. Cause for that could be the short time available for the evaluation and in the focus that the test persons gave to the primary driving task. In order to research more intensively this particular aspect, a different experimental design should be employed.

Surely, the evaluation methodology used in this work cannot be employed for assessing each new lighting feature. Nevertheless, it gives important advice on how to carry out future evaluations and which aspects to stress in them.

The driver's overall performance resulted to be not significantly influenced by the ambient lighting, although overall performance did effectively assess how the test persons followed the lane line. No measurements were made on the visual performance, since these have been already verified in other studies [36] [45].

The novel measurement method employed in this work guaranteed a reliable evaluation of the brightness of ambient lighting elements, as perceived by the driver. Thereby, correlations to the favourite luminance levels in different colours were made and favourite brightness levels were estimated. More measurements need to be carried out on different kinds of vehicles in order to get a wider picture of the existing ambient lighting features and scenarios in series car production. Through this process, narrower tolerance areas for the favourite brightness can be defined.

6.2 Transfer to practice

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

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. These qualities are independent and are maximised under different conditions.

In terms of perceived space and quality, a small number of light sources placed in order to cover the whole visual field can give the same results as many overlapping light sources. Thus, aimed ambient lighting can use fewer components, reduce production costs, and create a welcoming pleasant atmosphere in the car interior.

Moreover, ambient light sources are often not perceived consciously by the driver (in about 30% to 40% of the cases) singularly. As a whole though, they significantly influence ones subjective perception in various ways.

A higher luminance level, 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 and indeed it lessen the attractiveness and quality. This means that darker, less expensive light sources can achieve the same comfort effects.

Different lighting colours affect more assessment criteria in different ways. This has several causes: the diverse visual field 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, white profits from both short and long wavelength properties), the various emotional values carried by colours, and their different interactions with interior materials through reflection. Generally, blue enhances the space perception while red and orange increase the perceived value. White ambient lighting can enhance both aspects. Thus, the choice of colour for ambient lighting must meet many requirements in addition to brand identity and design compliance.

The proposed measurement method provides an easy way to catalogue the brightness of ambient lighting in the vehicle interior. By considering both luminance and area of the illuminated surfaces, a reliable measure of their brightness can be obtained. By relating these values with the subjective values, it was inferred under which conditions an optimal illumination can be realised. Thereafter, optimal values for each illuminated part were calculated. These have to be considered and used as goal values in the future development of such illumination systems in order to optimize their design, reduce costs and energy consumption, and achieve an optimal subjective perception by the driver.

6.3 Comparison with literature

In Table 6.1 the results of the most important studies on vehicle ambient lighting compared to the results of this study. For the comparison, the mean luminance was considered. These studies propose an optimal luminance level for determined positions in the vehicle interior or in some cases they signal a maximum value which shall not be exceeded by the lighting. An indication of how big is the light source or in which exact position of the driver's visual field is mostly not present.

The maximum values indicated by Grimm are the higher luminance values measured on single points in the interest zone and not the maximal mean luminance of the whole considered areas. When the authors indicate mean luminance values, normally the considered areas are not explicitly described. Therefore, it is not clear how to identify and measure them. The considered areas can be stretched and modified, so that almost any ambient lighting which does not exceed the maximum values can be considered as optimal.

Table 6.1 Luminance levels in cd/m^2 for ambient lighting given by different authors for several interior zones. KÖTH provides only a measure of spherical illuminance.

Area of the car	**Knollman [70]**			**Grimm [45]**		**Wamsganß [134]**	**Köth [74]**	**This work (orange)**
	Stationary	Driving	Street lighting	Optimal	Max	Red	(max E)	Luminance **L** (mean)
Centre console	-	-	-	0,046	0,208	-	-	0,005 – 0,01
Door trims	0,13	0,066	0,29	0,016	0,250	-	-	0,008 – 0,011
Foot space	0,0016	0,0017	0,0094	-	0,029	-	-	0,004 – 0,007
Roof	0,16	0,13	1,5	0,026	-	-	-	
Global	-	-	-	-	-	0,05	1,3lx	0,008 – 0,011

KÖTH [74] measures the spherical illuminance at the driver's eye. His method gives a perfect indication of the perceived brightness, but does not consider the spatial distribution of the lighting. The brightness index W, proposed in this work, solves this problem by evaluating luminance and solid angle at the same time, and by being specific for each considered illuminated part. So, there is an optimal range value for door trims, centre console, foot space as well as for the whole car interior. If all these values are met, the layout of ambient lighting in car interior can be considered optimal.

Considering the subjective perception of the lighting, all the mentioned authors dealt primarily with the safety aspect – the visual performance shall not be impaired – and in a second instance with comfort, mostly by asking the test persons which light level was perceived as optimal. These pieces of information are extremely useful, since they prevent possible objections on the safety of ambient lighting. They point out that discomfort glare occurs at a higher light level than what is felt *uncomfortable*.

In this work the words *comfort*, *perception* and *emotion* in relation to vehicle ambient lighting were investigated to a new depth. In fact, *to be comfortable* means different emotions or perceptions to different persons, and it does not only mean *not being uncomfortable*. Comfort was considered in the three different forms of *attractiveness and perceived quality*, *space perception and orientation*, and *perceived safety and attention*.

The present work shall help future lighting developers in understanding: how ambient lighting enhances the perception of the driver, and therefore how to lay it out; how the different lighting colours and their interactions with the interior materials give special space and value impressions; how it is possible to employ these effects in a intelligent way, in order to get the maximum outcome with the lowest costs; which are the difficulties and possibilities in measuring and specifying this kind of low light illumination.

6.4 Outlook

The focus of this work was on the driver's perception of ambient lighting. Further studies could also collect the subjective impressions of the passengers, which have not to focus on the driving task, and therefore have a different perception of the interior and could maybe pay attention to different aspects of the lighting.

Another aspect which has not been investigated in this work is the illumination of larger parts of the roof with ambient lighting or through contour lighting and their perception. This would be useful in order to complete the picture, since different manufacturers are introducing such features.

Moreover, dynamic lighting, as already outlined in several publications and throughout this work, is the future: an intelligent lighting system which adapts to the driver's preferences and environmental conditions, and offers the best visual environment for the driving task. Alternatively, it could be used as an entertainment tool, or an information carrier, through its brightness, colours, or the velocity in its transitions from a colour to the other or from a brightness level to the other, etc.: ideas are almost endless. Virtually, intelligent lighting can react to anything, provided that the right sensors and control systems are connected: radio volume, speed, temperature, fuel reserve, connection with mobile telephone, adaptation of the eye, attention of the driver, street lighting, etc. A huge potential is also present in the personalisation: in a future anyone could create their own lighting show and upload it to their vehicle. Still the advantages and problems arising from such systems, as well as theirs acceptance by the drivers have to be tested and verified. The challenge for the car manufacturer is to assure that none of that can impair the visual perception and therefore the driving performance. How will the driver react to the information brought to him by lighting systems? Which are the transitions thresholds (of colour and brightness), that the driver will perceive and identify, in a dynamic traffic situation, where the street lighting is always changing?

Therefore, more research has to be carried out in the area of dynamically changing lighting, and its perception by the driver. A most important aspect of this research field will also be the adaptation to the dynamic street lighting conditions, so that ambient lighting can provide an optimal luminance, similar to the one present on the road surface, for each kind of situation.

This will also lead to enhancements in the visual power of the driver, besides a new, interesting, emotional, and much more coloured vehicle interior lighting.

7 Bibliography

[1] Adrian, W. and Stemprok, R.: Required Visibility levels in road Scenes at night time driving. In: *ISAL 2005 - Proceedings of the Conference*, Darmstadt, 2005.

[2] Akashi, Y., Rea, M., and Bullough, J.: Driver decision making in response to peripheral moving targets under mesopic light levels. In: *Lighting Research and Technology*, vol. 39, no. 1, pp. 53-67, 2007.

[3] Baer, R.: *Beleuchtungstechnik. Grundlagen*. Huss, Berlin, 2006.

[4] Bierleutgeb, G.: Interior Lighting Control (ILC): System Aspects for a New Approach. In: *PAL 2001 Symposium -Proceedings of the Conference*, Darmstadt, 2001.

[5] Bortz, J. and Döring, N.: *Forschungsmethoden und Evaluation für Human- und Sozialwissenschaftler*. Springer Medizin Verlag, Heidelberg, 2006.

[6] Boyce, P. R.: *Lighting for Driving*. CRC Press, London, 2009.

[7] Boyce, P.R.: Lighting research for interiors: the beginning of the end or the end of the beginning. In: *Lighting Research and Technology* , vol. 36, no. 4, pp. 283–294, 2004.

[8] Boyce, P. R., Eklund, N.H., Hamilton, B.J., and Bruno, L.D.: Perceptions of safety at night in different lighting conditions. In: *Lighting Research and Technology*, vol. 32, no. 2, pp. 79-91, 2000.

[9] Bradley, M. M. and Lang, P. J.: Measuring Emotion: the Self-Assessment Manikin and Semantic Differential. In: *Journal of Behavior Therapy and Experimental Psychiatry* , vol. 25, no. 1, pp. 49-59, 1994.

[10] Brainard, G.C. et al.: Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. In: *Journal of Neuroscience*, vol. 21, no. 16, pp. 6405-6412, 2001.

[11] Bullough, J. and Rea, M.S.: Simulated driving performance and peripheral detection at mesopic and low photopic light levels. In: *Lighting Res. and Technol.*, vol. 32, no. 4, pp. 194-198, 2000.

[12] Caberletti, L., Elfmann, K., Kümmel, M., and Schierz, C.: Influence of ambient lighting in vehicle interior on the driver's perception. In: *Proceedings of EXPERIENCING LIGHT 2009 International Conference on the Effects of Light on Wellbeing*, Eindhoven, 2009, pp. 5-13.

[13] CIE, "Discomfort glare in interior lighting," Vienna, Technical Report Nr. 117 1995.

[14] CIE, Fundamentals of the visual task of night time driving, 1992.

[15] CIE, "Mesopic Photometry: history, special problems and practical solution," Vienna, Technical Report No. 81 1989.

[16] CIE, "Photometry - the CIE system of physical photometry -," Vienna, Standard CIE S 010 2004.

[17] CIE, "Road Transport Lighting for Developing Countries," CIE, Vienna, Technical Report 180 ISBN 9783901906619, 2007.

[18] Cifuentes, H.: *Test Platform for Adaptive Interior Lighting Systems in ASCET*. Technische Universität München, 2009, Diploma Thesis.

[19] Damasky, J.: *Lichttechnische Entwicklung von Anforderungen an Kraftfahrzeugscheinwerfer*. Herbert Utz Verlag, München, 1995.

[20] Decker, D.: Aspects of dynamic light control in automotive applications. In: *PAL 2001 Symposium - Proceedings of the conference*, Darmstadt, 2001.

[21] Devonshire, J. and Flannagan, M., "Effect of Automotive Interior Lighting on Driver Vision," University of Michigan, Ann Arbor, 2007.

[22] Diem, C.: *Blickverhalten von Kraftfahrern im dynamischen Straßenverkehr*. Herbert Utz Verlag, München, 2005.

[23] Diem, C.: Eye Movement Behaviour of Car Drivers. In: *International Symposium on Automotive Lighting 2005 - Proceedings of the conference*, Darmstadt, 2005.

[24] Diem, C.: LED Performance – Measure or Estimate? In: *ISAL Proceeding of the Conference*, Darmstadt, 2007.

[25] DIN V 5031-100, Strahlungsphysik im optischen Bereich und Lichttechnik -Teil 100: Über das Auge vermittelte, nichtvisuelle Wirkung des Lichts auf den Menschen - Größen, Formelzeichen und Wirkungsspektren, 2009.

[26] Ekrias, A., Guo, L., Eloholma, M., and Halonen, L.: Intelligent road lighting control in varying weather conditions. In: *Light & Engineering*, vol. 16, no. 1, pp. 72-78, 2008.

[27] Elfmann, K.: *Experimentelle Untersuchung zur Wahrnehmung von ambienten Beleuchtungselementen für die konzeptionelle Auslegung im Fahrzeug*. TU Ilmenau, , 2009, Diploma thesis.

[28] Eloholma, M. and Halonen, M., "MOVE - Performance Based Model for Mesopic Photomerty," Helsinki, 2005.

[29] Eloholma, M. et al.: Mesopic models - from brightness matching to visual performance in night-time driving: a review. In: *Lighting Research and Technology*, vol. 37,

no. 2, pp. 155-175, 2005.

