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Understanding light. A study on the perceived quality of car exterior lighting and interior illumination.

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Abstract

Illumination, or lighting, is one of the complex product attributes that significantly influences the perception of any motor vehicle. Car manufacturers are aiming to create a meaningful experience induced by the vehicle's lighting. This study seeks a deeper understanding of customer preferences regarding the perceived quality of illumination. We applied the Perceived Quality Attributes Importance Ranking (PQAIR) methodology to understand the importance of perceived quality attributes related to the lighting perception. The approach was tested on 79 respondents and was performed in collaboration with China Euro Vehicle Technology (CEVT). Our results contribute to the effectiveness of the design processes in the early product development phases.

Keywords: lighting; automotive; illumination; perceived quality; product development;

1. Introduction

Automotive lighting is one of the most complex domains, and has a dramatically growing relevance for the automotive industry. Present-day automotive engineering considers the car exterior and interior lighting to be an important quality communication channel [1-2]. Automotive illumination today is a melting pot of new technologies and design ideas that are evolving into a sophisticated and technologically rich environment. The environment that surrounds a driver and passengers provides not only the functional ability to operate the vehicle safely but also elicits both positive and negative emotional responses. Therefore, the perceived quality of lighting is becoming an increasingly important selling point for any automotive OEM (Original Equipment Manufacturer).

The main challenge of lighting development today is the ability to find an optimal balance between performance (luminous flux, light distribution, reliability) and perceived quality in combination with the development time/costs ratio [3]. To find equilibrium, the automotive OEM development teams must correctly define perceived quality requirements. The primary goal of formal perceived quality attributes definition is to secure correct content and execution of the specific component or lighting of a complete vehicle. Therefore, all design and system solutions have to be executed in a way that the customer will perceive the car lighting as one with high quality [4]. However, the perceived quality evaluation of lighting and illumination is a multisensory event, where visual appearance can trigger sensory input regarding the sensations expected from other senses; e.g., tactile or olfactory [5]. This fact adds another complexity level in the understanding of vehicle lighting and needs to be addressed holistically.

This study, as a first step towards the understanding of lighting design with high perceived quality in industrial settings, was performed in close collaboration with China Euro Vehicle Technology (CEVT). CEVT is an innovation center for the Geely Auto Group and was founded in 2013 to develop

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automotive technology for the Geely Auto Group brands, including Volvo Cars, Lynk & Co, and Geely Auto. As long as the Geely Group has the ambition to compete within the premium vehicle market segment, there is a need to ensure that the products developed by CEVT are among the leaders within all quality aspects. The objectives of CEVT regarding this study were as follows:

- How can perceived quality attributes related to car lighting and illumination be categorized?
- How can the end customer preferences regarding the visual appearance of car lighting and illumination be measured and quantified?

In this study we reflect on the perceived quality of exterior lighting (headlamps, tail/signal lamps), interior illumination (including the luggage compartment), and daylight opening (DLO). To fulfill the objectives of the study we applied the Perceived Quality Attribute Importance Ranking (PQAIR) method [6], using the Perceived Quality Framework (PQF) for mapping perceived quality attributes involved in the assessment procedure. We find quantitative evidence of the perceived quality attributes (related to vehicle lighting) relative importance tested on 79 respondents. Analysis of the results allowed CEVT professionals to understand the end customer's perception of "premium" vehicle lighting and quantify the impact of different perceived quality attributes related to light.

This paper is structured as follows: Section 2 discusses related work for this study. Section 3 describes the methodology applied in this study. Section 4 presents the analysis of the experimental data and discusses the results. Section 5 offers conclusions.

2. Background

It is possible to say that research into the perceived quality of automotive lightning and illumination is still at the inception phase. There are several reasons for this fact. Firstly, automotive lighting and illumination for a long time have been limited to compliance with functional requirements. Functional requirements generally address vehicle lighting in a stationary position to assist a customer in basic "utilitarian" tasks e.g., entering/exiting the vehicle, orienting before starting driving activity. Automotive OEMs have only recently considered interior illumination (ambient lighting) and exterior lightning from sociopsychological and aesthetical viewpoints [7]. Secondly, the ability to control perceived quality-related issues has not been addressed systematically in engineering science. A greater part of the methodology available for gathering information about customer preferences (e.g. lead-user workshops [8], Quality Function Deployment, Conjoint Analysis or Analytic Hierarchy Process [9]) either lacks the ability to quantitatively measure customers' perception, either is difficult to apply in industry settings. As a result, the automotive industry has developed specific knowledge regarding the perceived quality evaluation of the complete vehicle or its components as an iterative process where one issue can be resolved. At the same time, a new issue can occur at any point during a design release. Every decision at the level of vehicle components or functions can potentially become a new issue. This specific knowledge is based mainly on subjective empirical evidence. Therefore, the perceived quality of car lighting has not been addressed in an objective, measurable way in the past.

