Method for Adapting the Grayscale Standard Display Function to the Aging Eye

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Abstract Perceptual linearity of grayscale images based on a contrast sensitivity model is a widely recognized and used standard for medical imaging visualization. This approach ensures consistency across devices and provides perception of luminance variations in direct relationship to changes in image values. We analyze the effect of aging of the human eye on the precept of linearity and demonstrate that not only the number of just-noticeable differences diminishes for older subjects but also linearity across the range of luminance values is significantly affected. While loss of JNDs is inevitable for a fixed luminance range, our findings suggest possible corrective approaches for maintaining linearity.

Keywords Aging models · Human visual system · Contrast sensitivity · Grayscale visualization

Introduction

Ensuring perceptual consistency is of paramount importance in diagnostic imaging. For example, advanced noise cancellation methods [1] are typically validated through subjective image quality evaluation. Similarly, when contrast enhancement methods [2, 3] are applied, the selection of the corresponding parameters is typically a function of the user's

sensitivity to the luminance contrast. Moreover, prediction semantic content methods for diagnostic imaging [4] are calibrated for consistency with the user's perceptual characteristics.

The model-based grayscale standard display function has been in use since 1998 (Supplement 28, Part 14 of DICOM). It was developed by the US National Equipment Manufacturing Association as a standard for the presentation of medical images, known as Digital Imaging and Communications in Medicine (DICOM) document Part 3.14: Grayscale Standard Display Function (GSDF) [5]. Its main purpose is to provide a framework for the consistent visualization of medical images achieving some degree of perceptual linearity. The GSDF defines the relation between the numerical graylevel values that constitute an image and the corresponding luminance values as output by the display. It was derived using the notion of Just Noticeable Difference (JND), the minimum luminance difference perceivable by the human visual system. The modeling of the visual system, specifically the Contrast Sensitivity Function (CSF), was implemented based on work by Barten [6]. Barten's model includes components ranging from the optical transfer function of the eye to its neural response and to lateral inhibition phenomena, and was thoroughly validated by a direct comparison with a large number of experimental data. It should be noted that Barten published two further versions of his model in 1999 and 2003 [7, 8]. Some components of the model were modified in 1999, while in the 2003 version a dependence of the CSF on the orientation and the effects of surround illumination were introduced. Since the DICOM 3.14 document, even in its most recent releases, is based on the 1992 model, we will in most cases make reference to this version.

Clinical practice and laboratory studies (see for instance ref. [9]) have supported satisfactory performance of the display standard. It has also been shown that the use of the CSF

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affects the performance of observer models. In ref. [10], Park et al. used synthetic lumpy backgrounds to investigate the effect of a luminance function on signal detection. In their study, the authors incorporated a model of human contrast sensitivity into an anthropomorphic model using Barten's model. The results of the study suggest that with a single free parameter to account for efficiency, the model appropriately predicts mean human performance at different signal intensities. Other models have been realized to estimate the visibility of artifacts generated by compression techniques [11] or with mathematical observers to predict human performance in a discrimination task [12].

An aspect of human performance that models are unable to appropriately handle is the large variability in the characteristics of the visual system across individuals. In fact, the DICOM function for visualization aims at providing a standard setting for medical image visualization without claiming to achieve optimality. To improve the visualization quality, some modifications to Barten's model would allow the consideration of an important aspect: the age of the observer. With the progressive increase in life expectancy and with working life becoming longer, the age span of radiologists is becoming wider. For example, US statistics indicate that in 2012 the active physicians who were age 55 or older in the Diagnostic Radiology specialty were 48 % [13]. Barten's model, and as a consequence a potentially extended set of DICOM specifications, would benefit from the introduction of a few suitable age-related components.

Two components of the model deserve particular attention: optical aberrations and the variable size of the pupil. In this paper we describe how these components are affected by the degrading effects of aging and how the model can be modified to incorporate these effects. We make use of previous descriptions of aging characteristics and propose an integrated model for realizing perceptual linearity of grayscale images. We describe and analyze the effect of aging on linearity and show that not only the number of just noticeable differences diminishes for older subjects, but also linearity across the range of luminance values is significantly affected. Finally, we present corrective functions that would allow an improvement in the linearity when degradations due to aging are present.