[30] EN 13201-2 , Road Lighting - Performance requirements, 2003.

[31] Enz, E.: Electroluminescent Lighting Systems. In: *Intelligent Automotive Lighting* , 2009.

[32] Fischer, L., Brauns, D., and Belschak, F.: *Zur Messung von Emotionen in der angewandten Forschung*. Pabst Science Publishers, Lengerich, 2002.

[33] Fleischer, S. E., "Die psychologische Wirkung veränderlicher Kunstlichtsituationen auf den Menschen," ETH, Zürich, PhD Thesis 2001.

[34] Fleischer, S., Krueger, H., and Schierz, C.: Effects of brightness distribution and light colours on office staff. In: *Lux Europa 2001 - Proceedings of the conference*, Reykjavik, 2001, pp. 76-80.

[35] Fotios, S. and Houser, K.: Tuning the Spectrum of Lighting to Enhance Spatial Brightness: Investigations of Research Methods. In: *Proceedings of EXPERIENCING LIGHT 2009 International Conference on the Effects of Light on Wellbeing*, Eindhoven, 2009, pp. 41-52.

[36] Franzke, D.: *Einfluss ambienter Beleuchtung auf das Kontrastsehvermögen*. Diplomarbeit TU, Karlsruhe, 2006.

[37] Gall, D. u.a.: *Einzelplatzbeleuchtung und Allgemeinbeleuchtung am Arbeitsplatz*. Schriftenreihe der Bundesanstalt für Arbeitsschutz und Arbeitsmedizin: Forschungsbericht, Fb 753, , 1998.

[38] Gall, D. and Lapuente, V.: Beleuchtungsrelevante Aspekte bei der Auswahl eines förderlichen Lampenspektrums. In: *Licht*, no. 7/8, Mai 2002.

[39] Gall, D., Vandahl, C., and Bieske, K., "Ortsaufgelöste Messung von circadianen Strahlungsgrößen an Arbeitsplätzen," TU Ilmenau, 2005.

[40] Goodman, T. et al.: Mesopic visual efficiency IV: a model with relevance to nighttime driving and other. In: *Lighting Research and Technology*, vol. 39, no. 4, pp. 365-392, 2007.

[41] Gregory, R. L.: *Eye and Brain, The Psychology of Seeing , Fifth Edition, Oxford University Press, 1998*. Oxford University Press, Oxford, 1998.

[42] Gregory, R. L.: Seeing in the light of experience. Trotter-Paterson Memorial Lecture. In: *Lighting Research and Technology*, vol. 3, no. 4, pp. 247-250, 1971.

[43] Greule, R., "Emotionale Wirkung von farbiger LED-Beleuchtung im Innenraum," Fakultät DMI (Design Medien Information), Hochschule für Angewandte Wissenschaften (HAW) Hamburg, Hamburg, 2007.

[44] Grimm, M.: Driver's physiological needs for an interior lighting of vehicles. In: *PAL*

Proceedings of the conference, Darmstadt, 1999.

[45] Grimm, M.: *Requirements for an ambient interior lighting system for motor vehicles*. Herbert Utz Verlag, München, 2003.

[46] Grimm, M. and Löbig, P., "Ambiente Innenraumbeleuchtung für Kraftfahrzeuge," TU Darmstadt, Forschungsbericht 1998.

[47] Haferkemper, N., Frohnapfel, A., Paramei, G., and Khanh, T. Q.: A mesopic experiment series at automotive visual conditions. In: *Proceedings of the 7th International Symposium on Automotive Lighting*, Darmstadt, 2007.

[48] Hagemann, M. and al., e.: OLEDs for Automotive Lighting. In: *Proceedings of the 7th International Symposium on Automotive Lighting*, Darmstadt, 2007.

[49] Halonen, L. and Eloholma, M.: Spectral sensitivity at mesopic light levels. In: *PAL Proceedings of the conference*, Darmstadt, 1999.

[50] Hamm, M.: Down with CO2-Emissions - Ecologic Potential and Limits with Lighting Functions. In: *Proceedings of the 8th International Symposium on Automotive Lighting*, München, 2009.

[51] He, Y., Bierman, A., and Rea, M.: A system of mesopic photometry. In: *Lighting Research and Technology*, vol. 30, no. 1, pp. 75-81, 1998.

[52] Heinz, R.: Organische Lichtemittierende Dioden (OLEDs) - Technologie und Roadmap. In: *Licht 2008*, Ilmenau, 2008, pp. 418-426.

[53] Heller, E.: *Wie Farben wirken*. Rowohlt Taschenbuch, , 2006.

[54] He, Y., Rea, M., and Bierman, A. e.a.: Evaluating light source efficacy under mesopic conditions using reaction times. In: *J Illum Eng Soc*, vol. 26, no. 1, pp. 25-38, 1997.

[55] Hoffmann, D.: *Visual intelligence: How we create what we see*. W.W. Norton, New York, 1998.

[56] Houser, K.W. and Tiller, D.K.: Measuring the subjective response to interior lighting: paired comparisons and semantic differential scaling. In: *Lighting Research and Technology*, vol. 35, no. 3, pp. 183-198, 2003.

[57] Hubalek, S., Brink, M., and Schierz, C.: Office workers' daily exposure to light and its influence on sleep quality and mood. In: *Lighting research and technology*, vol. 42, pp. 33-50, 2010.

[58] Huber, H.: *Experimentelle Untersuchung zur subjektiven Wahrnehmung von Leuchtdichte und Farbton ambienter Beleuchtung mit LEDs im Fahrzeuginnenraum*. Hochschule Karlsruhe, 2009, Diploma Thesis.

[59] Huesmann, A., Ehmanns, D., and Wisselmann, D.: Development of ADAS by Means of Driving Simulation. In: *Proceedings of the Driving Simulation Conference Europe*, Paris, 2006, pp. 131-141.

[60] IESNA Roadway Lighting Committee, ANSI/IESNA RP-8-00 - American National Standard for Roadway Lighting , 2005.

[61] Irtel, H.: *Psychophysische Invarianzen in der Farb- und Helligkeitswahrnehmung*, Regensburg, U., Ed. Regensburg, 1991.

[62] Ishihara, S.: *Tests for colour-blindness*. Kanehara Shuppan Co., Tokyo, Kyoto, 1979.

[63] Kaltenbach, A.: Daylight simulation for the evaluation of rear lamps. In: *Proceedings of the 7th International Symposium on Automotive Lighting.* , Darmstadt, 2007.

[64] Ketomaki, J., Eloholma, M., and Halonen, L.: Visibility of Coloured Targets at Low Light Levels. In: *Progress in Automotive Lighting - Proceedings of the conference*, Darmstadt, 2003.

[65] Ketomäki, J., Eloholma, M., Orrevetailanen, P., and Halonen, L.: Mesopic lighting conditions and pedestrian visibility. In: *INGINERIA ILUMINATULUI-Lighting Engineering*, vol. 5, no. 11, pp. 29-40, 2003.

[66] Kleinkes, M.: *Objektivierte Bewertung des Gütemerkmals Homogenität für Scheinwerfer-Lichtverteilungen*. Shaker Verlag, Aachen , 2003.

[67] Kley, F., Gottschalk, M., Kliebisch, D., Völker, S., and Böhm, M.: Ein Helligkeitsvergleich verschiedener Lichtquellen im mesopischen Bereich. In: *Licht 7/8*, 2007.

[68] Klinger, K. and Lemmer, U.: Realisierung ambienter Innenraumbeleuchtungen in Personenwagen und deren Wirkungen auf den Fahrer. In: *LICHT*, Ilmenau, 2008, pp. 534-538.

[69] Klinger, K. and Lemmer, U.: The influence of ambient light on the driver. In: *Optical sensors 2008, Proc. SPIE, Vol. 7003, 700329*, Strasbourg, France, 2008, pp. 700329.1-700329.4.

[70] Knollmann, N. and Ivenz, R.: Interior lighting concept on the basis of psychological and physiological influences on night-time driving. In: *PAL 2001 Symposium*, Darmstadt, 2001.

[71] Kokoschka, S.: *Grundlagen der Lichttechnik - Script zur Vorlesung*. Karlsruhe, 2003.

[72] Konjhodzic, D. and Nägele, T.: Weiße LEDs - eine messtechnische Herausforderung. In: *LICHT 2008 - Proceedings of the conference*, Ilmenau, 2008, pp. 170-177.

[73] Kooijman, A.C.: Light distribution on the retina of a wide-angle theoretical eye. In: *J.*

Opt. Soc. Am., vol. V73, no. N11, pp. 1544-1550, 1983.

[74] Köth, K.: *Auslegung der Kraftfahrzeugbeleuchtung hinsichtlich Sicht und Signalisation*. Univesität Karlsruhe, Lichttechnisches Institut, Karlsruhe, 2009.

[75] Kraus, A., Benter, N., and Börner, H.: OLED Technology in Automotive Applications. In: *Proceedings of the 7th International Symposium on Automotive Lighting*, Darmstadt, 2007.

[76] Krüger, U. and Schmidt, F.: Spatially Resolved Measurement of Interior and Ambient Light in the Automotive Environment. In: *Proceedings of the 7th International Symposium on Automotive Lighting*, Darmstadt, 2007.

[77] Küller, R., Ballal, S., Laike, T., Mikellides, B., and Tonello, G.: The impact of light and colour on psychological mood: a cross-cultural study of indoor work environments. In: *Ergonomics*, vol. 49, no. 14, pp. 1496 - 1507, November 2006.

[78] Kümmel, M.: Licht als Gestaltungselement für wertige Fahrzeuginnenräume. In: *Karroseriebautage, Proceedings of the Conference*, Hamburg, 2008, pp. 222-232.

[79] Lang, P.J., "Behavioural treatment and bio-beavioural assessment: computer applications.," in *Technology in mental health care delivery systems*, Sidowski, J.B., Johnson, J.H., and Williams, T.A., Eds. Norwood, NJ: Ablex, 1980, pp. 119-137.

[80] Lange, H., Ed.: *Handbuch für Beleuchtung*. ecomed, Landsberg am Lech, 2009.

[81] Loe, D. and Rowlands, E.: The art and science of lighting: a strategy for lighting design. In: *Lighting research and technology*, vol. 28, no. 4, pp. 153-164, 1996.

[82] Marchl, W.: Standardisierte Bewertung der subjektive Farbwahrnehmung bei LED. In: *Licht 2008 - Proceedings of the conference*, Ilmenau, 2008, pp. 305-311.

[83] McCloughan, C.L.B., Aspinall, P.A., and Webb, R.S.: The impact of lighting on mood. In: *Lighting Research and Technology*, vol. 31, no. 3, pp. 81-88, 1999.

[84] McIntyre, I.M., Norman, T.R., Burrows, G.D., and Armstrong, S.M.: Quantal melatonin suppression by expoexposure to low intensity light in man. In: *Life Sciences*, vol. 45, no. 4, pp. 327-332, 1989.

[85] Mehrabian, A.: *Basic Dimensions for a General Psychological Theory*. O,G&H, Cambridge, MA, 1980.

[86] Mehrabian, A. and Russell, J. A.: *An approach to environmental psychology*. MIT, Cambridge, MA, 1974.

[87] Minich, M., "Automotive Lighting - What lies in the eyes of the beholder!," Intelligent Automotive Lighting , Präsentation 2009.

[88] Morante, P., "Mesopic street Lighting Demonstration and Evaluation Final Report," Lighting Research Center, Troy, New York, Foschungsbericht 2008.

[89] Nachtigall, K.: LEDs and OLEDs for Automotive Interior Applications. In: *Proceedings of the 7th International Symposium on Automotive Lighting*, Darmstadt, 2007.

[90] Narendran, N. and Deng, L.: Color Rendering Properties of LED Light Sources. In: *Solid State Lighting II: Proceedings of SPIE*, vol. 4776, 2002, p. 61 ff.

[91] Narisada, K.: Role of Adaptation in Perception under Traffic Lighting Conditions. In: *Progress in Automotive Lighting, Proceedings of the Conference*, Darmstadt, 2001.

[92] Nechwatal, J. and Porsch, T.: Messtechnische Erfassung der lichttechnischen Bewertungsgröße UGR in realen Beleuchtungslösungen unter Feldbedingungen basierend auf der LMK-Mobile-Technologie. In: *LICHT 2008 - Proceedings of the conference*, Ilmenau, 2008, pp. 144-149.

[93] Olson, P.L., "The effect of vehicle interior lighting systems on driver sight distance," Transportation Research Institute, University of Michigan, Ann Arbor, 1985.