2.1. Car lighting and emotions

When speaking of automotive illumination and the emotional aspects of lighting, we have to admit continually increasing research interest in this multidisciplinary field. The technological advancements in the area of ambient light have allowed conveying of the intended perception of physical space in the car interior, engagement of recognition of the brand core values, and triggering of emotions evoked by meaningful use of design language [2]. A variety of approaches addressing the emotional link to automotive lighting can be found in the literature [10-13]. However, a majority of studies consider lighting and illumination in isolation, making it very difficult in practice to balance perceived quality requirements on different product and system levels. It is important to stress that despite the accumulated experience and advanced methods for automotive lighting development – the evaluation of the perceived quality of lighting still remains largely a subjective or "hit or miss" action.

2.2. Challenges for perceived quality of lighting and illumination evaluation in the automotive industry

The automotive industry is one of the most technologically advanced industries today. A modern car's performance is determined by a variety of product attributes. One of the important attributes associated with overall car quality is perceived quality. A typical automotive OEM uses around 20-120 perceived quality attributes, depending on organizational structure [6]. The perceived quality attributes related to the lighting are responsible for the definition of requirements and requirement levels that determine the perceived quality of exterior and interior light, functional operation of indicator symbols and decorative illumination. Consequently, these attributes can be associated with the complete vehicle requirements, but also the component and system-level requirements. The evaluation of the vehicle's lighting is an ongoing process throughout the project. The group of experts responsible for the illumination competence area define the requirements for engineering and design, and then predict issues, verify engineering and design status and validate target values in production. The creation of a modern vehicle is an extremely complex design and engineering task impacted by the multi-dimensional nature of the perceived quality of light. Often the perceived quality attributes are distributed among different expertise areas within the OEM and perceived quality as a competence area. For example, interior ambient lighting may have a direct impact on the quality perception of materials execution, surface finish or color & gloss properties. The exterior lighting affects design perception of the vehicle, self-esteem of a customer and other hedonic values. What also has to be taken into account is the challenges that automotive professionals face while communicating complex design solutions to the customers. The average customer usually does not make any distinction between the lighting design and the manufacturing processes or technologies affecting the final solution (e.g., color tolerances or temperature). This fact brings another layer of complexity regarding the process of receiving meaningful feedback from the customer. In that case, if a company wants to communicate quality features of the exterior and interior lighting, there is eventually a need to bring these characteristics into the measurable space of perceived quality attributes.

2.3. Perceived Quality Framework (PQF)

Quality perception formed from physical and cognitive inputs is usually triggered by a physical signal received by our sensory apparatus. The information obtained through the human senses forms the basis of human experience.

Fig. 1. Attribute Levels of the Perceived Quality Framework (PQF)

Thus, it is possible to communicate perceived quality in connection with the customer's sensorial experience. In the Perceived Quality Framework (PQF) [6], the quality perception connected to the primary human senses forms the first level of perceived quality attributes: *Visual Quality*, *Tactile Quality*, *Auditory Quality*, *Olfactory Quality*, and *Gustatory Quality* (see Fig.1). PQF constitutes the primary human senses: olfactory, visual, tactile, and auditory. The quality perception related to the primary human senses forms the first level of attributes: Visual Quality, Tactile Quality, Auditory Quality, and Olfactory quality. The second attributes level of PQF is organized in Sensory Modalities. The Sensory Modalities are the nine distinctive sets of product attributes encoded for presentation to humans. Each of these sets has a description and includes several Ground Attributes (GA). The GA is the "lowest point," where the engineers can still communicate with the customer to receive meaningful feedback. Therefore, PQF acts as a communication channel and frame-of-reference for both the engineer and the customer.

2.4. Perceived Quality Attributes Importance Ranking (PQAIR) method

The core of the Perceived Quality Attributes Importance (PQAIR) method [6] is that all identified GAs are ranked with regard to their importance. These rankings, in combination with the PQF, contribute to the importance score for each branch of the attribute structure at all levels. Consequently, each OEM can apply the importance ranking on their own internal attribute structure (usually internal perceived quality attributes definitions and requirements are part of the classified documentation). As a result, each OEM can obtain an importance score for each perceived quality attribute, considering the PQF as a reference model for product quality assessment (see Fig.2).

