HUMAN VISION MODEL INCLUDING AGE DEPENDENCIES

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ABSTRACT

We extend a model of the human visual system to predict the effects of age. The extensions are based on the existing models of disability glare, aging of the crystalline lens and reduced pupil size with age. The complete model, including an empirical neural component, can well explain the differences in contrast sensitivity between old and young observers.

***Index Terms*—** Visual model, Visual difference predictor (VDP), aging effects, high dynamic range images

1. INTRODUCTION

Visibility predictors [1–3] assess the likelihood that an average observer will notice the difference between a test and a reference images. Most such models predict performance only in a restricted range of physical luminance levels, often limited to either photopic or scotopic vision. This is partly because psychophysical data often come from studies conducted on CRT monitors, which operate in the limited range of luminance, usually ranging from 0.1 to 80 cd/m^2. However, many applications require visual models that can account for a much broader range of luminance. The visual difference predictor for high dynamic range images (HDR-VDP) [4], later followed by its revised version HDR-VDP-2 [3], was one of the first visual models intended to predict differences in scenes that contain large variations of absolute luminance.

A typical problem that visual predictors suffer from is their inability to match precisely the actual visual performance of a particular individual. This is because the performance can differ substantially between people, while the visibility predictors are trained with the data averaged over a group of observers. Age is an attribute that is easy to specify and has strong influence on the visual performance of an individual. Therefore, in this paper we improve HDR-VDP-2, by incorporating age-related changes in the visual performance. We review the existing models predicting the impact of age on the visual performance and we incorporate them in the predictor based on their fit to the data.

The first stage of HDR-VDP-2 — *optical and retinal pathway* (Fig. 1) — simulates the optical properties of the eye and the receptor response. Most of the age-dependent components are introduced at that stage (shown in green in the diagram). The light entering the eye is scattered, thus causing *disability glare*. Then, the retinal illumination is further reduced due to the age-related effects. The light reaching the retina is absorbed by the receptors (L-, S-, M-cones and rods) according to their spectral sensitivities. The varying sensitivity of the receptors to light is simulated as *luminance masking* and the responses from rods and cones are combined into a single *achromatic response*.

Visual mechanisms are selective to narrow ranges of spatial frequencies and orientations. To mimic such a decomposition, which presumably happens in the retina and the visual cortex, the HDR-VDP-2 employs a *multi-scale image decomposition*, which is based on a steerable pyramid. The model assumes that the discrimination performance is limited by the neural noise, which in turn consists of two components: a signal-independent neural Contrast Sensitivity Function (nCSF) and the signal-dependent masking signal.

Sec.2 briefly describes the test data set we use. Then, the state of the art of some model components is reported, and tools that are deemed suitable for our improved HDR-VDP-2 model are described: Sec.3 is devoted to the optical pathway, while Sec.4 deals with the neural components. Sec.5 draws some conclusions. The novel model components are shown in color in the block scheme, and the (sub)section where each is described is indicated.

2. TEST DATA SET

A suitable test data set will be used to validate the predictions of the reviewed model we are proposing. We reconstruct the measurements of the spatial contrast sensitivity of Sloane et al. [5], which were measured for two age groups: young observers with the average age 24, and elderly observers with the average age 73. The CSF measurements were selected as they capture the holistic performance of the visual system near the threshold and can be reliably measured. The data of Sloane et al. is especially adequate for our purpose as it captures the drop of sensitivity with age as a function of both a spatial frequency and an absolute luminance level. These factors are the most relevant for testing sensitivity in complex images. Moreover, the measurements were made in relatively