[94] Osgood, C.E., Suci, G., and Tannenbaum, P.: *The measurement of meaning*. University of Illinois Press, Urbana, IL, 1957.

[96] OSRAM Opto Semiconductors. (2010, January) www.osram.de. [Online]. http://catalog.osram-os.com/catalogue/catalogue.do;jsessionid=799185CEA27445C96FE3ED1E18010931?favOid=000000020001c0b700030023&act=showBookmark

[95] OSRAM Opto Semiconductors. (2010, March) www.osram.de. [Online]. http://catalog.osram-os.com/catalogue/catalogue.do?favOid=000000000000ce4b000a0023&act=showBookmark

[97] Popp, R. F.J.: *Gegenmassnahmen bei Schlaefrigkeit: Der Effekt von kurzwelligem Licht und olfaktorischer Stimulation*. Dissertation, Universität Regensburg, , 2005.

[98] Raphael, S. and Leibenger, M.: Models of mesopic photometry applied to the contrast threshold of peripheral and foveal objects. In: *Proceedings of the 26th session of the CIE - Beijing*, vol. 1:D1, Vienna, 2007, pp. 38-41.

[99] Rea, M. and Bullough, J.: Making the move to a unified system of photometry. In: *Lighting Research and Technology* , vol. 39, pp. 393–408, 2007.

[100] Rea, M., Bullough, J., Freyssinier-Nova, J., and Bierman, A.: A proposed unified system of photometry. In: *Lighting Research and Technology*, vol. 36, no. 2, pp. 85-111, 2004.

[101] Rea, M., Figueiro, M., and Bullough, J.: Circadian photobiology: an emerging framework for lighting practice and research. In: *Lighting Research and Technology*, vol. 34, no. 3, pp. 177-190, 2002.

[102] Ripperger, J.: Lichttechnische anforderungen an Schluß- und Bremsleuchten für Kraftfahrzeuge. , München, 2001.

[103] Roddewig, W. and Schmits, P.: UGR-Blendungsbewertung für die Innenraumbeleuchtung. In: *Licht*, vol. 5, 2004.

[104] Rowlands, E. and Loe, D.L.: Lighting adequacy and quality in office interiors by consideration of subjective assessment and physical measurement. In: *CIE-Journal*, vol. 4, no. 1, pp. 23-37, 1985.

[105] Schellinger, S., Dorit, F., Klinger, K., and Lemmer, U.: Advantages of ambient interior lighting for drivers contrast vision. In: *Proceedings of the SPIE 6198: Photonics Europe: Photonics in the Automobile, 61980G*, 2006.

[106] Schielke, T.: Learning from architectural lighting for automotive interior lighting. In: *Proceedings of the 7th International Symposium on Automotive Lighting*, Darmstadt, 2007.

[107] Schierz, C.: Licht für die ältere Bevölkerung – Physiologische Grundlagen und ihre Konsequenzen. In: *Licht 2008*, Ilmenau, 2008, pp. 32-41.

[108] Schierz, C.: Licht und Wahrnehmung. In: *LuxJunior '99*, Dornfeld/Ilm, 1999.

[109] Schierz, C.: Zur Photometrie nichtvisueller Lichtwirkungen. In: *6. Symposium „Licht und Gesundheit“*, Berlin, 2008, pp. 112-123.

[110] Schierz, C. and Krueger, H.: Wahrnehmung und Bewertung künstlich beleuchteter Räume. In: *"Licht 96" Tagung*, Leipzig, 1996.

[111] Schierz, C. and Krueger, H., "Wahrnehmung und Bewertung künstlich beleuchteter Räume," ETH Zürich, Schlussbericht 1995.

[112] Schmidt, F. and Krüger, U.: Bildauflösende Leuchtdichtemesstechnik für kleine Leuchtdichte. In: *Licht 2008*, Ilmenau, 2008, pp. 114-121.

[113] Schrödter, A.: Flimmern und Flimmerverschmelzungsfrequenz beim Betrieb von Scheinwerfern und Leuchtenmit LED-Technik. In: *LICHT*, no. 9, pp. 722-728, 2007.

[114] Sekuler, R. and Blake, R.: *Perception*. McGraw Hill, New York, 1994.

[115] Serafin, C. and Green, P., "Driver Preferences for Instrument Panel Lighting Levels," The University of Michigan, Transportation Research Institute, 1990.

[116] Sivak, M.: The information that drivers use: is it indeed 90%visual? In: *Perception*, vol. 26, no. 9, pp. 1081–1089, 1996.

[117] Stone, P.T.: The effects of environmental illumination on melatonin, bodily rhythms and mood states: a review. In: *Lighting research and technology* , vol. 31, no. 3, pp. 71-79, 1999.

[118] Strahlenschutzkommission, E., "Blendung durch natürliche und neue künstliche Lichtquellen und ihre Gefahren," Strahlenschutzkommission, Bonn, 2006.

[119] Suk, H.J.: *Color and emotion: A Study on the Affective Judgment of Color*. Dissertation, Universität Mannheim, Mannheim, 2006.

[120] Szabo, Bodrogi, and Schanda,: A colour harmony rendering index based on predictions of colour harmony impression. In: *Lighting Research and Technology*, no. 41, pp. 165–182, 2009.

[121] Thapan, K., Arndt, J., and Skene, D.J.: An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans. In: *Journal of Physiology*, vol. 535.1, pp. 261-267, 2001.

[122] Tiller, D. K. and Rea, M. S.: Semantic differential scaling: Prospects in lighting research. In: *Lighting Research and Technology*, vol. 24, no. 1, pp. 43-52, 1992.

[123] Valdez, P. and Mehrabian, A.: Effects of Color on Emotion. In: *Journal of Experimental Psychology*, vol. 123, no. 4, pp. 394-409, 1994.

[124] Van de Kraatz, J. and van Norren, D.: Optical density of the aging human ocular media in the visible and the UV. In: *J. Opt. Soc. Am. A*, vol. V24 N7, pp. 1842-1857, July 2007.

[125] van der Burgt, P. and van Kemenade, J.: About color rendition of light sources: The balance between simplicity and accuracy. In: *Color Research and Application*, vol. 35, no. 2, pp. 85-93, 2010.

[126] Veitch, J.A., Newsham, G.R., and Boyce, P.R. a.J.C.C.: Lighting appraisal, well-being and performance in open-plan offices: A linked mechanisms approach. In: *Lighting Research and Technology* , vol. 40, pp. 133–151, 2008.

[127] Viikari M, E. A.E.M.H.: Modeling spectral sensitivity at low light levels based on mesopic visual performance. In: *Clinical Ophthalmology*, vol. 2, no. 1, pp. 1-13, 2008.

[128] Viola, A., James, L., Schlangen, L., and Dijk, D.J.: Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality. In: *Scandinavian Journal of Work, Environment & Health*, vol. 3, pp. 204-215, 2007.

[129] Völker, S.: Do light sources with a high part of shorter wavelength promote safety? In: *Proceedings of the 7th International Symposium on Automotive Lighting*, Darmstadt, 2007.

[130] Völker, S.: Sehen in der Dämmerung - aktuelle Forschungergebnisse zur Mesopik. In:

LICHT 2008 - Proceedings of the conference, Ilmenau, 2008, pp. 25-31.

[131] Wallentowitz, H. and Reif, K.: *Handbuch Kraftfahrzeugelektronik*. Vieweg , , 2006.

[132] Wambsganß, H.: Intelligent Lighting for Automotive Interior. In: *PAL - Proceedings of the conference*, Darmstadt, 2003.

[133] Wambsganß, H.: Stage Lighting for Automotive Interiors. In: *Proceedings of the 7th International Symposium on Automotive Lighting*, Darmstadt, 2007.

[134] Wambsganß, H., Eichhorn, K., and Kley, F.: Next Generation of Ambient Lighting: Physiology and Applications. In: *International Symposium on Automotive Lighting*, Darmstadt, 2005.

[135] Wernicke, A. and Strauß, S.: The analytical and experimental study of the effects of pulsewidth-modulated light sources on visual perception. In: *Proceedings of the 7th International Symposium on Automotive Lighting*, Darmstadt, 2007.

[136] Wiemers, S.: Munter durch die Nacht. In: *Licht*, vol. 7/8, 2007.

[137] Wördenweber, B., Wallaschek, J., Boyce, P., and Hoffman, D. D.: *Automotive Lighting and Human Vision*. Springer Verlag, Berlin, 2007.

A Appendix

A.1 Study A – BMW 3 Series in driving simulator

A.1.1 Experimental data

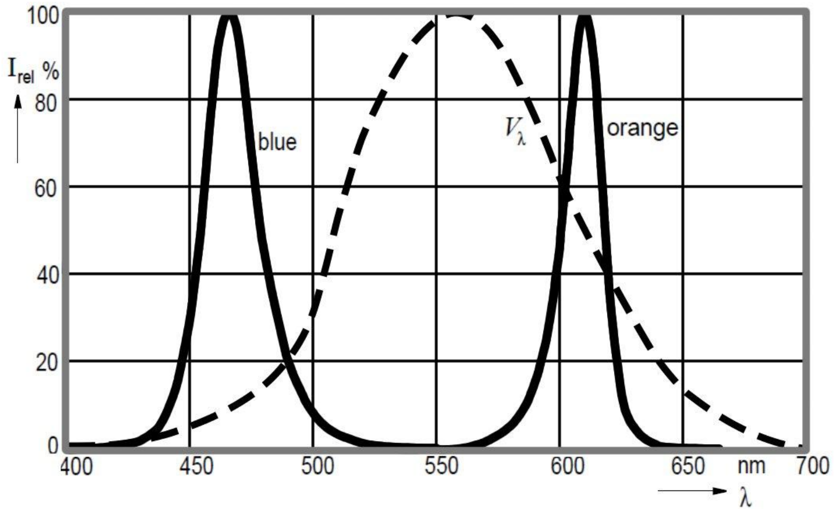


Figure A.1 Spectra of the two LEDs used in the experimental car: blue and orange [96].

Table A.1 Description of the tested lighting scenarios. Each scenario apart from A12 featured orange lighting colour.

Nr.	Lighting Scenario
A1	Everything on – bright level with accents
A2	Series (Centre console + Door trims)
A3	Doors only – bright level
A4	Doors only – low level
A5	Without lighting
A6	Everything on – bright level
A7	Everything on – low level
A8	Everything on – middle level
A9	Foot space only – bright level
A10	Foot space only – low level
A11	Centre console only
A12	Everything on blue – low level

Table A.2 Measured ambient lighting level for the scenes in study A.

Scenario		Zone	Mean luminance [cd/m²]	Solid angle [sr]	Brightness Index [W]
A1	**Everything on - bright with accents**	Foot space	0,0087	0,1220	2,0257
		Doors	0,0175	0,2186	2,5839
		Centre console	0,0095	0,0806	1,8863
		Whole interior	0,0078	1,3225	3,0135
A2	**Series**	Foot space	0,0040	0,0001	-1,3943
		Doors	0,0078	0,1011	1,8960
		Centre console	0,0084	0,0657	1,7412
		Whole interior	0,0075	0,2095	2,1946
A3	**Doors - bright**	Foot space	0,0040	0,0001	-1,3650
		Doors	0,0186	0,1616	2,4786
		Centre console	0,0066	0,0070	0,6705
		Whole interior	0,0137	0,2456	2,5284
A4	**Doors - low**	Foot space	0,0103	0,0000	-1,6570
		Doors	0,0120	0,0725	1,9376
		Centre console	0,0138	0,0021	0,4531
		Whole interior	0,0116	0,0784	1,9586
A5	**Without lighting**	Foot space	0,0142	0,0000	-1,7725
		Doors	0,0243	0,0000	-1,2384
		Centre console	0,0135	0,0018	0,3870
		Whole interior	0,0127	0,0021	0,4289
A6	**Everything on - bright**	Foot space	0,0088	0,1218	2,0299
		Doors	0,0174	0,1766	2,4871
		Centre console	0,0081	0,0728	1,7722
		Whole interior	0,0097	0,5762	2,7452
A7	**Everything on - low**	Foot space	0,0039	0,0742	1,4599
		Doors	0,0111	0,0798	1,9482
		Centre console	0,0054	0,0321	1,2368
		Whole interior	0,0082	0,2175	2,2520
A8	**Everything on - middle**	Foot space	0,0039	0,0796	1,4915
		Doors	0,0124	0,1501	2,2697
		Centre console	0,0081	0,0665	1,7320
		Whole interior	0,0085	0,3520	2,4745
A9	**Foot space - bright**	Foot space	0,0086	0,1198	2,0108
		Doors	0,0033	0,0115	0,5851
		Centre console	0,0113	0,0029	0,5192
		Whole interior	0,0074	0,1736	2,1111
A10	**Foot space - low**	Foot space	0,0039	0,0712	1,4390
		Doors	0,0034	0,0007	-0,6293
		Centre console	0,0122	0,0024	0,4642
		Whole interior	0,0041	0,0832	1,5330
A11	**Centre console**	Foot space	0,0058	0,0001	-1,5169
		Doors	0,0136	0,0001	-1,1087

		Centre console	0,0085	0,0619	1,7236
		Whole interior	0,0078	0,0838	1,8166
A12	**Everything blue - low**	Whole interior	0,0128	0,4387	2,7480
		Doors	0,0153	0,1358	2,3179
		Centre console	0,0104	0,1101	2,0573
		Foot space	0,0045	0,0899	1,6102

Table A.3 Measured luminance levels for the scenarios used for the choice of the favourite brightness in study A.