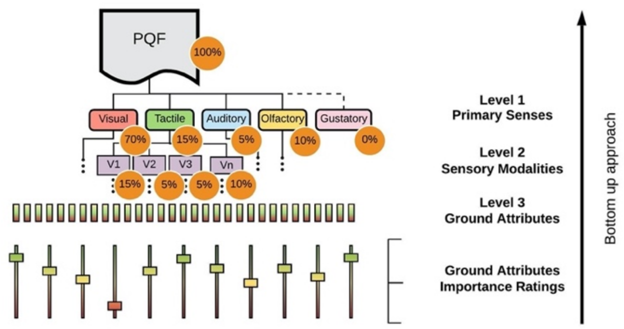

Fig. 2. The attribute-centric sensorial approach of PQF combined with the PQAIR method.

3. Methodology and case study design.

The PQAIR method, as a part of engineering design, is concerned with the open problem of perceived quality evaluation that involves objective and subjective elements. Therefore, we designed the experimental study according to the procedure of the PQAIR method (see Fig.3). The study procedure was first a listing of the CEVT internal perceived quality attributes primarily responsible for the vehicle's lighting and interior illumination. To be able to communicate the lighting design features to their customers, CEVT's internal perceived quality attributes involved in the study have been mapped against GAs responsible for Illumination Quality (see Table 1) in the PQF. The identified attributes were analyzed further regarding the possible appearance, positioning, and execution variations according to the current design and manufacturing capabilities of CEVT. As soon as all possible variations were listed, we created a set of photo images depicting a specific perceived quality attribute, or several in combination. For the estimation of the relative importance of variances in GAs, a quantitative survey technique was used called Best–Worst Scaling (BWS). The BWS method was originally developed by Louviere [14] to understand a respondent's or respondent group's relative valuations of different products or product attributes. According to Marley and Louviere [15], best–worst tasks also positively affect the consistency of the responses and can be easily understood by respondents.

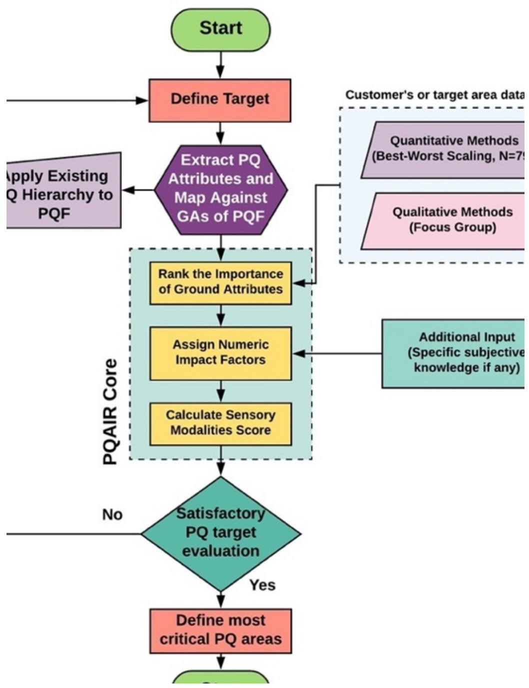

Fig. 3. PQAIR method analysis procedure applied to the case.

Table 1. Description of the Ground Attributes related to Illumination Quality in PQF [6].

Ground Attribute	*Description*
Illumination Function	The logical function of illumination. Timing patterns. Timing synchronization. Ramping up of light signature or function. Coordination of light sources.
Execution & Harmony	An arrangement of light sources designed to show their mutual relations. Uniformity, intensity, consistency within the ramping of light sources. Execution is relevant for all different types of light sources, such as lights, displays, HMI, exterior light.

The BWS study has been designed for 30 variances of Illumination Quality GAs (see Table 2). The choice tasks were presented to the respondents with different permutations of the thirty items (variances). The permutations and numbers of questions were automated using the Sawtooth Discover online survey software module. In each task, the target group (CEVT employees not related to the engineering tasks and departments) participants (N=79) have been asked to select the "most preferable" and "least preferable" attributes for the lighting and illumination design solutions. This included exterior, interior and daylight opening (DLO) areas of the vehicle. The average completion time was approximately 20 minutes. Survey design and results were subjected to data analysis using Discover Survey Software [16]. During the survey, three items (photorealistic image representation and description) in randomized position order were displayed per set, with a total number of thirty sets (see Fig.4).

Table 2. Description of the items included in the experimental set up.

