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RECEPTIVE FIELD MECHANISM AND PUPILLARY LIGHT REFLEX FOR THE ASSESSMENT OF VISUAL DISCOMFORT*

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ABSTRACT

Discomfort glare is defined as glare that causes discomfort without necessarily impairing the vision of objects. Traditional glare metrics fail for non-uniform luminaires. As an alternative, visual discomfort is determined by a physiological model incorporating the centre-surround receptive field mechanism and the pupillary light reflex. The pupil area, controlled by the pupillary light reflex, regulates the retinal illuminance. A centre-surround receptive field, described by a difference of Gaussians, represents the visual signal. The centre excites the signal whereas the surround controls the inhibition. A forced choice paired comparison experiment involves 7 non-uniform rear projected stimuli with different spatial frequencies. Inspired by a promising coefficient of determination of 0.90, the model is a candidate to replace current glare metrics as UGR or VCP, especially when non-uniform luminaires are to be evaluated.

Keywords: discomfort glare, luminance map, receptive fields

1. INTRODUCTION

Discomfort glare is defined by the International Commission on Illumination (CIE) in the international lighting vocabulary as: "glare that causes discomfort without necessarily impairing the vision of objects" [1]. Ever since the beginning of the previous century, researchers have been attempting to quantify the amount of visual discomfort [2]. A multitude of glare indices have been developed. The Unified Glare Rating (UGR) is proposed by the CIE for the assessment of discomfort glare for interior lighting and is included in the European standard for indoor workplace environment EN12464–1 [3, 4]. The International Engineering Society of North America (IES) proposed the VCP for the assessment of discomfort glare [5].

Traditional glare metrics often include an average luminance level calculated from the far field luminous intensity distribution [3, 5]. Any non-uniformity in luminance distribution is ignored. Since a non-uniform luminaire produces more discomfort glare than a uniform one of equal average luminance, the applicability of traditional glare metrics for non-uniform light sources is under discussion [6–12]. The non-uniformities of a luminance distribution are accurately described by a luminance map [13]. With a growing market share of highly non-uniform LED luminaires for interior and exterior lighting, a valid assessment of visual discomfort based on luminance maps becomes essential.

Although some mechanisms involved in glare perception are known, sometimes already for decades, traditional glare formula are merely phenomenological and lack any physiological or psychological justification. In the model presented in this paper, the receptive field concept is extended with the pupillary reflex for the calculation of visual discomfort.

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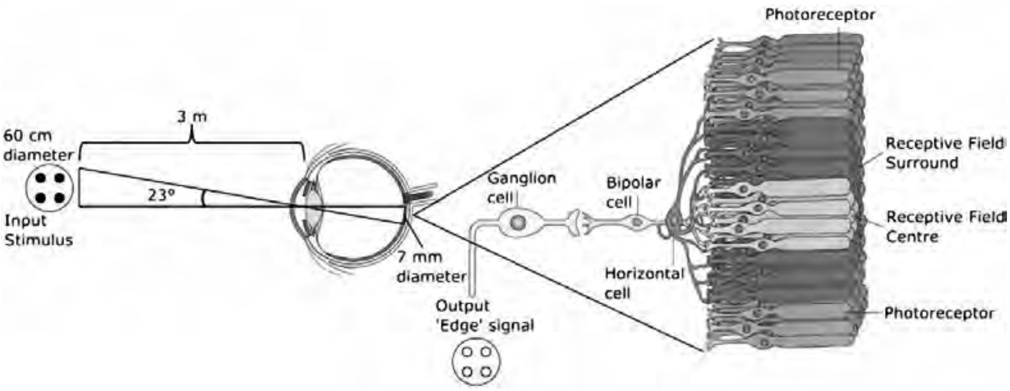

Fig.1. The human visual system includes the pupillary light reflex and receptive field mechanism

The pupillary light reflex controls the retinal illuminance as part of the adaptation process. Different formulas for the pupil size are developed [14]. Early formulas only include the luminance level of the stimulus [15–18]. Next to the luminance level, also the stimulus size is a determining factor [19, 20].

The receptive field neural pathways have been studied already from the 1930's on [21, 22]. By physically stimulating the retina of mammals and other animals, the neuron response is directly recorded [23, 24]. Patterns with different spatial frequencies invoke a neural stimulation [25, 26]. The computation of the neural stimulation forms a physiological basis for visual discomfort and is recently applied in lighting design [27].