Scenario		**Zone**	**Mean luminance [cd/m²]**	**Solid angle [sr]**	**Brightness Index [W]**
AL1	**Orange1**	Whole interior	0,0089	0,0836	1,8717
AL2	**Orange2**	Whole interior	0,0083	0,1201	1,9990
AL3	**Orange3**	Whole interior	0,0078	0,1988	2,1914
AL4	**Orange4**	Whole interior	0,0075	0,2738	2,3126
AL5	**Orange5**	Whole interior	0,0078	0,3940	2,4878
AL6	**Orange6**	Whole interior	0,0083	0,4492	2,5723
AL7	**Orange7**	Whole interior	0,0089	0,5151	2,6604
AL8	**Orange8**	Whole interior	0,0094	0,5526	2,7177
AL9	**Orange9**	Whole interior	0,0097	0,5869	2,7572
AL10	**Orange10**	Whole interior	0,0101	0,6009	2,7810
AL11	**Orange11**	Whole interior	0,0103	0,6135	2,8019
AL12	**Orange12**	Whole interior	0,0104	0,6331	2,8172

A.1.2 Experimental results

Table A.4 Results of subjective research in study A. For each scenario is listed the mean value and standard deviation obtained for each question. Scenarios are described in Table A.1. The questions numbers and items of the differential pairs are listed in Table 3.3.

	Scenario A1		**Scenario A2**		**Scenario A3**		**Scenario A4**		**Scenario A5**		**Scenario A6**	
Qu. N.	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
1	0,62	0,16	0,61	0,16	0,57	0,13	0,54	0,17	0,42	0,17	0,55	0,14
2	0,66	0,20	0,56	0,18	0,50	0,18	0,50	0,18	0,25	0,16	0,61	0,18
3	0,62	0,17	0,68	0,14	0,64	0,17	0,63	0,11	0,54	0,09	0,64	0,16
4	0,49	0,26	0,67	0,18	0,50	0,19	0,57	0,12	0,38	0,14	0,57	0,19
5	0,75	0,16	0,44	0,10	0,61	0,18	0,47	0,08	0,32	0,16	0,60	0,18
6	0,47	0,20	0,66	0,15	0,53	0,18	0,59	0,12	0,47	0,09	0,57	0,18
7	0,46	0,18	0,67	0,15	0,55	0,18	0,59	0,14	0,45	0,15	0,57	0,16
8	0,57	0,24	0,68	0,18	0,59	0,16	0,57	0,13	0,44	0,14	0,63	0,17
9	0,58	0,19	0,67	0,18	0,59	0,15	0,61	0,13	0,45	0,13	0,63	0,15
10	0,48	0,18	0,52	0,12	0,49	0,08	0,46	0,13	0,39	0,13	0,48	0,10
11	0,63	0,16	0,63	0,20	0,53	0,17	0,53	0,17	0,28	0,14	0,66	0,15
12	0,63	0,18	0,58	0,19	0,43	0,17	0,44	0,15	0,26	0,16	0,62	0,19
13	0,25	0,30	0,84	0,15	0,78	0,19	0,78	0,20	0,84	0,19	0,76	0,21
14	0,42	0,17	0,57	0,09	0,50	0,09	0,49	0,08	0,51	0,12	0,42	0,13
15	0,46	0,17	0,54	0,08	0,48	0,09	0,50	0,06	0,46	0,13	0,47	0,14
16	0,56	0,16	0,52	0,09	0,52	0,08	0,50	0,07	0,40	0,12	0,51	0,11
17	0,55	0,13	0,52	0,08	0,53	0,08	0,51	0,08	0,43	0,12	0,54	0,10
18	0,46	0,17	0,57	0,13	0,51	0,15	0,50	0,08	0,41	0,16	0,51	0,12

	Scenario A7		**Scenario A8**		**Scenario A9**		**Scenario A10**		**Scenario A11**		**Scenario A12**	
Qu. N.	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
1	0,63	0,15	0,62	0,13	0,54	0,12	0,45	0,14	0,49	0,07	0,64	0,19
2	0,63	0,22	0,65	0,21	0,40	0,18	0,34	0,15	0,40	0,19	0,71	0,20
3	0,67	0,18	0,69	0,15	0,61	0,15	0,59	0,17	0,61	0,15	0,55	0,25
4	0,63	0,17	0,69	0,17	0,46	0,17	0,45	0,16	0,53	0,18	0,55	0,27
5	0,48	0,14	0,48	0,07	0,45	0,12	0,44	0,18	0,38	0,13	0,59	0,15
6	0,63	0,19	0,69	0,16	0,51	0,15	0,49	0,16	0,58	0,16	0,53	0,22
7	0,63	0,13	0,66	0,18	0,50	0,15	0,50	0,13	0,53	0,13	0,44	0,19
8	0,66	0,17	0,69	0,15	0,48	0,14	0,49	0,14	0,53	0,15	0,53	0,20
9	0,65	0,17	0,66	0,16	0,49	0,12	0,49	0,14	0,54	0,13	0,54	0,20
10	0,52	0,11	0,55	0,12	0,45	0,12	0,39	0,14	0,44	0,16	0,55	0,17
11	0,62	0,17	0,69	0,14	0,46	0,13	0,41	0,13	0,52	0,17	0,71	0,20
12	0,62	0,18	0,68	0,15	0,40	0,13	0,39	0,16	0,55	0,19	0,71	0,18
13	0,65	0,24	0,80	0,20	0,82	0,18	0,82	0,20	0,84	0,17	0,57	0,32
14	0,51	0,16	0,53	0,10	0,45	0,12	0,46	0,12	0,54	0,08	0,54	0,16

15	0,52	0,09	0,55	0,11	0,46	0,08	0,48	0,11	0,53	0,10	0,52	0,16
16	0,56	0,11	0,56	0,12	0,47	0,10	0,46	0,08	0,47	0,11	0,59	0,17
17	0,55	0,10	0,53	0,10	0,47	0,09	0,49	0,09	0,46	0,12	0,59	0,15
18	0,56	0,12	0,62	0,13	0,48	0,06	0,45	0,15	0,48	0,13	0,55	0,18

Table A.5 Pearson's coefficient of correlation between the answers to the 18 semantic differential pairs in study A. In light grey shade are the coefficient $\varrho>0,5$, in dark grey $\varrho>0,75$.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**□0**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1	*1,0*	0,62	0,24	0□ 39	0,26	0,38	0,37	0,42	0,38	0,37	0,58	0,54	-0,1	0,14	0,22	0,41	0,40	0,32
2	0,62	*1,00*	0,29	0,54	0,39	0,4	0,□ 8	0,□ 1	0,47	0,53	0,□ 9	0,77	-0,2	0,24	0,29	0,5	0,46	0,47
3	0,24	0,29	*1,□ 0*	□ ,5	0,04	0,61	0,60	0,62	0,61	0,34	0,35	0,25	0,16	0,28	0,32	0,35	0,26	0,38
4	0,39	0,54	0,54	*1,00*	0,02	0,80	0,72	0,80	0,78	0,59	0,60	0,52	0,09	0,50	0,53	0,55	0,47	0,61
5	0,26	0,39	0,04	0,02	*1,00*	-0,1	-0,1	0,11	0,11	0,13	0,37	0,35	-0,4	-0,2	-0,2	0,25	0,28	0,05
6	0,38	0,44	0,61	0,80	-0,1	*1,00*	0,79	0,68	0,67	0,49	0,52	0,46	0,20	0,53	0,56	0,45	0,36	0,59
7	0,37	0,38	0,60	0,72	-0,1	0,79	*1,00*	0,67	0,66	0,43	0,43	0,34	0,19	0,41	0,48	0,41	0,35	0,54
8	0,42	0,51	0,62	0,80	0,11	0,68	0,67	*1,00*	0,89	0,52	0,54	0,46	0,06	0,39	0,39	0,52	0,43	0,54
9	0,38	0,47	0,61	0,78	0,11	0,67	0,66	0,89	*1,00*	0,47	0,51	0,43	0,09	0,35	0,34	0,49	0,40	0,50
10	0,37	0,53	0,34	0,59	0,13	0,49	0,43	0,52	0,47	*1,00*	0,58	0,50	-0,1	0,49	0,54	0,66	0,57	0,56
11	0,58	0,79	0,35	0,60	0,37	0,52	0,43	0,54	0,51	0,58	*1,00*	0,80	-0,1	0,30	0,34	0,59	0,52	0,59
12	0,54	0,77	0,25	0,52	0,35	0,46	0,34	0,46	0,43	0,50	0,80	*1,00*	-0,2	0,25	0,31	0,54	0,49	0,48
13	-0,1	-0,3	0,16	0,09	-0,4	0,20	0,19	0,06	0,09	-0,1	-0,1	-0,2	*1,00*	0,18	0,09	-0,1	-0,1	0,07
14	0,14	0,24	0,28	0,50	-0,2	0,53	0,41	0,39	0,35	0,49	0,30	0,25	0,18	*1,00*	0,63	0,39	0,30	0,52
15	0,22	0,29	0,32	0,53	-0,2	0,56	0,48	0,39	0,34	0,54	0,34	0,31	0,09	0,63	*1,00*	0,48	0,43	0,54
16	0,41	0,53	0,35	0,55	0,25	0,45	0,41	0,52	0,49	0,66	0,59	0,54	-0,1	0,39	0,48	*1,00*	0,78	0,55
17	0,40	0,46	0,26	0,47	0,28	0,36	0,35	0,43	0,40	0,57	0,52	0,49	-0,1	0,30	0,43	0,78	*1,00*	0,36
18	0,32	0,47	0,38	0,61	0,05	0,59	0,54	0,54	0,50	0,56	0,59	0,48	0,07	0,52	0,54	0,55	0,36	*1,00*

Table A.6 Significance level p of the comparisons between ambient lighting scenarios. The comparisons focus on the change of luminance level in the whole car interior (from dark to bright: A5 - A7 – A8 – A6 – A1). Highly significant results (p<0,01) are highlighted by two asterisks, significant results (p<0,05) by one asterisk. The scenario numbers are listed in Table 3.1. The question numbers in Table 3.3.

	Comparison				
Question Number	**A5-A7**	**A7-A1**	**A7-A8**	**A8-A6**	**A6-A1**
1	0,002**	0,493	0,767	0,059	0,090
2	0,000**	0,509	0,898	0,674	0,274
3	0,001**	0,100	0,647	0,061	0,321
4	0,000**	0,076	0,380	0,006**	0,188
5	0,001**	0,000**	0,197	0,002**	0,001**
6	0,000**	0,013*	0,175	0,015*	0,030*
7	0,000**	0,000**	0,658	0,035*	0,005**
8	0,000**	0,084	0,976	0,026*	0,040*
9	0,001**	0,117	0,696	0,203	0,127
10	0,002**	0,311	0,263	0,004**	0,879
11	0,000**	0,449	0,095	0,696	0,405
12	0,000**	0,493	0,241	0,431	0,846
13	0,001**	0,000**	0,037*	0,065	0,000**
14	0,658	0,047*	0,542	0,003**	0,982
15	0,185	0,170	0,079	0,014*	0,951
16	0,000**	0,198	0,554	0,091	0,142
17	0,000**	0,788	0,236	0,903	0,673
18	0,001**	0,042*	0,074	0,001**	0,139

Table A.7 Significance level p for several scenarios comparisons for each question. The comparisons are the ones listed in the text (section 3.3.4) and are indicated by the scenes number at the top of each column. Above them the category of the comparison is indicated: brightness, colour or position. Highly significant results ($p<0.01$) are highlighted by dark grey cells. Significant results ($p<0.05$) are highlighted by light grey cells. Scenarios are described in Table 3.1.