Area	*Sub Area*	*Light type*
Interior Front	Front Driver AC Symbol	Symbol
Interior Front	Front Driver Tunnel_UP	Ambient
Interior Luggage	Luggage Sides	Luggage
DLO Second row	Second Row Door_HS2	Ambient
Interior Front	Front Passenger IP	Ambient
Interior Front	Front Driver Tunnel_ FrIN2	Ambient
Interior Front	Front Driver Tunnel_FrLL1	Ambient
Interior Front	Front Driver Steering Wheel	Reading
Exterior Front	Front Sides Ex_CH1	Position Lamp
DLO Second row	Second Row Door	Ambient
Interior Front	Front Driver Tunnel_ FrCH2	Ambient
Interior Front	Front Passenger Map pocket	Map pocket
Interior Front	Front Driver Steering Wheel	Reading
DLO Front	Front Driver Door Window	Symbol
Exterior Front	Front Sides Ex_FrLL2	Position Lamp
Interior Front	Front Passenger Door Other	Ambient
Interior Front	Front Driver Tunnel_FrCH0	Ambient
Interior Front	Front Driver IP	Ambient
Exterior Rear	Rear License Plate_CH2	License plate
Exterior Front	Front Sides Ex_NHS2	Position Lamp
Exterior Rear	Rear License Plate_HS0	License plate
DLO Front	Front Driver Door M 1 2 Symbol	Symbol
Interior Front	Front Passenger IP_Hs1	Ambient
Interior Front	Front Passenger Tunnel_CH2	Ambient
Interior Front	Front Passenger Door_HS2	Ambient
Exterior Rear	Rear Sides	Position Lamp
Interior Front	Front Passenger IP_Ch2	Ambient
Interior Luggage	Luggage Sides_CS0	Luggage
DLO Second row	Second Row Door_CH2	Ambient
Interior Second row	Second Row Footwell	Footwell

Together with the screening questions, we also collected information about participants' age, income level, willingness to buy a car of a certain price range, number of cars owned, interest in cars in general, working department, attitude towards importance of car lighting and illumination.

Finally, an interview with the focus group (five participants) was performed to validate and evaluate results of the BWS exercise. The focus group discussion was voice-recorded and transcribed verbatim for further analysis.

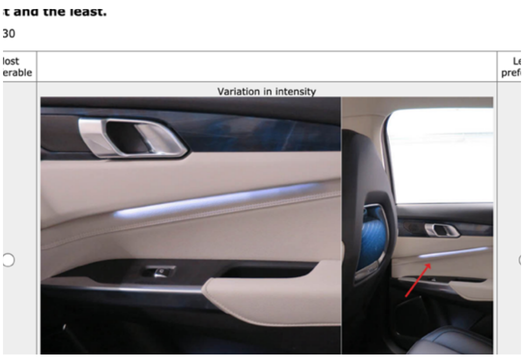

Fig. 4. Example BWS choice task for respondents.

4. Results and Discussion

The results of the BWS rank-order exercise regarding areas of a car are displayed in Fig.5 and Table 3

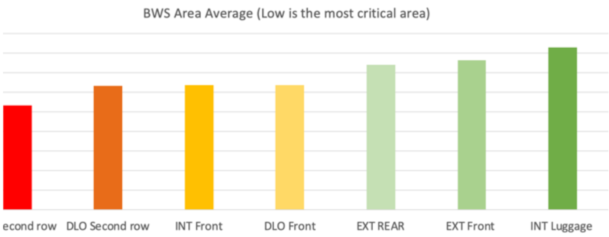

Fig. 5. Car areas importance regarding lighting and illumination.

Table 3. The importance ranking of GA variances related to the car areas.

Area	*Areas mean importance score*	*Number of images Displayed for Evaluation.*
Interior Second row	2.67	1
DLO Second row	3.16	4
Interior Front	3.17	16
DLO Front	3.19	2
Exterior Rear	3.69	3
Exterior Front	3.8	3
Interior Luggage	4.15	2

The results of the BWS rank-order exercise regarding items related to the sub areas of a car depicted in Fig.6 and Table 4

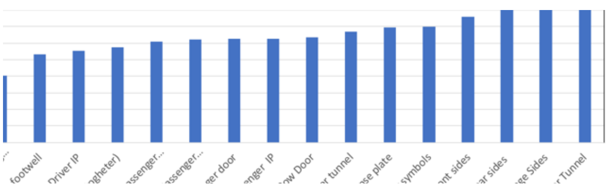

Fig. 6. Car sub-areas importance regarding lighting and illumination.

Table 4. The importance ranking of GA variances related to the car sub areas.