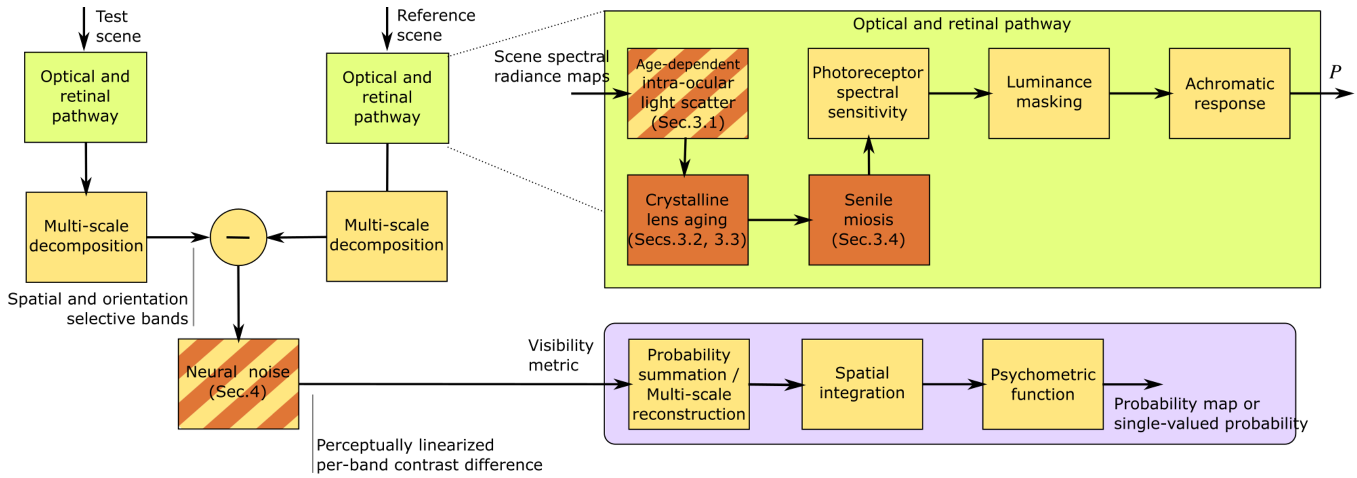

Fig. 1. The data-flow-diagram for the visual model (HDR-VDP-2). The new components that account for the aging effects are shown in orange (dark) and the components that have been extended to account for age are shown in a striped yellow-orange color.

natural (though monocular) viewing conditions with a natural pupil and refraction corrected for the target distance. The original Sloane et al. measurements and the HDR-VDP-2 predictions for the younger age-group are shown in Fig. 2.

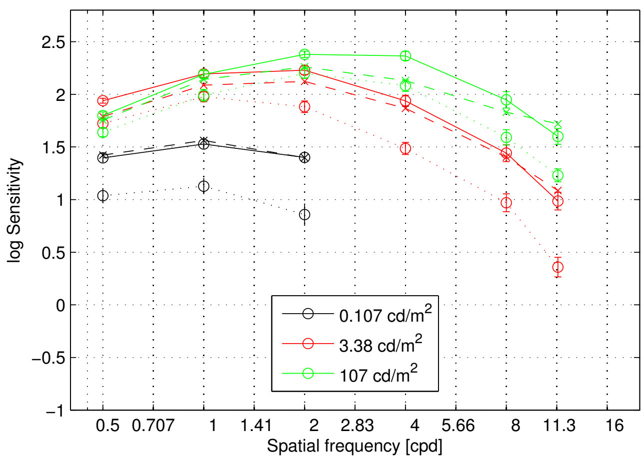

Fig. 2. The Contrast Sensitivity Function [5] for three luminance levels, for 24 year old (continuous line, circles) and 73 year old (dotted line, circles) age groups. The dashed lines with the 'x' show the HDR-VDP-2 prediction (without age-dependent extensions) for the 24 year old mean observer.

3. OPTICAL AND RETINAL PATHWAY

We review in this section the models that account for the effect of aging on vision, and we report their influence on predictions when incorporated into the HDR-VDP-2.

3.1. Disability glare

A small portion of the light that travels through the eye is scattered in the cornea, lens, inside the eye chamber and on the fundus [6]. Such scattering attenuates the high spatial frequencies but more importantly it causes a light pollution that reduces the contrast on the retina. The effect is especially pronounced when observing scenes containing sources of strong light. It is commonly known as disability glare [7] and has been thoroughly measured, using both direct measurement methods and psychophysical measurement, such as the equivalent veiling luminance method [6]. The measurements performed for different age groups clearly indicate that the effect of glare is stronger for elderly observers [6].

The model of the disability glare that is particularly suitable to be incorporated in the predictor is based on the measurements of Vos and van den Berg [6, 7]. To incorporate this model, the original intra-ocular scatter function has been replaced with the age-dependent CIE glare spread function [7]. The visual glare is simulated as a convolution with a linear filter.