Comparison:	**Brightness**					**Colour**	**Position**	
Question Number	**A5 –A7**	**A7 –A1**	**A3–A4**	**A9–A10**	**A5–A11**	**A7–A12**	**A4–A9**	**A4–A11**
1	0,002	0,493	0,147	0,007	0,026	0,710	0,945	0,130
2	0,001	0,509	0,958	0,152	0,003	0,099	0,011	0,034
3	0,001	0,097	0,549	0,878	0,005	0,148	0,165	0,871
4	0,001	0,076	0,135	0,944	0,003	0,456	0,008	0,700
5	0,001	0,001	0,004	0,747	0,112	0,002	0,253	0,002
6	0,001	0,012	0,123	0,794	0,005	0,096	0,004	0,699
7	0,001	0,001	0,270	0,731	0,009	0,001	0,005	0,168
8	0,001	0,092	0,702	0,702	0,022	0,023	0,020	0,133
9	0,001	0,136	0,277	0,592	0,011	0,042	0,001	0,032
10	0,002	0,322	0,103	0,063	0,126	0,201	1	0,983
11	0,001	0,475	0,808	0,288	0,001	0,064	0,058	0,597
12	0,001	0,456	0,628	0,726	0,001	0,007	0,183	0,022
13	0,002	0,001	0,562	0,955	0,325	0,187	0,241	0,116
14	0,658	0,047	0,938	0,919	0,474	0,218	0,144	0,099
15	0,185	0,166	0,921	0,337	0,014	0,656	0,047	0,098
16	0,001	0,203	0,271	0,649	0,025	0,141	0,085	0,032
17	0,001	0,777	0,319	0,837	0,052	0,056	0,203	0,013
18	0,001	0,042	0,616	0,146	0,081	0,563	0,154	0,987

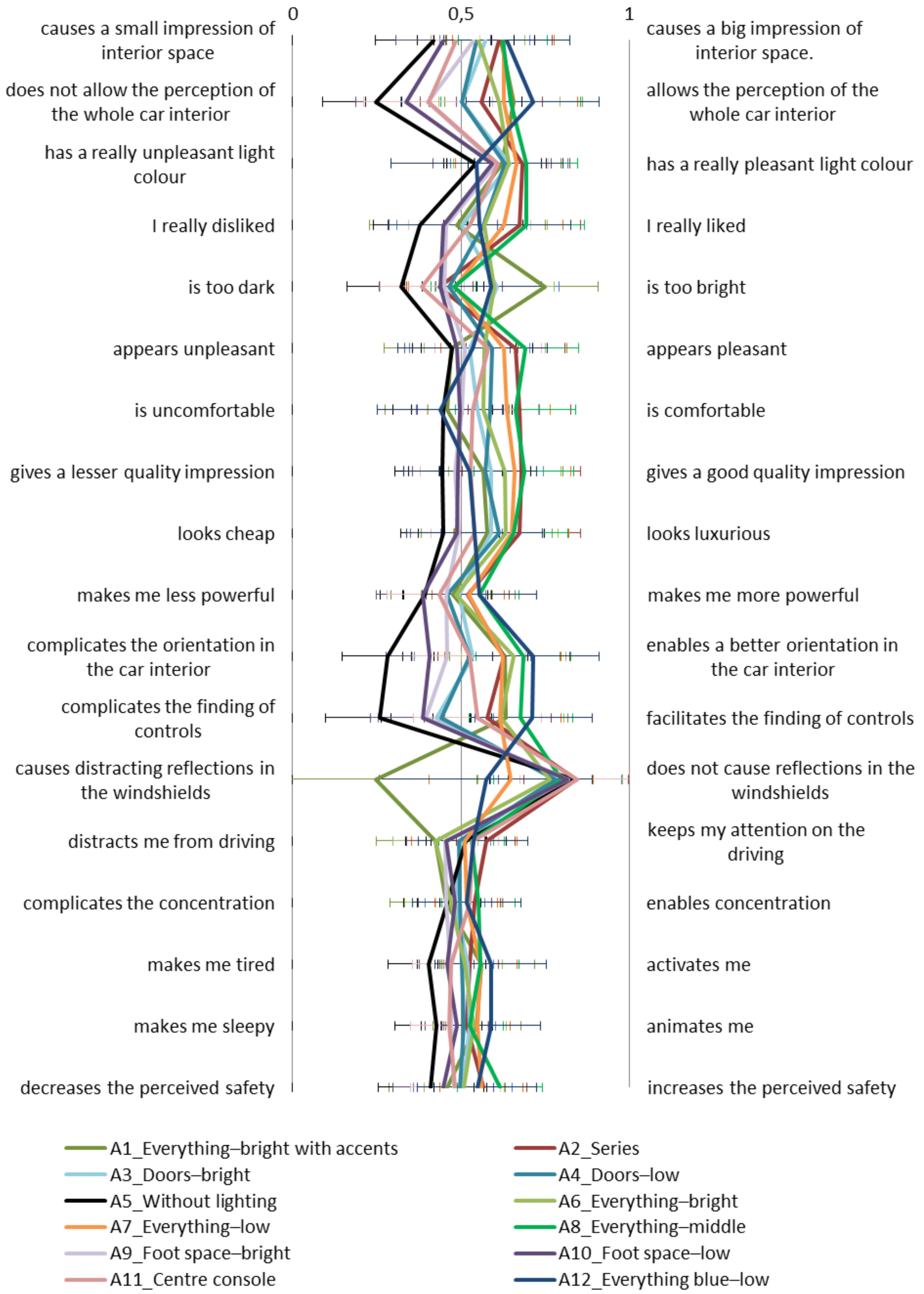


Figure A.2 Results of the questionnaire of study A. For each question the mean value and the standard deviation of the answers are represented. In this graph all 12 scenarios are displayed.

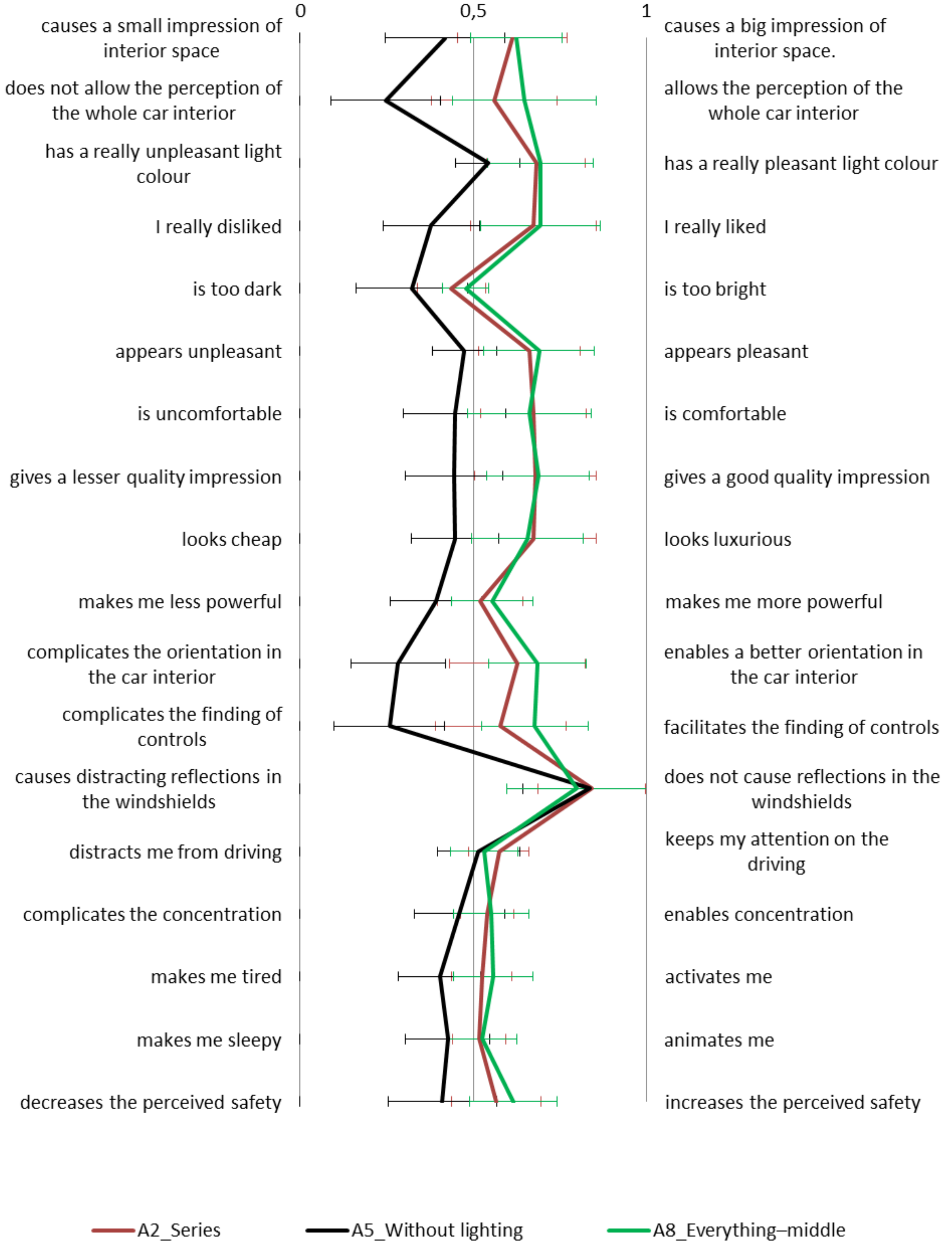


Figure A.3 Results of the questionnaire of study A. The comparison between the optimal scenario (A8) and the worst one (A5 without lighting) and the actual series-production standard (A2). For each question the mean value and the standard deviation of the answers are represented.

A.2 Study B – MINI

A.2.1 Experimental data

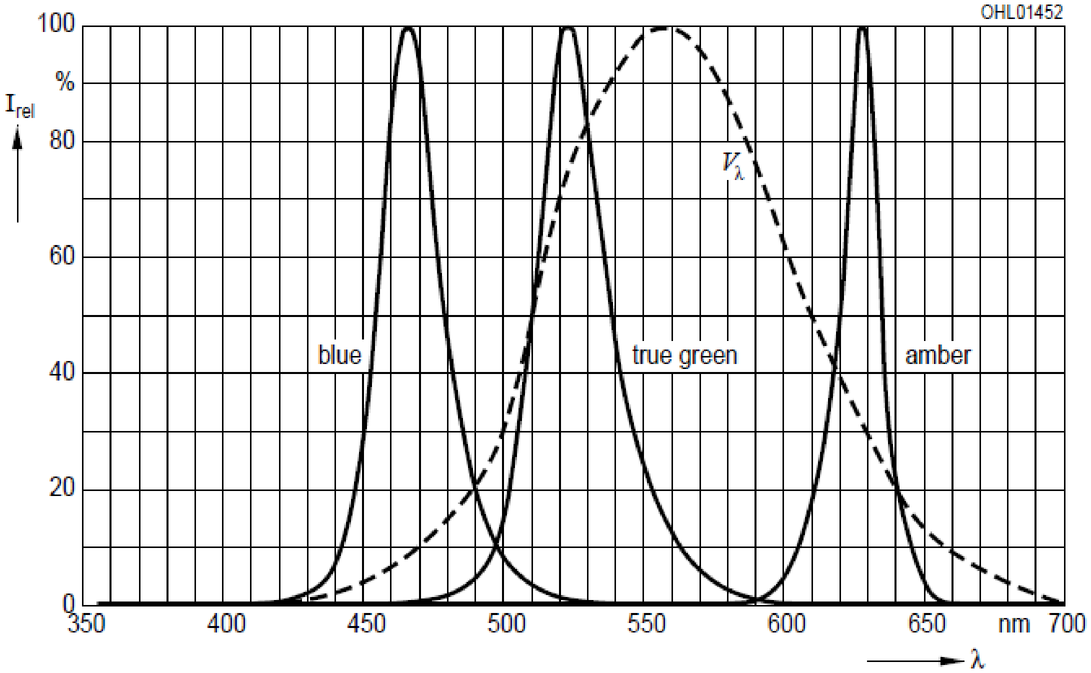


Figure A.4 Spectrum of the RGB LEDs employed in the MINI prototype used in the study B. [95]

Table A.8 Overview of the ambient lighting scenarios presented in the study B

Scenario	Colour	Brightness level
B1	-	No lighting
B2	Red	Series
B3	Blue	Series
B4	Green	Series
B5	Turquoise	Bright
B6	Red	Bright
B7	White	Bright
B8	Green	Bright
B9	Blue	Bright
B10	Blue	Brightest

Table A.9 Measured light levels for the scenarios of study B.