Area	*Areas mean importance score*	*Number of images Displayed for Evaluation.*
Front Driver Steering Wheel	2.03	2
Second Row Footwell	2.67	1
Front Driver IP	2.76	1
Front Driver	2.89	6
Front Passenger Map pocket	3.05	1
Front Passenger	3.12	6
Front Passenger Door	3.13	2
Front Passenger IP	3.14	3
Second Row Door	3.18	4
Front Driver Tunnel	3.36	5
Rear License Plate	3.48	2
Front Driver Symbols	3.50	3
Exterior Front Sides	3.80	3
Exterior Rear Sides	4.13	1
Luggage Sides	4.15	2
Front Passenger Tunnel	4.30	1

The results of the BWS rank-order exercise regarding items related to the light type are illustrated in Fig.7 and Table 5

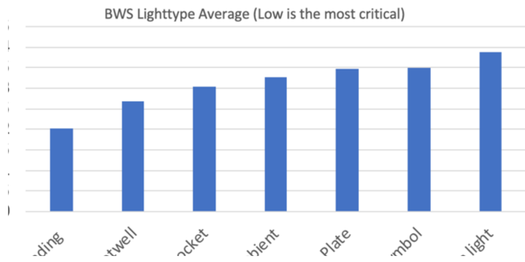

Fig. 7. Importance of car light types.

Table 5. The importance ranking of GA variances related to the light type.

Type of the light	*Mean importance score*	*Number of images Displayed for Evaluation.*
Reading	2.03	2
Footwell	2.67	1
Map pocket	3.05	1
Ambient	3.26	15
License Plate	3.48	2
Symbol	3.50	3
Position Light	3.89	4
Luggage	4.15	2

As one can see, interior and DLO areas appeared as most important, in comparison with exterior lighting and luggage illumination. However, the focus group revealed that exterior lighting is more important regarding the first impression of a vehicle. At the same time, interior illumination seems to be more important in the long term and can act successfully as a brand communication tool. When it comes to minor defects the perceived quality of the interior illumination is more important than the exterior lighting. These findings contradict the CEVT experts' opinion, as they often prioritize exterior lighting over interior illumination. The results of the BWS exercise indicate that the second row and first row are almost equally important, but the focus group suggested that the first row is the most important. Further analysis of sub-areas shows that the front driver side is most important, except for the symbol light on the front driver side, which plays a smaller part. This is followed by the front passenger side, excluding the tunnel, which also received a lower score. Luggage compartment illumination seems to be the least important, and exterior rear lighting second least important, with exterior front lighting third least important. Notably, for the premium customers (respondents who stated willingness to pay a premium price for the car) illumination of symbols and tunnels is more important compared to the rest of respondents. The same applies to the second row, which is less important for the "premium" customer than the others. The major limitation of this study is in the use of images referring to the lighting and illumination. The focus group confirmed that the images looked realistic, even if one could notice that some were manipulated. Images appeared too static, while the experience with light is dynamic. Some images were taken from angles that were unusual for the average customer, which made it difficult to evaluate. It was hard for the participants to ignore interior and exterior design of the vehicle while assessing light. This fact only supports the idea that the perceived quality attributes do not exist and are judged in isolation, but they influence one another. To conclude, despite the statistically insignificant number of participants in the BWS task, ranking of the relative importance of Illumination Quality Ground Attributes produced indices where the respondents' choice estimations allowed metric comparisons of the perceived quality of light. This approach in the future can help to translate the subjective opinions of individuals into quantifiable measures and to avoid subjectivity in the assessment of car lighting perceived quality. The application of the PQAIR methodology to the assessment of exterior lighting and interior illumination provided CEVT professionals with meaningful information about customer preferences regarding the elements comprising the car light quality impression. This information has a significant impact on the process of customer requirements definition. Suggested future research would be design of exploratory studies, including larger samples of respondents. The use of extended reality (AR/VR) to achieve better results providing the dynamic context to participants is also essential.

5. Conclusions

Summarizing the outcomes of this study, it is possible to say that the initial objectives were fulfilled. Categorization of perceived quality attributes related to car lighting and illumination can be performed with the use of PQF. The study demonstrated that the implementation of the PQAIR methodology was able to help to identify customer preferences regarding the different lighting and illumination related attributes and can be applied to measure visual appearance of the various light sources. This study is the first of its kind for CEVT, where ranking of the relative importance of Ground Attributes related to vehicle lighting and illumination produced indices capturing respondents' choice estimations. The obtained indices allowed metric comparisons of perceived quality attributes. This can be seen as an important contribution to car industry practices, by translating subjective opinions of individuals into quantifiable measures; therefore avoiding subjectivity in the assessment of the perceived quality of light.

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