Research Article

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A unified homogeneity criterion for rear lamps

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Abstract: In this paper, we introduce a novel homogeneity criterion based on a just noticeable difference (JND) estimation model. An extensive study is presented to validate the proposed criterion exhibiting an unprecedented agreement between data and methodology. Current criteria are reviewed and compared to the proposed criterion.

Keywords: homogeneity criteria; image processing; just noticeable difference estimation; luminance.

1 Introduction

Throughout the last decade, there has been a growing interest in assessing the homogeneity of signal functions based on analytical criteria and luminance measurements [1, 2] to reduce the necessity of subjective evaluations and accelerate the development process. Consequently, a broad range of criteria and methodologies has been proposed [3, 4] and studied extensively. However, due to the complexity of the human visual system (HVS), the topic has remained challenging, and no unified criterion has been established so far [4]. Many of them rely on the Weber contrast, which was originally developed for simple situations, e.g. sinusoidal gratings in well-defined experimental conditions, which are effectively one dimensional. Thus, to fully grasp more complex situations like images, additional concepts are necessary [5, 6]. Particularly for image/video compression techniques, a thorough understanding of the HVS is crucial to avoid undesired distortions. Consequently, a lot of research has been conducted in the last decades to understand and model the human eye efficiently [7, 8], and systems to predict visual differences [9, 10] have been developed.

Here, similar techniques are used to model crucial properties of the HVS to assess the homogeneity of rear lamps – particularly, the tail function. Current criteria are reviewed, and a new criterion is proposed and validated by an extensive study.

2 Experimental study

The experimental study is conducted in the Volkswagen light tunnel with an ambient luminance resembling a typical situation of two cars standing behind each other, e.g. at a traffic light. The resulting illuminance at the driver's eye in the trailing car has been measured in a separate experiment with the tail function of the car ahead switched on and the low beam as well as the dashboard illumination in the trailing car switched on, too. It was measured at approximately 4 lx and checked at multiple times during the study. All rear lamps are mounted at a height of approximately 1.2 m, and adjustable office chairs are used to achieve a vertical observation angle of approximately 0°. Although this value is not reached in typical driving conditions, it was chosen to ensure comparable observation angles for all test persons regardless of their height. Furthermore, this angle resembles large distances to the car in front, where the vertical angle is at least close to 0°. For smaller distances, the vertical angle reaches up to 10°, reducing the intensity to approximately 20% of the maximum value due to legal requirements. Tape arrows on the ground mark the horizontal observation angles (±45°, ±25°, ±10°, 0°) as well as the observation distances of 2 m for all angles above and 6 m for 0°. The latter distance was chosen to resemble a drive up situation to a standing car. Four rear lamps with comparable optical systems were chosen for the study (VW Scirocco 2015, VW Passat 2015, VW Touran 2016, and Audi A1 2011). They all employ volume-scattering materials to achieve a homogeneous tail light appearance and were powered by an external power supply with pulse width modulation. Figure 1 shows a picture of the experimental setup.

In total, 31 test persons took part in the study. Details on the test group are given in Table 1. For the study, every test person involved in lighting development or testing is considered an expert, whereas test persons working in other fields are regarded as non-experts. To ensure proper adaptation, each test person spent 10 min in the experimental conditions prior to the study and was also checked for limited color vision. Each lamp is evaluated in several steps: first, at a distance of 6 m, followed by each angle given above at a distance of 2 m, and finally a total assessment is given. At each angle, two relative scales as well as a sketch of the illuminated area for the particular rear lamp are provided on an evaluation sheet. Scales range from 0 to 10, with higher values corresponding to a more uniform appearance. The second scale allows test persons to correct their

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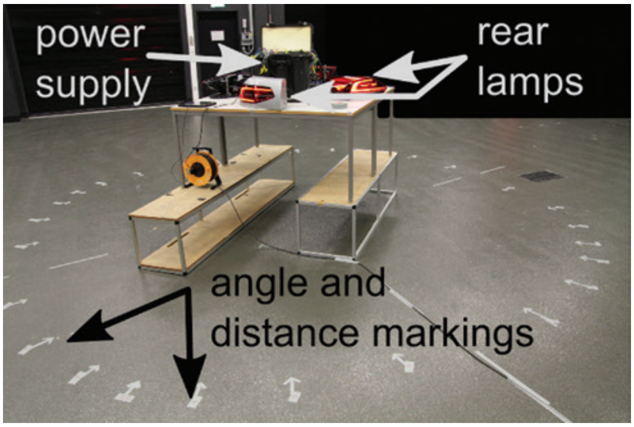

Figure 1: Experimental setup with tape arrows marking the respective viewing angles and distances.

earlier assessment if desired without eliminating previous findings. Hot spots and shadows are marked via the sketch provided. The measurement accuracy equates to ±1%, which is given by the marking accuracy on the evaluation sheets.