Barten's Model of the Human Visual System

Barten's model [6] describes the minimum perceivable contrast $M_t = \Delta L/L$ of a sinusoidal grating having average luminance L and amplitude ΔL . The grating consists in several cycles displayed on a square target having size $X = Y$. M_t is a direct function of the spectral density φ_{int} of an internal noise generator and an inverse function of the size X and of the eye integration time T (for static targets). M_t is supposedly measured outside the eye, so that its expression has to be divided

by the optical Modulation Transfer Function (MTF) of the eye, M_{opt} :

$$M_t = k \sqrt{2\varphi_{\text{int}}/(XYT)}/M_{\text{opt}} \quad (1)$$

Barten's "threshold constant" k is in fact a scaling term used to match the peak sensitivity found in different experiments. This is how it has been used in his paper and will be used in this work. φ_{int} is the sum of the spectral densities of the photon noise, φ_{pho} , and of the neural noise, φ_{neu} . With respect to the former, if the target has a luminance of L (cd/m^2), and d is the size of the pupil, the flux of photons entering the eye is

$$J = \left(\pi/4\right)pd^2L, \quad (2)$$

where $p = 357 \text{ ph}/(\text{td.s.arcmin}^2)$, and the photon noise can be expressed as $\varphi_{\text{pho}} = 1/(\eta J)$. Barten found a wide range of values for η , a global conversion efficiency parameter, in the different experiments he surveyed [6]. The expression for neural noise used in the model is

$$\varphi_{\text{neu}} = \varphi_0 / \left(1 - \exp\left(-u^2/u_0^2\right)\right), \quad (3)$$

where u_0 is a reference spatial frequency and φ_0 is the noise density at that frequency.

The MTF of the eye is described by the expression

$$M_{\text{opt}} = \exp\left(-\pi\sigma^2u^2\right), \quad (4)$$

with

$$\sigma = \sqrt{\sigma_0^2 + (C_{\text{sph}}d^3)^2}. \quad (5)$$

Here, u is the spatial frequency of the grating in the target, σ is the radial standard deviation of the optical point-spread function of the eye, and $\sigma_0 = 0.0133$ is the value of σ for a small pupil size. C_{sph} is a parameter representing the spherical aberration of the eye. The value for aberration is $0.006 \text{ arcmin/mm}^3$, both in the model and in the DICOM standard. C_{sph} is in fact collecting various contributions that, in view of the central limit theorem, are assumed to have Gaussian behavior. A plot of the MTF for three different values of the pupil diameter is showed in Fig. 1. Finally, the CSF of the eye in Barten's model is $1/M_t$.

The pupil diameter formula used in ref. [6], for which we use the subscript $B92$, is the one developed by de Groot and Gebhard [14]:

$$d_{B92} = 4.6 - 2.8 \tanh\left(0.4 \log_{10}\left(L/L_0\right)\right), \quad (6)$$

where d_{B92} is the diameter of the pupil in millimeter, L is the luminance of a large uniform object in front of the observer, and L_0 is 1.6 cd/m^2 . Even if the DICOM standard relies on this

Fig. 1 Optical MTF of the human eye, according to Barten's model, for three different values of the pupil's diameter

expression, its author later abandoned it. He developed a new expression in 1999 [7]:

$$d_{B99} = 5 - 3 \tanh \left(0.4 \log_{10} \left(L X_0^2 / 40^2 \right) \right). \quad (7)$$

Here it is assumed that the observed object is of size X_0 (deg), and that the eye averages a field of 40 deg. An X_0 of 10 deg can be chosen, following [15]. The result is similar to the Stanley-Davies [16] formula:

$$d_{SD} = 7.75 - 5.75 \left(La / 846 \right)^{0.41} / \left(\left(La / 846 \right)^{0.41} + 2 \right), \quad (8)$$

where a is the adapting area in deg [13]. Specifically, Barten's formula has the peculiarity that the maximum diameter is less than 7 mm, while typical maximum values determined in many experiments are closer to 8 mm. Figure 2 shows the diameter of the pupil as a function of the luminance to which the visual system is adapted, according to the three mentioned models. In our work, we adopt the Stanley-Davies formula for the pupil size.

Barten used several parameters to fit his model to the experimental data of other researchers. The threshold constant k

Fig. 2 Pupil diameter as a function of the luminance to which the visual system is adapted, according to the three models mentioned in the text

(gain term for the CSF) takes values ranging from 2.6 to 4.7. DICOM 3.14 adopts $k = 3.3$. For the total quantum efficiency η , expressing the percentage of photons entering the eye that elicit a neural response, Barten initially expected values around 20 % [6] (page 61); he later chose 3 % [8]. DICOM 3.14 adopts an η of 2.5 %. An additional constant is the reference term for the radial standard deviation of the optical PSF, σ_0 . The range of σ_0 values is $[0.60 \dots 1.70]/60^\circ$. DICOM 3.14 adopts a σ_0 of 0.0133 deg. In the following we shall refer to the pupil diameter and to the parameters k , C_{sph} , and η in order to include the effects of the aging eye.