In the present study, visual discomfort is calculated from a luminance distribution by applying a model including the receptive field mechanism and pupillary light reflex. The model is analysed with a forced choice paired comparison (PC) experiment involving 7 non-uniform rear projected stimuli with different spatial frequencies.

2. METHOD

2.1. Human Visual System

The human visual system includes several mechanisms (Fig. 1). The eye images an object plane characterized by a luminance distribution on the retina. The retinal illuminance is proportional to the pupil area, controlled by the pupillary light reflex, and the object luminance. In lit environments, a constriction of the iris reduces the pupil area and limits the incident light. In dimmed settings, an iris dilation increases the pupil aperture maximizing the retinal illuminance. The pupil size ranges approximately between 2 mm and 8 mm. In this paper, the pupil diameter is obtained from the average stimulus luminance level and the stimulus field size [19]:

$$D = 5 - 3\tanh\left(\frac{0.4\log(L_s a}{40^2}\right), \quad (1)$$

where D is the pupil diameter (mm), L_s the average stimulus luminance level (cd/m²), a is the stimulus field size (deg²).

The pupil area controls the retinal illuminance (E_{ret}) by scaling the luminance distribution (L, cd/m²). For direct view, the retinal illuminance can be approximated as:

$$E_{ret} \sim L\left(\frac{D}{2}\right)^2 \pi. \quad (2)$$

Seen from the back of the eye to the front, three retinal layers can be distinguished: the photoreceptors, the layers with the bipolar and horizontal cells and the ganglion cell layer. Under photopic conditions (Hunt, 1998), the cone photoreceptors convert the incident light into an electrical signal. Since photoreceptors are situated in the deepest retinal cell layer, nerve cells in other layers must be transparent. Centre photoreceptors link directly to a bipolar cell. The horizontal cells parallel to the retina connects several surround photoreceptors and also relay the signal to the bipolar cell in an indirect path. A bipolar cell in turn transfers the direct and indirect photoreceptor signal to a ganglion cell. The ganglion cell sends a pulsed signal train to the brain.

Combining the direct and indirect signals is resulting in centre-surround receptive fields formation. In an ON-centre OFF-surround receptive field, the ganglion signal is excited by the centre but inhibited by the surround signal and vice versa for an

OFF-centre ON-surround receptive field. Photoreceptors can be part of multiple centre and/or surround fields [22]. A receptive field is modelled by a difference of 2-dimensional Gaussian distributions. Subtracting a surround Gaussian from a centre Gaussian results in the total difference of Gaussians (DoG) receptive field pattern. When a single receptive field is uniformly illuminated, the net signal will be marginal. At a sharp dark-light edge where the surround is not entirely illuminated, the centre is not maximally supressed. A receptive field consequently acts as an edge filter (Fig. 2).

A luminaire can be represented by a luminance map. To each pixel of a high definition luminance map, a luminance value and spatial coordinate in the luminaire can be attributed. A centre-surround receptive field is modelled by a Mexican hat shaped difference of Gaussians (DoG), Fig.3. The difference between the maximum centre signal and maximum surround signal is reflected in the weighing factor (WF). The DoG kernel is scaled and discretized to correspond to the retinal illuminance map resolution. A single ganglion cell receptive field signal is calculated by overlaying the DoG kernel on one specific area of the luminance map, pointwise multiplying the overlapping matrices and adding all obtained products. The response of all ganglion receptive field signals in the eye is modelled by the convolution of the luminance map with the DoG kernel. The convoluted luminance map represents a measure for the transmitted signal to the brain for each pixel. To count both the ON- and OFF-centre receptive field contributions, the absolute signal value of the convoluted luminance map is considered. The sum of all pixel signals is a measure for the total visual signal of the luminaire. The total number of pixels is dependent on the luminance camera field of view and the luminance map resolution. To normalise for the difference in number of pixels for different resolution luminance maps, the pixel signal is weighed with the pixel visual solid angle. A natural logarithm accounts for the compression mechanisms, as can be found in multiple perception formulae [3, 5]. A centre and surround field width have previously been reported [11]. The natural logarithm is arbitrarily chosen in this paper. The total calculation procedure used in this paper is summarized below:

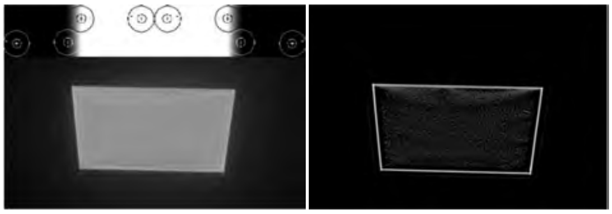

Fig.2. Left: at a dark area, there is no excitation by the centre and no suppression by the surround field; at a uniform area, the excitation of the centre is suppressed by the surround; and in both, the dark and uniform case, the net receptive field signal will be marginal; wherein at a sharp dark-light edge, the centre (or surround) is not entirely illuminated resulting in a net receptive field signal; right: the receptive field mechanism, and consequently the human vision, acts like an edge filter

$$\textit{Visual Discomfort Model} = \\ = \ln \sum_{pix} \omega_{pix} \left| (C - WFS) * E_{ret} \right|, \quad (3)$$

where *ln* -is the natural logarithm; ω_{pix} is the pixel solid angle; C is the centre kernel; S is the surround kernel; WF is the Surround-to-Centre Weighing Factor; E_{ret} is the retinal illuminance map; * is the convolution operator.

2.2. Paired Comparison Visual Experiment

Seven non-uniform stimuli were rear projected on a diffusor screen creating Lambertian light distributions (Fig. 4). Light patches with a luminance level of 1500 cd/m² were arranged in a 33.5 cm by 34.0 cm matrix observed from a fixed 3 m distance. While increasing the number of squares, the luminous surface per square and spatial separation between squares was decreased maintaining an average luminance level 350 cd/m² and a total light emitting surface 0.0042 m^2. The matrix consisted of 2 by 2, 6 by 6, 26 by 26, 60 by 60, 179 by 179 and 360

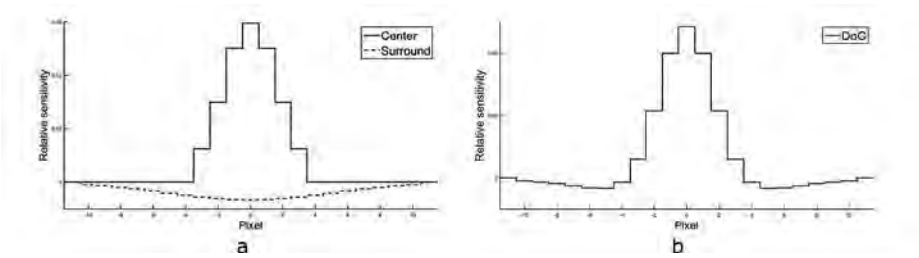

Fig. 3. Left: cross section of a discretised centre and surround kernel; right: a discretised difference of Gaussians (Centre minus Surround) kernel representing a receptive field with a WF of 1

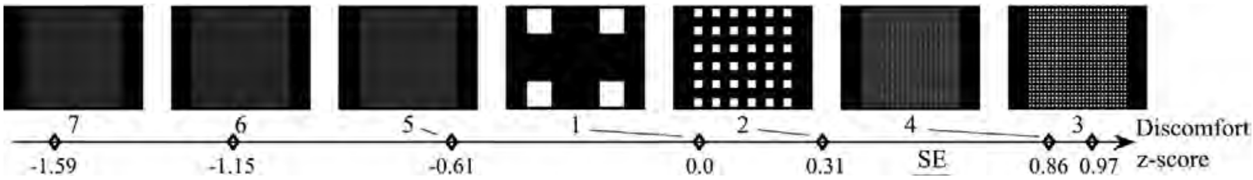

Fig. 4. The 7 rear projected stimuli and subjective PC results with standard error

by 360 light patches complemented with a uniform stimulus.

DALI controlled wall washers produced a uniform background luminance ranging (40–50) cd/m² with an average luminance level 45 cd/m². In a full forced choice PC experiment, all 20 observers were shown 42 pairs and were asked to indicate the most visual discomforting stimulus per pair. The observers were between 20 and 38 years old with an average of 26 years. The experiment took about half an hour and observers could ask for a break whenever they wanted. A generalised linear model produced a z-score on an interval scale for each stimulus and a standard error for visual discomfort (Fig. 3) [28, 29]. Luminance maps were measured with a LMK Labsoft luminance camera with a total reported uncertainty of 2.8 %.