As each test person uses an individual scale for their evaluations, values are rescaled onto a common axis by taking the respective minima and maxima into account:

$$x' = \frac{x - \min x}{\max x - \min x}$$

As a consequence, 0% represents the minimum and 100% the maximum, respectively. Moreover, it is not possible to return to absolute values because of differing minima and maxima.

Figure 2 shows median values from the study for non-experts (A) and experts (B). Both plots exhibit similar principal features: evaluations decrease toward outboard (positive) angles. At several angles, evaluations are indistinguishable within the given measurement accuracy, e.g. Touran, Passat, Scirocco at 0° and ±10° in subfigure (B). Although both plots are generally quite similar, major differences between both test groups occur for the total evaluation. Whereas the A1, Touran and Scirocco are practically indistinguishable for non-experts, the spread between those cars is considerable for experts, and the A1 comes out as a favorite both for experts as well as non-experts. In conclusion, the study indicates that experts are more critical in their homogeneity assessment than non-experts.

2.1 Comparison with current criteria

As described by Paroni et al. [4], several criteria from OEMs exist to evaluate the homogeneity. Figure 3 depicts a measured luminance image (top row), a local threshold criterion (L_2 in [4], middle row) and a gradient image (bottom row). Ellipses plotted on top indicate shadows, whereas circles denote hot spots marked by test persons in the study. Different gray values correspond to the number of occurrences, with white representing high values and gray low ones, respectively.

Most strikingly, the gradient image only shows very few features, which correspond only partially with markings by test persons. Similarly, the threshold criterion L_2 does also mostly not coincide with those markings. Both criteria, therefore, have limited value in a development or approval process where a criterion with a higher accuracy is desirable.

3 Proposed criterion

Most of the criteria mentioned in Ref. [4] neglect the tail function's geometrical shape and are, thus, quasi one dimensional. However, many optical illusions occur due to particular spatial arrangements, i.e. local factors [5].

Table 1: Test group details.

(a)					(b)				(c)
Male	Female	Total	Experts	Non-experts	Total	Age group/year	20–30	31–40	41–50
22	9	31	16	15	31	Number	9	15	7

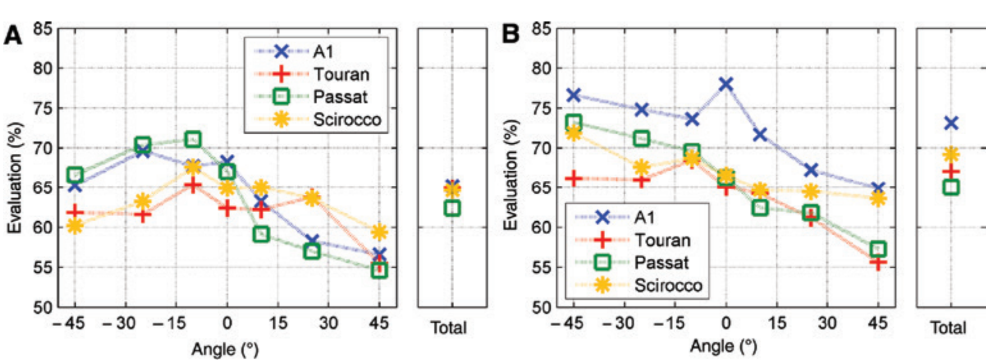

Figure 2: Study results for all four cars. (A) Data from non-experts and (B) for experts, respectively. Dashed lines serve as a guide to the eye. Outboard angles are positive.