Model Elements of the Changing Eye

A review on aging effects is reported in ref. [17]. It should be kept in mind that it is motivated by assessing the quality of life in the elderly while our study focuses on medical professionals and on diagnostic tasks. Several interesting concepts are relevant, however. First, it is observed that the presence of undetected pathologies can affect the results of experiments in the literature and that the border between physiology and pathology is blurred in vision-related studies. In addition, most aging effects can be ascribed to optical rather than neurological causes. Among optical causes, senile miosis can have positive effects for certain vision tasks, since in principle it reduces the optical aberrations of the lens and increases the depth of field.

In addition, changes in visual acuity (VA) with age are reported in ref. [18], demonstrating acuity loss beyond age 60, at a rate of 2 lines per decade in decimal acuity. The authors do not discuss this fact, but it can be supposed that acuity was measured at a typical optometrist distance (approximately 5 m). Indeed, smaller distances are used only for low-vision patients [19, 20]. A near-distance test would be more significant for our purposes. Other studies indicate that a CSF test can provide more reliable and complete information even in simple primary care settings [21].

Even more significant aging effects are reported in ref. [22] for the case of scotopic vision. Only two groups were studied, with mean ages 26 and 75, respectively. More studies, such as the often-cited one shown in ref. [17] (Fig. 2 in the reference), confirm the observation using a spatiotemporal study where stimuli are presented at a minimum frequency of 0.5 Hz. These experiments may be considered relevant since the low luminance values reached by advanced displays entail the action of a scotopic contribution in the human visual system. In addition, glare effects are studied in ref. [23] but are related to VA only with a small constant loss in younger subjects and with an exponential increase after age 55.

Results from a large set of experiments on the aging eye have been recently presented in two separate studies: a report about 472 Australian male subjects aged 35–80 years [24],

and a study of more than 4000 eyes of Japanese subjects aged 40–79 years [25]. In both cases, professional optician charts have been used (Vectorvision CSV-1000 at 85 cd/m² and Vistech VCTS 6500 at 390 lx, respectively), which are known to be able to provide reliable results [26]. Estimates of the shape of the CSF were obtained by sampling a few spatial frequencies (3, 6, 12, 18 cpd and 1.5, 3, 6, 12, 18 cpd, respectively). Both studies showed a decrease in CSF, sometimes even when VA was good. A study presented in ref. [24] correlates the decrease in CSF to the presence of early cataract which could explain the large dispersion of the results when, instead, only age is taken into account. The resulting values are shown in Fig. 3.

The described results from the literature have some limitations with respect to our analysis. In ref. [24], the test distance is 2.5 m, which is quite large if compared to the distance of the observer of a radiology display; the luminance of the target is 85 cd/m², while a radiology display provides a large range of luminance values, above and (more importantly) much below such a value. On the other hand, ref. [23] reports experiments at lower luminance (15 cd/m²) and small distance (40 cm). The slope of the VA data is larger at low luminance. However, the study assessed VA and only for ages above 55. In addition, it should be noted that the CSFs reported by Barten in ref. [6], both for its model and for the comparison experiments he

referred to, are significantly larger than those found in refs. [24] and [25]. This may be due to the different testing procedures (sine grating targets vs. optician charts).

As anticipated above, we can use the threshold constant k to set up a first fit of Barten's model to the experimental data in refs. [24] and [25]. The maximum value of the CSFs for the youngest subjects can be derived, and k chosen to make the model coincide at this point. The values of $k = 12$ and $k = 11$ were obtained, respectively.

An ample set of experiments concerning the changes in pupil elasticity with age was performed in ref. [27]. The authors determined a typical slope (in mm/year) for the change of the pupil diameter as a function of age. These results have been recently confirmed in ref. [15], where the slope function was also extended to lower luminance values using a formula devised by Stanley and Davies in 1995. As mentioned earlier, this approach is similar to the one adopted in ref. [7].