The effect of age on the glare is shown in Fig. 3, which visualizes the difference in sensitivity between the young and elderly eye as predicted by the HDR-VDP-2. The plot shows only a minor drop in sensitivities, up to 0.04 $\log_{10}$ units for an 11.3 cpd sinusoidal grating. The performance is nearly the same for all three luminance levels as glare is modelled as a linear filter, independent of the absolute light level. The small differences are mostly due to non-linearities in the further stages of the predictor.

Our goal is to make the predictions (continuous lines) match the data of Sloane et al. (dashed lines in Figure 3). From the plot is clear that the disability glare alone cannot account for the loss of sensitivity observed in the elder popu-

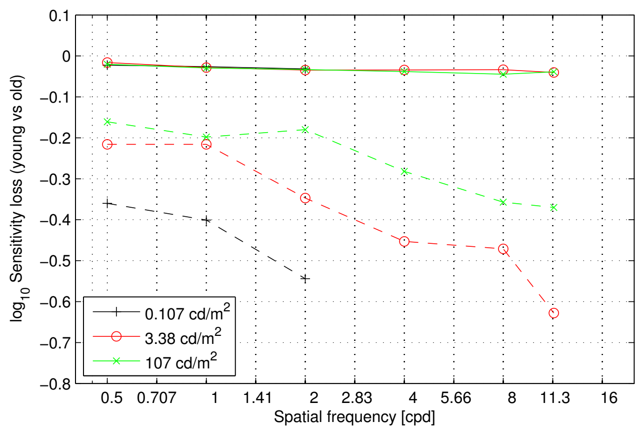

Fig. 3. The predicted loss of sensitivity due to disability glare (solid lines). The values indicate the difference in sensitivity between elderly (mean 73 years) and young (mean 24 years) observers. Different line colors and markers denote different luminance levels. The dashed lines show the measurements of Sloane et al. [5] (for reference).

lation. It must be noted, however, that the effect of glare may be much more significant for different stimuli, in particular for dark scenes that contain strong sources of light. Therefore, we decided to include the age-dependent model of glare in the predictor despite its small effect for our test data.

3.2. Aging of the crystalline lens

Lens aging effects are among the most significant contributions to changes in vision over time. Apart from suffering from a reduced accommodation ability, the lens increases its optical density with time. Such increase in density varies with respect to the wavelength of light. Both accommodation and density changes are due to the fact that in the entire lifespan the lens continues to generate new fibres; its older parts get compacted and accumulate in the central region of the lens itself, making it less transparent and more rigid. These physiological changes often turn into pathology, leading to cataracts of different types.

Pokorny et al. [8] proposed a model of lens aging in terms of optical density. The authors rely mainly on the data from a study in [9] for the age range 16-55, and a study in [10] that extends to age 13-83. They demonstrate that the change in density is different at different wavelengths and that the rate of density increase can be modelled by two different equations for age values below and above 60. The relevant computations take as a reference an average 32-year old subject, for whom the total density of the lens L is deemed due to the sum of two contributions: L_1, affected by aging after age 20, and L_2, a constant residual. L_1 and L_2 values are provided as tables, derived from data by [9] and by several other studies.

The optical density O_D as a function of age is determined as

$$O_D(a) = \begin{cases} L_1\,(1 + 0.02 \cdot (a - 32)) + L_2 & \text{if } a \leq 60 \\ L_1(1.56 + 0.0667 \cdot (a - 60)) + L_2 & \text{if } a > 60 \end{cases}, \tag{1}$$

where a denotes age in years, and L_1, L_2 are the values from Table 1 in [8].

We have introduced the model of aging of crystalline lens into the HDR-VDP-2, as a wavelength-dependent optical filter, which reduces the light that reaches the retina. The effect is straightforward to integrate with HDR-VDP-2, as the model already operates on spectral data and accounts for the spectral sensitivities of the photoreceptors. Equation 1 is used to find the corrected transformation from the input colors space into the response of cones and rods.

After introducing the model into the HDR-VDP-2 we observed that photopic vision is little affected by the overall changes in the retinal illumination (as the consequence of the Weber law). However, in the mesopic and scotopic vision range below 3 cd/m^2, the sensitivity gradually decreases with decreasing retinal illuminance.