Scenario		Zone	Mean luminance [cd/m²]	Solid angle [sr]	Brightness Index [W]
B1	**Without lighting**	Centre console	0,0027	0,0006	-0,8028
		Doors	0,0027	0,0033	-0,0520
		Foot space	0,0043	0,0052	0,3508
		Information cluster	0,0038	0,0123	0,6753
		Whole interior	0,0056	0,0468	1,4177
B2	**Red series**	Centre console	0,0037	0,0255	0,9784
		Doors	0,0063	0,0523	1,5191
		Foot space	0,0036	0,0039	0,1469
		Information cluster	0,0051	0,0314	1,2072
		Whole interior	0,0056	0,1440	1,9038
B3	**Blue series**	Centre console	0,0042	0,0011	-0,3358
		Doors	0,0071	0,0547	1,5868
		Foot space	0,0032	0,0031	0,0006
		Information cluster	0,0041	0,0074	0,4849
		Whole interior	0,0067	0,0816	1,7378
B4	**Green series**	Centre console	0,0034	0,0011	-0,4480
		Doors	0,0094	0,0664	1,7934
		Foot space	0,0032	0,0037	0,0701
		Information cluster	0,0038	0,0098	0,5694
		Whole interior	0,0080	0,0995	1,9010
B5	**Turquoise bright**	Centre console	0,0357	0,0823	2,4676
		Doors	0,0168	0,0986	2,2199
		Foot space	0,0037	0,0255	0,9776
		Information cluster	0,0135	0,0899	2,0847
		Whole interior	0,0177	0,3545	2,7963
B6	**Red bright**	Centre console	0,0532	0,0938	2,6978
		Doors	0,0059	0,0527	1,4944
		Foot space	0,0039	0,0060	0,3649
		Information cluster	0,0198	0,0939	2,2689
		Whole interior	0,0263	0,2898	2,8815
B7	**White bright**	Centre console	0,0571	0,1045	2,7757
		Doors	0,0176	0,1072	2,2750
		Foot space	0,0043	0,0296	1,1086
		Information cluster	0,0246	0,1137	2,4460
		Whole interior	0,0254	0,4473	3,0559
B8	**Green bright**	Centre console	0,0172	0,0559	1,9822
		Doors	0,0087	0,0657	1,7547
		Foot space	0,0032	0,0050	0,2134

		Information cluster	0,0120	0,0490	1,7686
		Whole interior	0,0124	0,1975	2,3896
B9	**Blue bright**	Centre console	0,0178	0,0547	1,9895
		Doors	0,0070	0,0545	1,5844
		Foot space	0,0032	0,0056	0,2554
		Information cluster	0,0119	0,0475	1,7517
		Whole interior	0,0123	0,1851	2,3569
B10	**Blue brightest**	Centre console	0,0413	0,0770	2,5024
		Doors	0,0078	0,0782	1,7844
		Foot space	0,0041	0,0326	1,1290
		Information cluster	0,0160	0,0926	2,1698
		Whole interior	0,0177	0,3480	2,7903

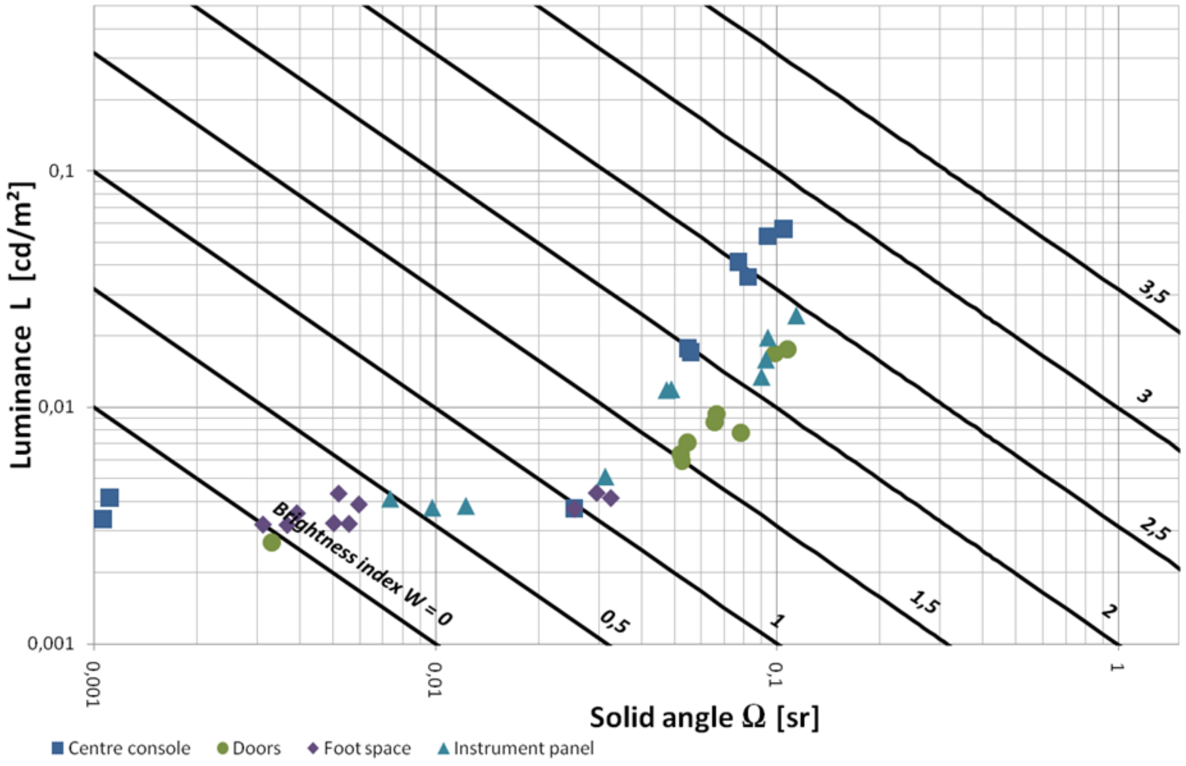


Figure A.5 Brightness level of the different measure zones for the 10 scenarios employed in study B.

Table A.10 Luminance levels in the MINI in the scenarios which allowed the choice of the favourite luminance for the three colours: red, green, blue. Since the scenarios could be varied almost continuously, here are represented only the 10%-steps, from 10 to 100%.

Scenario		**Zone**	**Mean luminance [cd/m²]**	**Solid angle [sr]**	**Brightness Index [W]**
BLr1	**Red 10%**	Whole interior	0,0122	0,1127	2,1374
BLr2	**Red 20%**	Whole interior	0,0204	0,1775	2,5583
BLr3	**Red 30%**	Whole interior	0,0244	0,2121	2,7140
BLr4	**Red 40%**	Whole interior	0,0274	0,2352	2,8095
BLr5	**Red 50%**	Whole interior	0,0304	0,2550	2,8897
BLr6	**Red 60%**	Whole interior	0,0328	0,2741	2,9539
BLr7	**Red 70%**	Whole interior	0,0348	0,2933	3,0088
BLr8	**Red 80%**	Whole interior	0,0356	0,3114	3,0450
BLr9	**Red 90%**	Whole interior	0,0357	0,3302	3,0715
BLr10	**Red 100%**	Whole interior	0,0351	0,3495	3,0881
BLg1	**Green 10%**	Whole interior	0,0118	0,1028	2,0827
BLg2	**Green 20%**	Whole interior	0,0134	0,1589	2,3267
BLg3	**Green 30%**	Whole interior	0,0141	0,2015	2,4519
BLg4	**Green 40%**	Whole interior	0,0151	0,2350	2,5512
BLg5	**Green 50%**	Whole interior	0,0160	0,2679	2,6321
BLg6	**Green 60%**	Whole interior	0,0167	0,2990	2,6974
BLg7	**Green 70%**	Whole interior	0,0173	0,3276	2,7534
BLg8	**Green 80%**	Whole interior	0,0179	0,3528	2,7999
BLg9	**Green 90%**	Whole interior	0,0186	0,4380	2,9119
BLg10	**Green 100%**	Whole interior	0,0184	0,4066	2,8749
BLb1	**Blue 10%**	Whole interior	0,0136	0,0272	1,5664
BLb2	**Blue 20%**	Whole interior	0,0110	0,0624	1,8357
BLb3	**Blue 30%**	Whole interior	0,0108	0,0904	1,9882
BLb4	**Blue 40%**	Whole interior	0,0113	0,1115	2,1008
BLb5	**Blue 50%**	Whole interior	0,0116	0,1312	2,1835
BLb6	**Blue 60%**	Whole interior	0,0117	0,1500	2,2451
BLb7	**Blue 70%**	Whole interior	0,0119	0,1677	2,2993
BLb8	**Blue 80%**	Whole interior	0,0119	0,1852	2,3420
BLb9	**Blue 90%**	Whole interior	0,0118	0,2025	2,3787
BLb10	**Blue 100%**	Whole interior	0,0118	0,2195	2,4148

A.2.2 Experimental results

Table A.11 Results of subjective research in study B. For each scenario the mean value and standard deviation obtained for each question are listed. Scenarios are described in Table A.8. The questions numbers and items of the differential pairs are listed in Table 3.5.

	Scenario B1		Scenario B2		Scenario B3		Scenario B4		Scenario B5	
Question number	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
1	0,17	0,22	0,42	0,23	0,53	0,25	0,39	0,24	0,65	0,22
2	0,08	0,17	0,23	0,27	0,48	0,27	0,22	0,22	0,67	0,22
3	0,12	0,23	0,37	0,30	0,53	0,26	0,28	0,20	0,70	0,22
4	0,08	0,19	0,22	0,22	0,36	0,21	0,22	0,18	0,53	0,21
5	0,45	0,22	0,60	0,23	0,65	0,24	0,52	0,25	0,54	0,33
6	0,21	0,24	0,40	0,27	0,53	0,27	0,37	0,24	0,53	0,30
7	0,30	0,25	0,51	0,25	0,62	0,22	0,52	0,26	0,57	0,25
8	0,24	0,22	0,48	0,28	0,61	0,21	0,40	0,24	0,61	0,24
9	0,48	0,28	0,42	0,19	0,43	0,19	0,49	0,21	0,47	0,24
10	0,44	0,21	0,44	0,24	0,43	0,18	0,42	0,18	0,53	0,23
11	0,23	0,22	0,44	0,21	0,56	0,19	0,39	0,21	0,54	0,23
12	0,96	0,12	0,89	0,19	0,81	0,25	0,93	0,14	0,69	0,25

	Scenario B6		Scenario B7		Scenario B8		Scenario B9		Scenario B10	
Question number	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
1	0,61	0,20	0,77	0,18	0,53	0,21	0,70	0,13	0,72	0,14
2	0,61	0,26	0,79	0,23	0,52	0,26	0,71	0,22	0,74	0,21
3	0,59	0,24	0,79	0,20	0,60	0,22	0,69	0,23	0,78	0,20
4	0,46	0,20	0,55	0,18	0,36	0,17	0,53	0,18	0,70	0,21
5	0,59	0,33	0,66	0,31	0,45	0,26	0,58	0,31	0,65	0,26
6	0,64	0,30	0,67	0,31	0,40	0,26	0,68	0,22	0,58	0,29
7	0,70	0,21	0,68	0,27	0,52	0,25	0,70	0,20	0,58	0,29
8	0,66	0,20	0,70	0,28	0,49	0,23	0,68	0,21	0,66	0,22
9	0,39	0,20	0,46	0,23	0,47	0,18	0,44	0,20	0,58	0,26
10	0,47	0,30	0,45	0,25	0,42	0,22	0,42	0,25	0,56	0,26
11	0,59	0,17	0,62	0,22	0,53	0,18	0,63	0,18	0,49	0,25
12	0,81	0,21	0,73	0,28	0,79	0,22	0,71	0,25	0,51	0,34