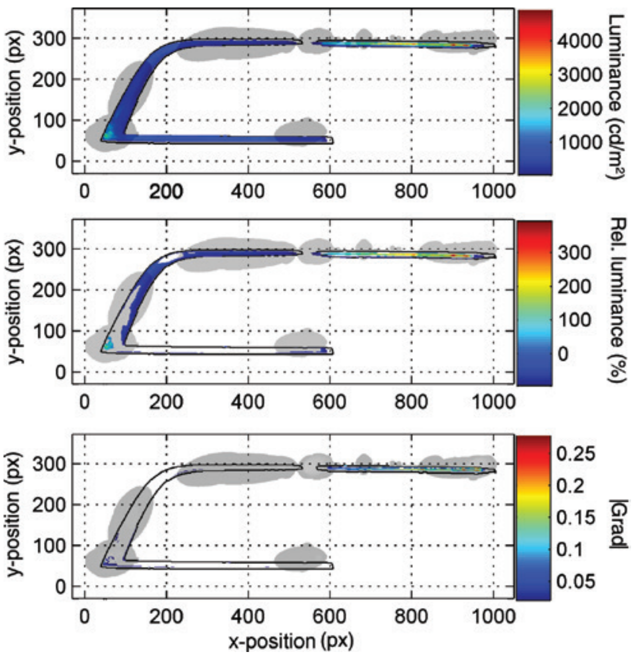

Figure 3: Comparison of current homogeneity criteria according to Ref. [4]. Top row: measured luminance image, middle row: threshold image, bottom row: gradient image. Different gray values correspond to the number of occurrences from test person markings in the study. White denotes high values and gray low ones, respectively.

Many of the involved effects are even non-linear and, therefore, have a profound impact on the appearance of an image. Moreover, they might not be directly apparent by analyzing a luminance image alone. Taking them as well as other properties of the HVS into account is, thus, crucial for a more robust homogeneity evaluation method.

3.1 Dynamic range of the HVS

Luminance measurements inherently cover a high-dynamic range [11], which is often larger than the corresponding one of the HVS. The latter is commonly given as approximately three decades, centered around the adaptation luminance L_{adapt} on a logarithmic scale, thus, imposing an upper L_{max} and a lower limit L_{min} to perceivable luminances. These limits are not fixed and change with L_{adapt}, which is usually calculated as the mean luminance of the scene under consideration. However, it is unclear whether the whole field of view needs to be considered or only a smaller subset of it. In this paper, we leave L_{adapt} as the model's only free parameter and found best agreement with the study for a viewing angle $\alpha = 8°$. This corresponds to the paracentral part of the human field of vision and leads to a circular section being considered for the mean. We assumed a step-like distribution function, which is equal to zero for $\alpha \geq 8°$ (white area in Figure 4) and one for $\alpha < 8°$ (colored area in Figure 4), although this is expected to be more complex and cannot necessarily be generalized to every situation. Calculated adaptation luminance values are in the range of 7 cd m^{-2} to 150 cd m^{-2}. The particular lamp shown in Figure 4 was considered very bright by many test persons. This is also reflected in the calculated adaptation luminance of 107 cd m^{-2}, which is well in the photopic vision range. Considering the ambient conditions, perception and measurement match well and support the methodology.

Alternatively, the ambient luminance can be set to a fixed level to assess a rear lamp in varying conditions, e.g. dawn, night, or daylight. Prior to further calculations, L_{max} is determined to set luminance values larger than L_{max} to L_{max} and equivalently for the lower limit L_{min}, thereby, adjusting the measured dynamic range to the one of the HVS.

3.2 Just noticeable difference estimation

According to Weber's law, only differences larger than a certain threshold are perceivable, and the latter is, therefore, also commonly known as a just noticeable difference (JND). JND thresholds, hence, correspond to the minimum visibility threshold of the HVS and are, as a result, useful in perceptual image/video processing systems [12–15]. One calculation approach are pixel-based JND estimation models [13, 16–18], which already consider luminance adaptation and spatial masking. However, they underestimate JND thresholds on disorderly components of the image such as textured regions. Recently, an extended model based on the free-energy principle was proposed

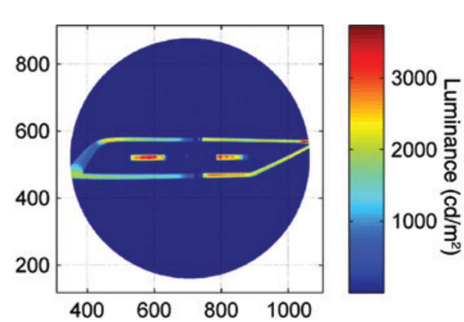

Figure 4: Calculation of adaptation luminance L_{adapt} to adjust luminance measurements to the dynamic range of the HVS. Colored regions correspond to the paracentral part of peripheral vision, whereas white areas are not considered due to a larger viewing angle.

to overcome this limitation [15]. It is employed in this paper to model the HVS and assess the homogeneity of tail lights. Figure 5 shows typical calculation results with ellipses plotted on top to indicate shadows, whereas circles denote hot spots marked by test persons in the study, again. Like in Figure 3, different gray values correspond to the number of occurrences for respective features. Subfigure (A) contains data given by non-experts only and (B) by experts, respectively. JND values smaller than one are neglected as they are not resolved by the HVS as stated by Weber's law.