3.3. Changes of luminous efficiency

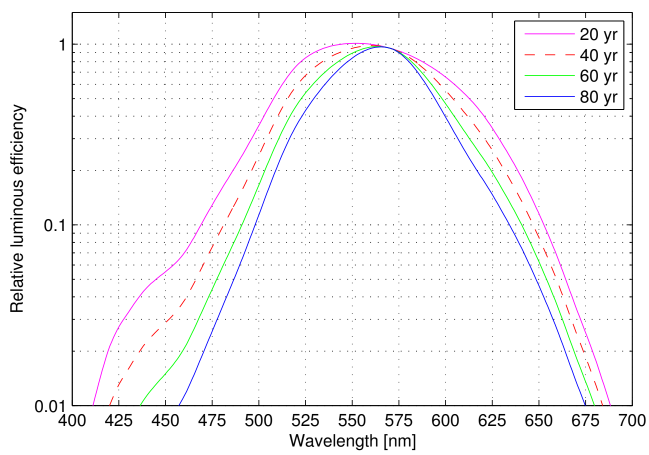

Fig. 4. Changes in the luminous efficiency function with age. The luminous efficiency is based on the Smith and Pokorny cone fundamentals [11]. The curves for different ages were obtained by applying the correction proposed by Sagawa and Takahashi [12].

Aging of the visual system also causes differences in the luminous efficiency function. The luminous efficiency function captures the differences in perceived brightness between monochromatic light of different wavelengths. The CIE 1924 photopic luminous efficiency function V is the basis for photometry and the SI unit of candela [cd]. Sagawa and Takahashi [12] measured the changes in the photopic (100 Td) luminous efficiency function for 99 observers, spanning the age range from 11 to 78 years. Two procedures were used: flicker photometry and direct brightness matching. We consider their direct matching results, to avoid introducing the effects of time-dependent stimuli in our analysis. In Fig. 4 we plot the changes of the luminous efficiency function based on their measurements. The measurements were applied to Smith and Pokorny's [11] cone fundamentals.

We incorporated data of [12] in the HDR-VDP-2 as the wavelength-dependent filter, which reduced the amount of light reaching the retina, in a similar fashion as for the aging of the crystalline lens in the previous section.

3.4. Senile miosis

Several models exist that represent the relationship between the pupil diameter and the luminance of an extended light source placed in front of the observer, when other light sources are absent or have negligible effect. They yield pupil diameter vs. luminance plots that have an aspect similar to the one in Fig.5. More sophisticated models take into account the field size (in deg^2) of the source and differentiate between monocular and binocular viewing. A comprehensive review of these studies is presented in [13].

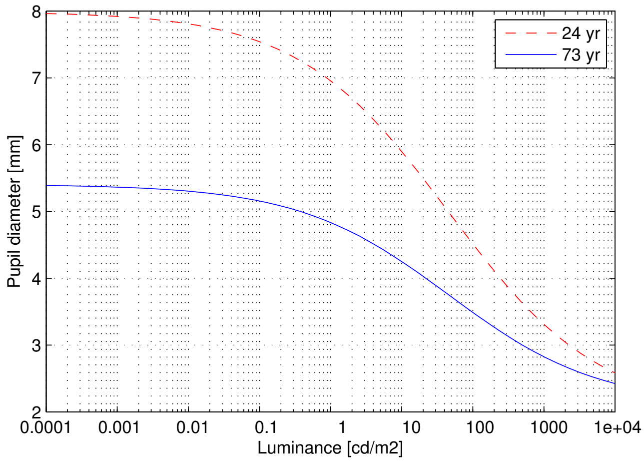

Fig. 5. Pupil diameter vs. adaptation luminance for two age groups.

As the eye gets older, the average diameter of the pupil for a given value of illumination tends to become smaller. The effect is known as senile pupillary miosis. In dim light, the diameter at age 80 can be one half of the one at age 20.