Table A.12 Pearson correlation coefficients between the answer distributions to the 12 semantic differential pairs in study B. In light grey shade are the coefficient ϱ>0,5, in dark grey ϱ>0,75.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	1,00	0,78	0,72	0,68	0,35	0,65	0,59	0,70	-0,14	-0,03	0,56	-0,37
2	0,78	1,00	0,84	0,76	0,16	0,59	0,48	0,58	-0,04	-0,□ 6	0,56	-0,45
3	0,72	0,8	1,00	0,70	0,18	0,54	0,50	0,60	-0,06	-0,01	0,57	-0,37
4	0,68	0,76	0,70	1,00	0,0	0,44	0,30	0,49	0,15	-0,24	0,34	-0,62
5	0,35	0,16	0,18	0,09	1,00	0,47	0,55	0,46	-0,31	0,24	0,33	0,08
6	0,65	0,59	0,54	0,44	0,47	1,00	0,79	0,79	-0,38	0,24	0,63	-0,08
7	0,59	0,48	0,50	0,30	0,55	0,79	1,00	0,73	-0,53	0,37	0,70	0,07
8	0,70	0,58	0,60	0,49	0,46	0,79	0,73	1,00	-0,34	0,15	0,61	-0,12
9	-0,14	-0,04	-0,06	0,15	-0,31	-0,38	-0,53	-0,34	1,00	-0,41	-0,43	-0,34
10	-0,03	-0,06	-0,01	-0,24	0,24	0,24	0,37	0,15	-0,41	1,00	0,31	0,34
11	0,56	0,56	0,57	0,34	0,33	0,63	0,70	0,61	-0,43	0,31	1,00	-0,04
12	-0,37	-0,45	-0,37	-0,62	0,08	-0,08	0,07	-0,12	-0,34	0,34	-0,04	1,00

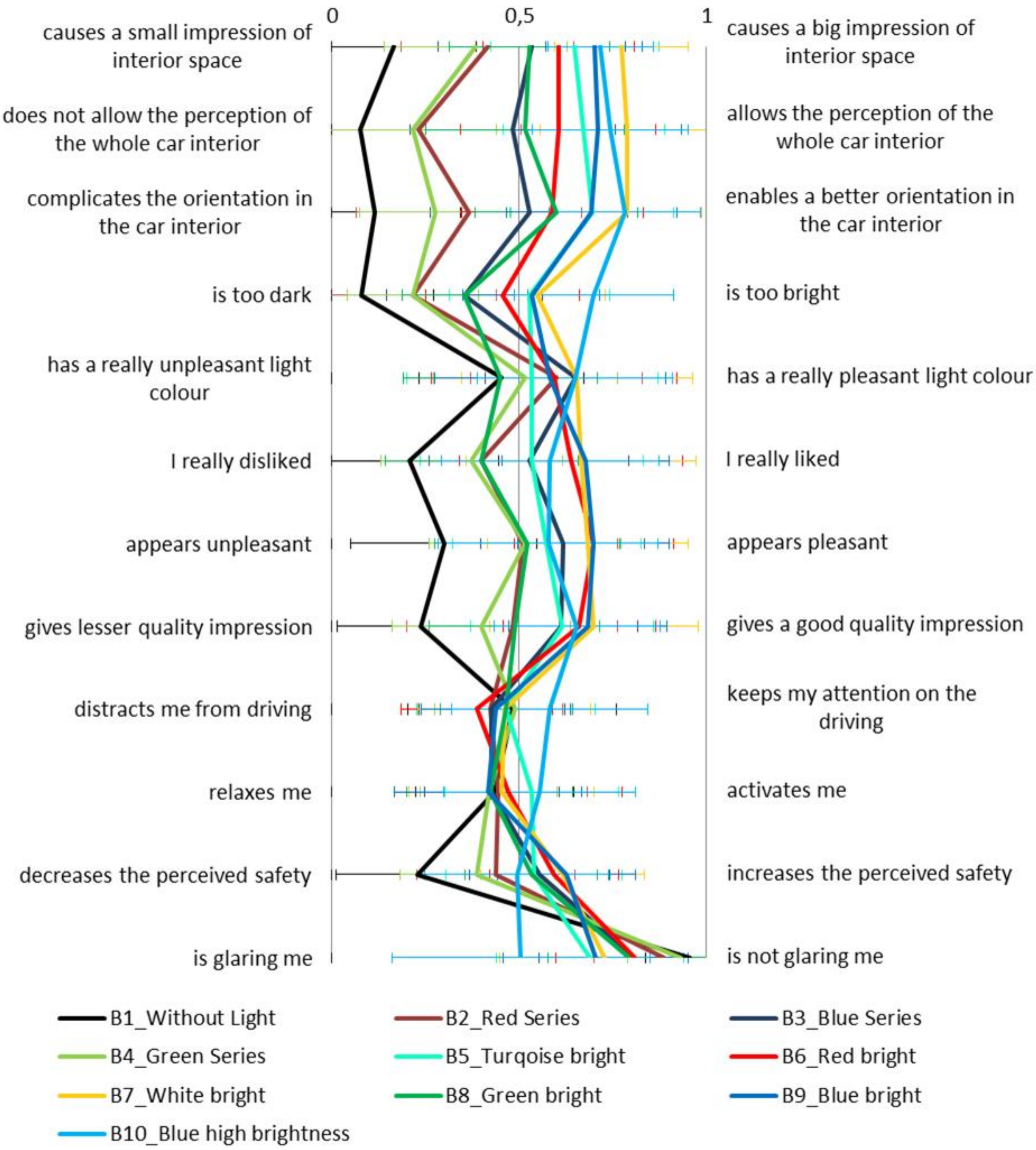


Figure A.6 Results of the questionnaire of study B. All 10 scenarios are listed. For each question the mean value and the standard deviation of the answers are represented

Table A.13 Significance level of the comparisons between scenarios at *series* luminance level. B2 is red series, B3 blue series and B4 green series. Highly significant results (p<0,01) are highlighted by dark grey cells. Significant results (p<0,05) are highlighted by light grey cells. Question numbers are listed in Table 3.5.

Comparison		**Question Number**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
B2	**B3**	0,023	0,002	0,040	0,012	0,352	0,060	0,118	0,089	0,808	0,778	0,066	0,174
B2	**B4**	0,551	0,806	0,096	0,917	0,107	0,757	0,961	0,128	0,168	0,948	0,140	0,143
B3	**B4**	0,005	0,000	0,000	0,002	0,013	0,016	0,133	0,002	0,223	0,844	0,006	0,017

Table A.14 Significance level of the comparisons between scenarios at *bright* luminance level. B5 is turquoise, B6 red, B7 white, B8 green and B9 blue. Highly significant results (p<0,01) are highlighted by dark grey cells. Significant results (p<0,05) are highlighted by light grey cells. Question numbers are listed in Table 3.5.

Comparison		**Question Number**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
B5	**B6**	0,178	0,271	0,040	0,078	0,547	0,240	0,105	0,679	0,123	0,458	0,458	0,034
B5	**B7**	0,074	0,081	0,048	0,739	0,111	0,126	0,161	0,221	0,896	0,134	0,189	0,519
B5	**B8**	0,008	0,004	0,047	0,000	0,208	0,035	0,453	0,022	0,757	0,034	0,765	0,020
B5	**B9**	0,430	0,555	0,666	1,000	0,571	0,023	0,028	0,247	0,913	0,020	0,235	0,533
B6	**B7**	0,004	0,003	0,000	0,067	0,440	0,672	0,927	0,601	0,182	0,731	0,330	0,121
B6	**B8**	0,261	0,194	0,807	0,006	0,118	0,011	0,031	0,005	0,125	0,516	0,392	0,727
B6	**B9**	0,016	0,077	0,097	0,043	0,900	0,433	0,776	0,581	0,190	0,262	0,500	0,045
B7	**B8**	0,000	0,001	0,001	0,000	0,011	0,001	0,015	0,009	0,896	0,684	0,075	0,140
B7	**B9**	0,085	0,117	0,032	0,810	0,293	0,760	0,793	0,734	0,924	0,637	0,903	0,832
B8	**B9**	0,000	0,004	0,106	0,000	0,063	0,000	0,011	0,004	0,735	0,794	0,064	0,129

Table A.15 Significance level of the comparisons between scenarios with same light colours and different luminance level. B2 is red series, B6 red bright; B4 green series, B8 green bright; blue: B3 series, B9 bright, B10 brightest. Highly significant results (p<0,01) are highlighted by dark grey cells. Significant results (p<0,05) are highlighted by light grey cells. Question numbers are listed in Table 3.5

Comparison		**Question Number**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
B2	**B6**	0,003	0,000	0,001	0,000	0,845	0,003	0,003	0,005	0,506	0,431	0,005	0,043
B3	**B9**	0,013	0,002	0,013	0,001	0,305	0,029	0,087	0,052	0,913	0,743	0,038	0,091
B3	**B10**	0,005	0,002	0,002	0,000	1,000	0,253	0,640	0,369	0,026	0,002	0,443	0,001
B4	**B8**	0,019	0,000	0,000	0,001	0,337	0,625	0,978	0,099	0,732	0,844	0,003	0,006
B9	**B10**	0,561	0,766	0,088	0,002	0,454	0,118	0,034	0,544	0,035	0,008	0,037	0,017

Table A.16 Significance level of the comparisons between all the scenarios and the one without ambient lighting (B1). B2 is red series, B3 blue series, B4 green series, B5 turquoise bright, B6 red bright, B7 white bright, B8 green bright, B9 blue bright, B10 blue brightest. Highly significant results (p<0,01) are highlighted by dark grey cells. Significant results (p<0,05) are highlighted by light grey cells. Question numbers are listed in Table 3.5.

Comparison		**Question Number**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
B1	**B2**	0,002	0,017	0,008	0,019	0,049	0,005	0,001	0,002	0,208	0,999	0,002	0,254
B1	**B3**	0,000	0,000	0,000	0,001	0,007	0,000	0,000	0,000	0,732	0,952	0,000	0,029
B1	**B4**	0,007	0,010	0,010	0,006	0,268	0,019	0,002	0,013	0,883	0,641	0,018	0,848
B1	**B5**	0,000	0,000	0,000	0,000	0,532	0,001	0,001	0,000	0,970	0,080	0,000	0,000
B1	**B6**	0,000	0,000	0,000	0,000	0,243	0,000	0,000	0,000	0,080	0,895	0,000	0,004
B1	**B7**	0,000	0,000	0,000	0,000	0,025	0,000	0,000	0,000	0,600	0,525	0,000	0,001
B1	**B8**	0,000	0,000	0,000	0,000	0,553	0,023	0,003	0,000	0,936	0,714	0,000	0,002
B1	**B9**	0,000	0,000	0,000	0,000	0,226	0,000	0,000	0,000	0,431	0,667	0,000	0,000
B1	**B10**	0,000	0,000	0,000	0,000	0,058	0,000	0,001	0,000	0,290	0,014	0,001	0,000