Winn et al. [27] measured the rate of change of the pupil diameter at five different luminance values (8, 40, 150, 1000, 4000 cd/m²). The corresponding slope values are reported as circles in Fig. 4. We found that a reasonable interpolating function $d_{sl}(L)$ for this set of values is

$$d_{sl} = -0.05 / \left(1 + \left((0.0025L)^{0.5} \right) \right), \quad (9)$$

which is shown in the same figure as a continuous line. If the values of the d_{sl} interpolating function are applied to the Stanley-Davies formula for the pupil diameter d_{SD} in (8), the aging effect known as pupil miosis can be calculated. Figure 5 shows the resulting pupil diameters d_{SDa} for luminance in the range (10^{-2} , 10^4), which we derived at several age decades using the expression

$$d_{SDa} = d_{SD} + d_{sl}(A-20). \quad (10)$$

Similarly, aging effects can be included in the parameter that in Barten's formulation takes into account eye aberrations. Barten changed his approach to spherical aberration over time.

Fig. 3 Contrast sensitivity values measured in experiments described in the literature (see text for citations)

Fig. 4 Yearly rate of change of the pupil's diameter as a function of luminance

Fig. 5 Pupil diameters as a function of luminance, at different ages

He used a parameter C_{sph} in his 1992 paper, where he stated he did not expect strong inter-subject variability. In 1999 and 2003, he used a different formulation. However, the study did not consider age effects, which were studied only recently. A significant increase of the overall optical aberrations in the aging eye is reported in ref. [28]. Reference [29] separates the different components of the aberration mainly resulting from the cornea and the lens.

In the young eye, a compensation effect exists that is no longer effective in older age. The result is, on average, an almost doubled aberration even in the presence of high inter-subject variability: the linear fit of the data for the fourth-order spherical aberration C_4^0 (Fig. 3a in the referenced paper) shows an increase from approximately 0.5 μm at age 20 to more than 1.0 μm above age 70. A similar change can be imposed on the C_{sph} parameter in Barten's model.

We collected clinical data of total high-order aberration at the Ophthalmological University Clinic of Trieste (Trieste, Italy) from 60 subjects aged 25–82 years. The results reported in Fig. 6 as a function of age show a moderate but significant increase even at young age, with a much larger slope starting from age 60. High-order aberrations are those which can be modeled with Zernike moments [30] of the third order and

Fig. 6 Measured high-order aberration data (circles) and related polynomial fit (continuous line) used in the model

above and cannot be corrected by spectacles or corneal lenses. The curve shows a simple polynomial fit to the data using

$$C_{\text{sph}} = 0.11 \left(1 + \left(A/65 \right)^5 \right) \quad (11)$$

where A is age of the subject. This expression is used in our analysis.

In addition, the photon noise parameter η can become smaller in the aging eye. Barten described quantum efficiency in photon conversion as lower than predicted by other authors. We can also represent it as a function of age as follows,

$$\eta = 0.025 / (A - 30) / 5 \quad (12)$$

for ages larger than 30.

It should also be noticed that there is a stronger attenuation of light inside the older eye due to lens opacification while glare effects become stronger due to increased dispersion in the vitreous. It should be remembered that η is a total conversion efficiency that takes account not only the actual conversion efficiency but also the reduced amount of light reaching the fovea.

The optical density of the lens is quite heuristically evaluated in clinical practice. Reference [31] provides pseudo-objective (comparison with a photograph) classification, distinguishing among nuclear opalescence (NO) and color (NC), cortical opacity (C), and posterior opacity (P), in five or six grades. NC is shown to correlate to the X chrominance component in CIE 1931. Reference [32] uses LOCS-III to provide a table for nuclear opalescence/color, cortical cataract, and posterior cataract, as a function of age (above 55). Similarly, ref. [33] uses the older LOCS-II method.

Different models are found in the literature for the wavelength-dependent optical response of the lens and to predict its change with age. In most cases, it is accepted that opacity increases in an accelerated way at older age. Reference [34] describes the structure and physiology of the lens, with its aging chemical mechanisms. Backscattered light by the different lens substructures shows an exponential increase with age. This report coincides with results reported in ref. [35] to which the authors add that the exponent is highest for wavelengths between 460 and 470 nm. Exponential growth of the absorption was also reported in ref. [36]. Linear regression analysis leads to minimum MSE when the natural log of absorbance is used. Suitable parameters are determined for 350, 400, 450, 500 nm wavelengths, but the study is mainly focused in the UV-A region of the spectrum. A recent report by Pokorny et al. [37] proposes a model from which one can determine the total lens optical density (od), L_{od} , normalized for a 32-year-old observer. The authors propose an age-sensitive and an age-insensitive component (TL1

and TL2, respectively). The total lens spectral density, $L_{od}(\lambda, A)$ is modeled as the weighted sum of these two factors

$$L_{od}(\lambda, A) = L_{od}^0 TL1(\lambda) + TL2(\lambda), \quad (13)$$

where L_{od}^0 is a scalar dependent on the observer's age. The scalar is described by two functions, one corresponding to ages below 60 and a second for ages above 60. For ages between 20 and 60, $L_{od}^0 = 1.00 + 0.02(A - 32)$, and for ages larger than 60, $L_{od}^0 = 1.56 + 0.0667(A - 60)$.