Watson and Yellot [13] derived a comprehensive formula, exploiting Stanley and Davies' model of a pupil size [14] and pupil measurements collected on 91 healthy subjects in the age range 17 - 83 [15]. The formula predicts the diameter of the pupil, $S(\cdot)$, as the function of adapting luminance (L), age (a), and field area (f):

$$S(L,a,f) = (a - 28.58)\cdot(0.02132 - 0.009562\, D_{sd}) \quad (2)$$

$$D_{sd} = 7.75 - \frac{5.75\, k}{k+2} \quad (3)$$

$$k = \left(\frac{L\, f}{846}\right)^{0.41} \quad (4)$$

The function is plotted for two age groups in Fig. 5. The plot indicates 2.5 mm reduction in the diameter and 65% reduction in retinal illuminance between 24 and 73 year age groups for low luminance.

Senile miosis can be readily incorporated in the HDR-VDP-2 as a factor that limits retinal illumination. Since HDR-VDP-2 was calibrated for a young eye and a natural pupil, the factor is computed as the ratio $S(L,a,f)/S(L,24,f)$, where $S()$ is the function from Equation 2.

4. NEURAL COMPONENT OF THE MODEL

All the considered factors reduce the amount of retinal illumination. Since the luminance of 107 cd/m^2 is in the Weber region of the luminance sensitivity curve, the sensitivity stays constant despite the significant loss of retinal illumination. Therefore, such a loss of sensitivity can be only explained by changes affecting receptors and neural mechanisms. A similar conclusion was also made in [5] and in [16].

Burton et al. [17] directly measured the loss of sensitivity between young and old observers using laser interferometry, a technique that bypasses the optics of the eye in presenting a gratings target on the retina. They found a moderate loss of sensitivity, between 0.1 and 0.2 log. Such a loss could explain the difference between the predictions and the data. Instead of modeling their data, which the authors admit are noisy, we fit an empirical model that alters the neural CSF component of the HDR-VDP-2. A good fit can be achieved for the function:

$$\log_{10}(\Delta S) = -\left(\beta\, \log_2(\rho + \alpha)\right) \cdot \max(a - 24, 0) \quad (5)$$

which describes the changes in log-10 sensitivity for the age (a) in years and spatial frequency (ρ) in cpd. The best fit was achieved for the parameters $\alpha = 0.75$ and $\beta = 0.00195$. The result of that fitting can be found in Fig. 6, which shows the overall performances of our modified HDR-VDP-2 model.

5. CONCLUSIONS

We extended the HDR-VDP-2 visibility predictor to include the effect of aging. The model and the data predict reduced sensitivity with age, with stronger reduction for higher frequencies and for lower luminance levels. It should be mentioned that — based on some preliminary experiments — age is not the only parameter that influences the sensitivity of the HVS: in the same age group the inter-subject variability of

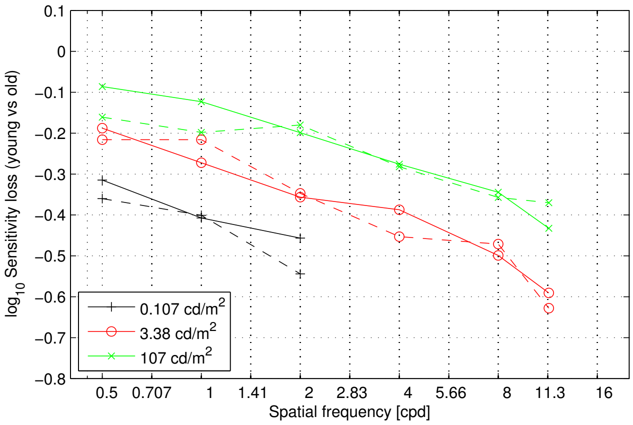

Fig. 6. The predicted loss of sensitivity due to all factors described in this paper (solid lines). Other lines and markers are the same as in Fig. 3.

the sensitivity is high. As an example, surgical treatments that a user may have undergone can change dramatically the response of the optical component of the visual system. Thus, future study will be devoted to employ and refine the proposed model to determine the "effective age" of a specific user.

The proposed model can be used in many different contexts. Medical diagnostic displays, for which the ability of the user to detect subtle luminance variations is of paramount importance, can certainly benefit from it. Also all the cases in which image processing is used to enhance the perception of details are promising fields of application. E.g., modern versions of unsharp masking take into account ambient illumination, display size, resolution and viewing distance, and the content of the displayed scene [18]. A detailed vision model like the one we propose can be adopted to set the operating parameters of the enhancement algorithm, to improve the quality of the image as perceived by a given individual.

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