A.3 Study C – BMW 3 Series on a real street

A.3.1 Experimental data

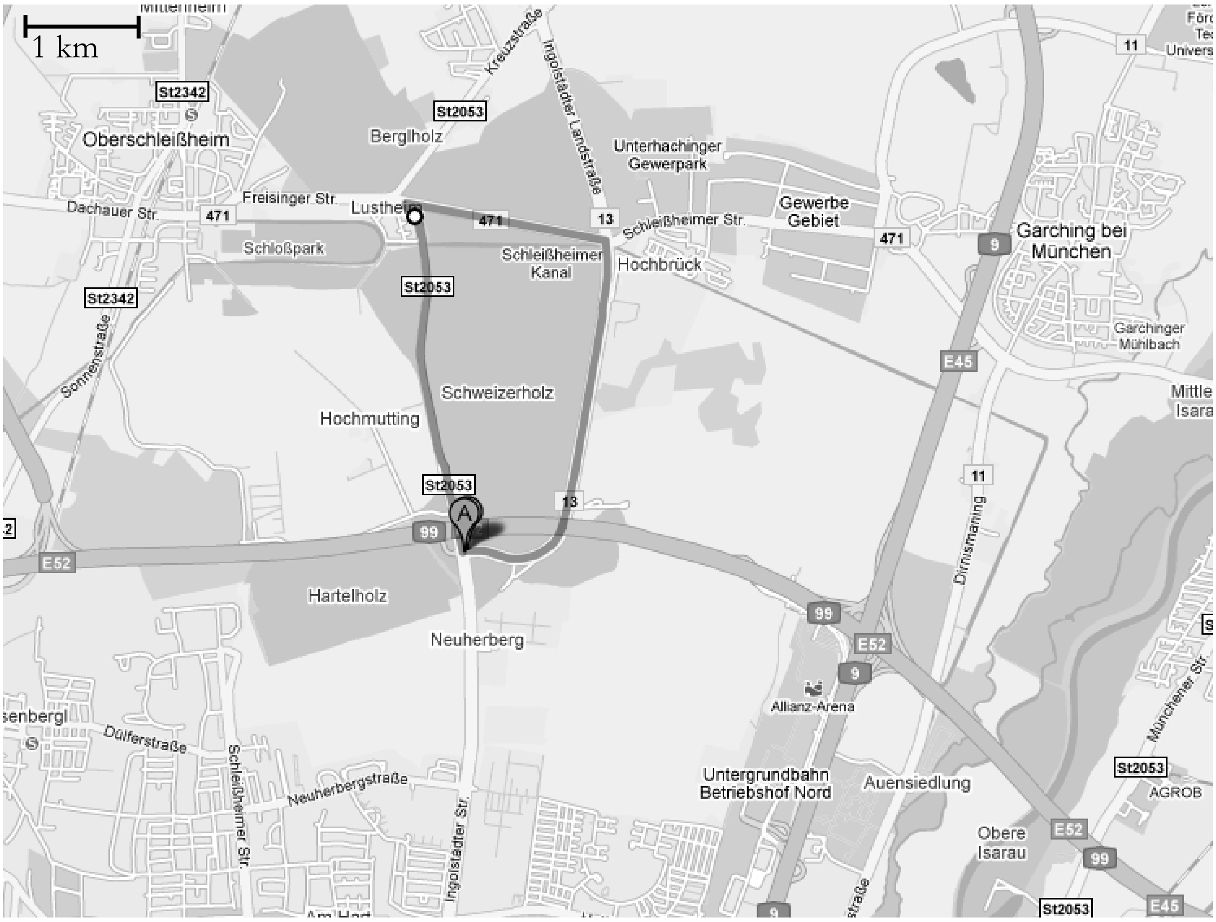


Figure A.7 Route driven while the scenarios C1 to C4 were presented. No street lighting was present on this route. The course was driven two times clockwise (the driver always had to steer right). The circuit was about 8 km long.

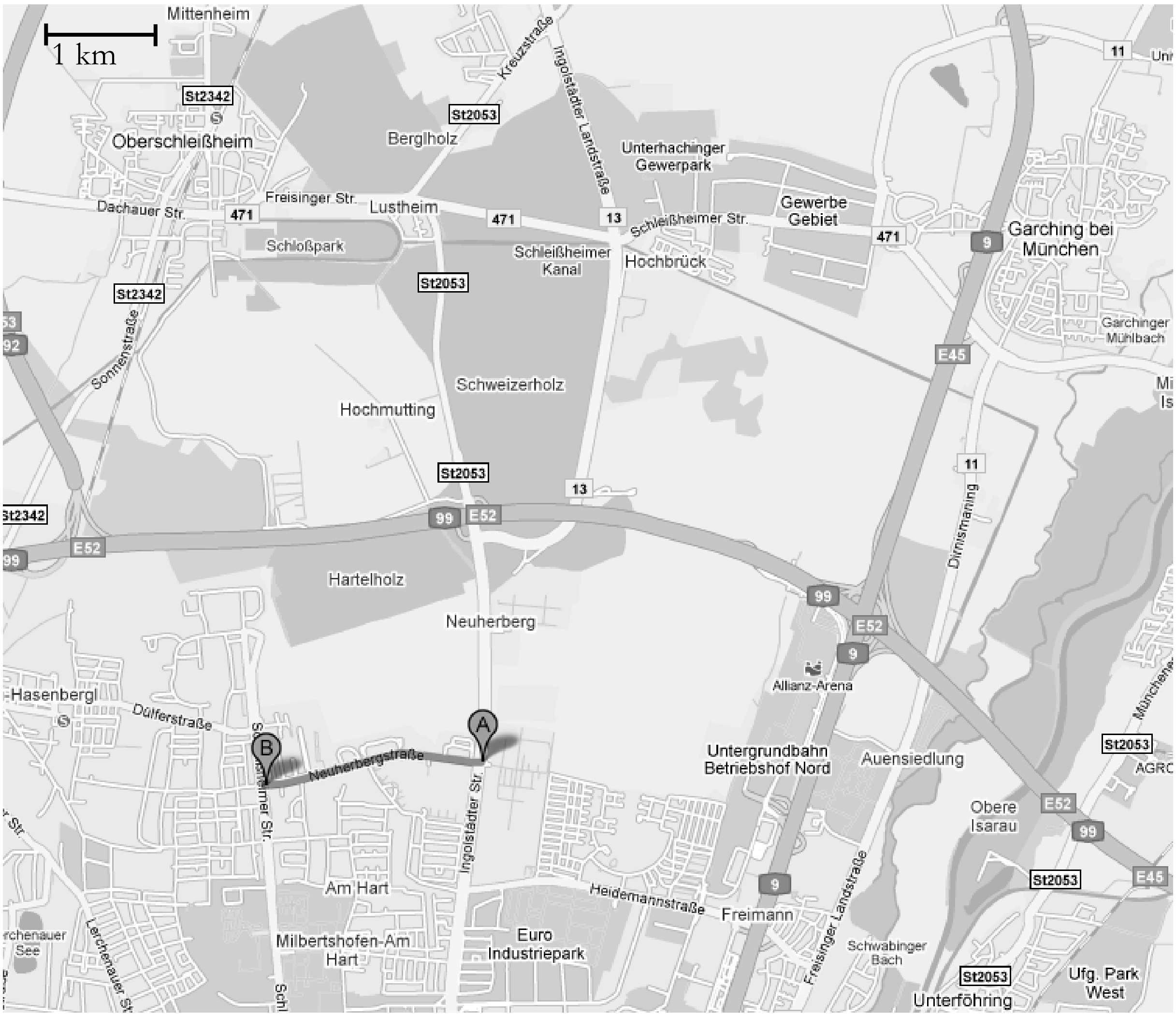


Figure A.8 Route driven while the scenario C5 was presented. The drive went from A to B, on a street illuminated by street lighting on the right hand-side. The whole length from A to B was about 2 km.

A.3.2 Experimental results

Table A.17 Results of subjective research in study C. For each scenario the mean value and standard deviation obtained for each question are listed. Scenarios are described in Table 3.7. The questions numbers and items of the differential pairs are listed in Table 3.3.

	Scenario C1		Scenario C2		Scenario C3		Scenario C4		Scenario C5	
Question Number	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
1	0,40	0,18	0,59	0,20	0,61	0,13	0,63	0,19	0,63	0,17
2	0,19	0,19	0,54	0,23	0,70	0,21	0,72	0,17	0,74	0,15
3	0,45	0,07	0,77	0,15	0,74	0,19	0,69	0,22	0,77	0,15
4	0,34	0,14	0,63	0,18	0,60	0,22	0,49	0,30	0,74	0,14
5	0,26	0,16	0,38	0,16	0,49	0,06	0,73	0,15	0,48	0,10
6	0,42	0,13	0,72	0,15	0,67	0,20	0,46	0,20	0,73	0,15
7	0,44	0,14	0,75	0,16	0,64	0,19	0,42	0,23	0,71	0,16
8	0,41	0,16	0,68	0,17	0,63	0,19	0,56	0,24	0,73	0,14
9	0,42	0,13	0,68	0,19	0,61	0,18	0,56	0,25	0,73	0,16
10	0,39	0,17	0,48	0,12	0,52	0,12	0,49	0,14	0,56	0,09
11	0,33	0,16	0,64	0,17	0,72	0,15	0,61	0,24	0,70	0,14
12	0,29	0,16	0,61	0,19	0,74	0,16	0,57	0,18	0,71	0,11
13	0,92	0,13	0,94	0,07	0,95	0,05	0,17	0,30	0,95	0,06
14	0,60	0,14	0,58	0,13	0,55	0,13	0,34	0,21	0,62	0,14
15	0,56	0,12	0,56	0,10	0,49	0,10	0,42	0,21	0,59	0,09
16	0,44	0,14	0,49	0,13	0,53	0,11	0,63	0,15	0,57	0,08
17	0,44	0,13	0,50	0,14	0,54	0,12	0,70	0,14	0,57	0,10
18	0,41	0,14	0,54	0,11	0,56	0,10	0,46	0,16	0,59	0,14

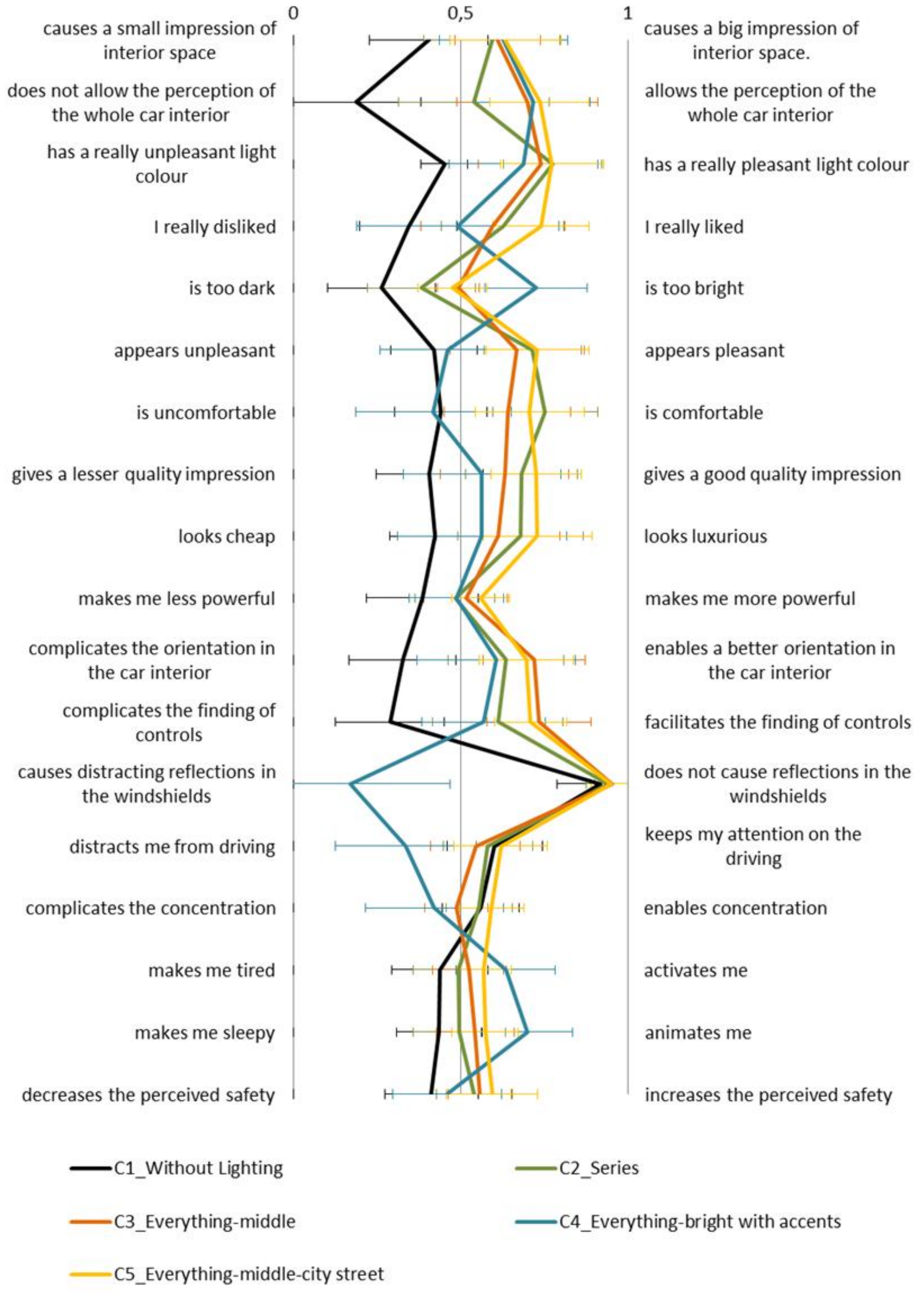


Figure A.9 Results of the questionnaire for study C. For each question the mean value and the standard deviation of the answers are represented.

B Curriculum Vitae

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1996 – 2001	Liceo Scientifico Galileo Galilei in San Giovanni in Persiceto
2001 – 2004	Bachelor Degree, Mechanical Engineering, Universitá degli Studi di Bologna
2004 – 2007	Master Degree, Mechanical Engineering, Universitá degli Studi di Bologna
Work Experience	
2007 – 2010	BMW Group, Doctoral Thesis.
2010 – present	BMW Group, Methods for dynamic motor test bed