3. RESULTS AND DISCUSSION

The subjective assessment with error bars is plotted against the modelled value in Fig. 5. The numbers in Fig. 5 correspond to the numbers in Fig. 4. A high coefficient of determination of 0.90 is found. The impact of the spatial luminance frequency on discomfort glare has been studied and recently applied in lighting design using a Fourier transformation [25, 27]. In this paper, this relation is explained by the model including the receptive field mechanism and pupillary light reflex. Visual discomfort initially increases with increasing

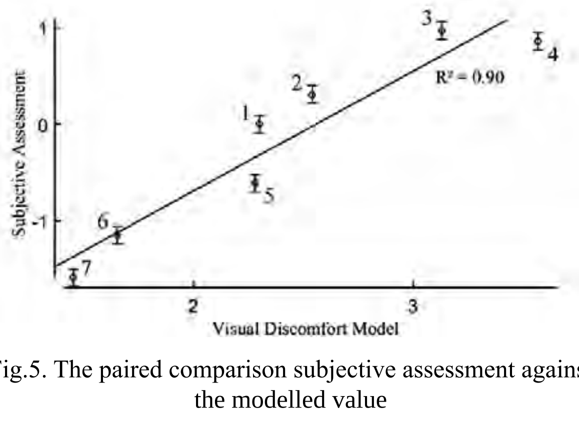

Fig.5. The paired comparison subjective assessment against the modelled value

frequency (stimuli 1 to 3). An increase in the number of light patches results in an increasing amount of edges while the spatial separation decreases. In agreement with the subjective assessment, a higher amount of edges initially results in a higher modelled value since the model acts as an edge filter. The light-dark edges become less clear when the spatial separation of the light patches reaches the spatial eye resolving power. At a certain frequency, the human eye will not clearly resolve the edges and the visual discomfort saturates at a maximum. In the model, the spatial separation of the stimuli reaches the dimensions of the centre-surround receptive field kernel. The excitation from one light patch on the centre starts to be supressed by another light patch on the surround of a receptive field. If the spatial separation of the light patches further decreases (increasing amount of patches), the edges will progressively appear less clear and the stimuli will steadily be seen as more uniform. The observed visual discomfort starts to decrease (stimuli 4 to 7). Stimulus 3 produces the maximum visual discomfort corresponding to a frequency of 4.0 cycles per degree. Conservatively, any stimulus in the range between 1.0 and 9.3 cycles per degree will produce the maximum discomfort. A quadratic fit predicts a stimulus with maximum discomfort within the range of 4.0 to 9.3 cycles per degree. From the contrast sensitivity function (CSF) [30], a maximum frequency sensitivity between 6 and 11 cycles per degree for direct view is observed. A satisfactory agreement in the range of 6 to 9.3 cycles per degree is noted.

In the formula for the pupillary light reflex (1), only the product of luminance level and stimulus field size is considered. Also age can be included in the pupil diameter calculation, but proves to be tedious [31]. In this study, the age effect is ignored. The maximum deviation in pupil diameter from age differences is 7 % relative to the pupil diameter of the average observer.

The luminance level of some projected pixels at the edge is 50 % lower than the maximum pixel luminance at the centre. None of the observers reported a drop in luminance level at the edges, even when this was explicitly mentioned. The measured luminance maps were used for the analysis. To test the robustness of the model, the light emitting patches were equalised in theoretical luminance maps. The light emitting surface was defined as all pixels with a luminance level above 50 % of the maximum luminance to include all pixels at the edge. The luminance level of all light emitting pixels was fixed at the average luminance level of the light emitting surface. The modelled value for the actual measured luminance maps was compared with the value for the theoretical maps resulting in a difference of only 4 %. In agreement with visual perception, the model is robust to gradual changes in luminance level.

Donners et al. proposed a similar receptive field model including the pupillary light reflex to assess the discomfort glare for both office and road lighting luminaires [32]. An additional local normalisation mechanism for the dark outdoor environment had to be included since luminance contrast and range is larger in a road lighting setting than in an indoor environment. The normalisation mechanism is not included in this paper.

4. CONCLUSION

A model including the receptive field mechanism and pupillary light reflex has been developed for the assessment of visual discomfort. The pupillary light reflex regulates the retinal illuminance were a centre-surround receptive field describes the visual signal. The model has been analysed with a paired comparison experiment involving 7 non-uniform rear projected stimuli with different spatial frequencies. A spatial luminance frequency in the range of 4.0 to 9.3 cycles per degree will produce the maximum visual discomfort. Inspired by a promising coefficient of determination of 0.90, the model is a candidate to replace current glare metrics as UGR or VCP, especially when non-uniform luminaires are to be evaluated.

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