In contrast to previous criteria depicted in Figure 3, JND values exhibit an appreciable overlap with study data both for experts and non-experts. Particularly, regions with large occurrences show JND values greater or equal to 10, and even for lower occurrences, values of approximately 6 are calculated. Analyzing all available data yields a threshold of ≥ 4 for lower occurrences (i.e. gray regions) and ≥ 8 for large occurrences (i.e. white regions). Thus, regions with a JND value of up to 4 can be regarded as homogeneous, whereas regions with values ≥ 8 are perceived as inhomogeneous. The range in between is less clear and needs to be evaluated by further studies. Nonetheless, inhomogeneous regions are clearly identified by the proposed calculation method.

To determine the method's accuracy, test person markings and calculations were compared manually by counting marked features. This procedure was chosen because the graphical accuracy in collecting test person data for shadows/hot spots limits a numerical comparison with JND calculations. Overlap between study and method amounts to approximately 90% with a false-alarm rate of approximately 10%, i.e. the method is slightly more critical than a human observer. Overall, the method shows an unprecedented accuracy in comparison with existing criteria.

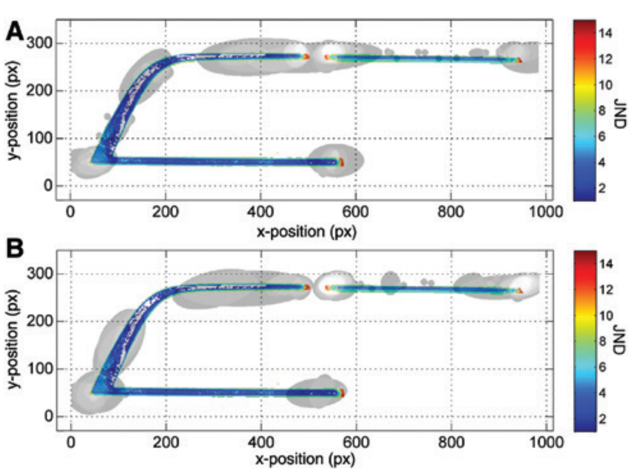

Figure 5: JND calculation with overlayed test person data from the study. Different gray values correspond to the number of occurrences from test person markings in the study. White denotes high values and gray low ones, respectively. (A) Data given by non-experts only and (B) equivalently by experts.

A detailed analysis between expert and non-expert markings yields only minor differences regarding the perception of shadows/hot spots. However, the respective evaluations for experts exhibit a larger spread as shown in Section 2, suggesting that experts rate particular features more critically than non-experts. Image analysis methods, therefore, provide more robust results and are, thus, favorable to simpler rating schemes.

3.3 Limitations

The proposed method cannot predict whether a particular feature with a given JND value constitutes a hot spot or a shadow. It merely indicates regions, which will be recognized by a human observer with a certain probability. However, a lighting engineer should be able to discern between both cases by comparing the calculated JND image with a false color plot of the measured luminance image. Hence, for practical purposes in a development or approval process, this property is not expected to pose a severe limitation.

Lighting functions are designed with well-defined boundaries by suitably positioning bezels in their illuminating system, and consequently, a sharp step in luminance occurs at its edges. This translates into a small border with a width of a couple of pixels of JND values in the range of approximately 4–6. Its actual width is limited by the size of the operator used to determine local luminance (typically 5 px × 5 px) and the spatial luminance distribution. For illuminated areas of several operator sizes, the border becomes negligible and does not limit the ability to assess homogeneity. In this case, it is also possible to suitably erode the considered area without eliminating important information. For thin stripes, however, the situation is more difficult because erosion could easily lead to information loss and is, therefore, undesirable. The effect is best avoided by choosing a sufficiently large resolution of the region of interest to suitably erode it after determining the JND image. This requires either a high-resolution luminance camera for the analysis or taking several overlapping images to stitch together an image with the required resolution. Although the effect can lead to additional technical complexity depending on available equipment, it does not restrict the method's applicability.

4 Conclusion

In this paper, a novel homogeneity criterion based on a JND model has been proposed and compared with existing criteria. The model considers essential properties of the HVS and exhibits an unprecedented agreement with data collected in a study. It outperforms existing criteria and, thus, offers a novel methodology for homogeneity evaluation in the development process of signal functions. Furthermore, it offers previously unavailable additional information for approval processes or quality control.

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