Later, Xu et al. [38] compared the models in refs. [37] and [36], and a third linear model, for a set of 27 observers aged 22–74 years. The model in ref. [37] proves to be the most adequate. The method provides good correlation between the estimated lens age and the actual chronological age of the test cases. The model provides a lens attenuation function (10^{od}) as seen in Fig. 7.

By integrating each of the seven curves for all wavelengths, average values for the lens attenuation (μ) at different ages can be derived. A curve that produces a reasonable approximation of this parameter as a function of age can be obtained as follows:

$$\bar{\mu} = 2.6 + 10^{(A-40)/28}. \quad (14)$$

In our model, the average lens attenuation is included in the overall threshold constant k with age. To match Sia's experimental results [24], we can name this value of k as k_{Sia} and derive it as follows

$$k_{Sia} = 12 + 10^{(A-40)/40}. \quad (15)$$

Notice that an aging contribution is already present in η (see Eq. 12) and this motivates the smaller exponential term in k_{Sia} .

Fig. 7 Lens attenuation as a function of wavelength at different ages

Age-Corrected Perceptually Linear Model

In this section, we describe the modifications we propose to Barten's model in order to incorporate the effects of senile miosis, increased eye aberration, and other effects. The results are presented in Fig. 8 where we show CSF results for the indicated age groups.

First, we calculate pupil diameter according to

$$d_{SDa} = d_{SD} + d_{sl}(A - 20), \quad (16)$$

for a luminance of 85 cd/m² as used in Ref. [24].

Secondly, we calculate the C_{sph} parameter with a multiplicative factor given by

$$C_{sph}^{factor} = 0.11 \left(1 + (A/65)^5 \right), \quad (17)$$

seen in Fig. 6 to be a good approximation to the age-related change in measured aberration data.

Thirdly, as indicated in (12), we alter the value of the η parameter by dividing by the factor

$$\eta_{factor} = (A - 30)/5 \quad (18)$$

(valid for ages larger than 30).

Finally, the threshold constant is expressed as a function of age using the expression in (15) rather than the fixed value $k = 12$. Note that in Fig. 8 the circles represent the experimental values reported in ref. [24].

In summary, the threshold k in Eq. 1 becomes an age-dependent term as per Eq. 15. Equation 16 provides an age-dependent value for the pupil size in Eq. 2. The C_{sph} term in Eq. 5 is modified by the factor in Eq. 17. Equation 18 is used as a scale factor for the expression of the photon noise.

From each CSF, a corresponding Grayscale Display Function can be derived. It is sufficient to start from the minimum luminance of the destination display and move by one JND step up to the maximum available luminance. If the CSF comes from the standard Barten's model, the DICOM GSDF

Fig. 8 CSF at different ages. Modified Barten model (continuous lines) and experimental data from Sia (circles)

is obtained. Otherwise, if the age-corrected CSF is employed, what results is the function corresponding to the given age range.

A final consideration before computing the age-related model is the value of the threshold constant k that yields a response similar to the one of the standard Barten's model in absence of aging effects. This is easily obtained by selecting

$$k = 3 + 10^{\frac{(A-40)}{40}}. \quad (19)$$

Note that in this way one obtains, at age 20, $k = 3 + 10^{-1/2} = 3.3$, identical to the value in the GSDF formulation. This choice disregards the different maximum values of the sensitivity that are respectively found in the experiments reported by Barten, in refs. [25] and [24]. The latter were instead taken into account by the formulation Eq. 15.

We have now described all the required elements to formulate the age-dependent grayscale display model. Setting $L(1) = L_{\min}$, the sequence of luminance values $L(j)$ that differ by one JND one from the other is obtained from

$$L(j+1) = L(j)(S(j)+1)/(S(j)-1), \quad (20)$$

where $S(j)$ is the value of the CSF obtained for M_i from the model in Eq. 1 after having substituted the age-dependent terms as described above. Specifically, using the values suggested in the GSDF specifications ($L_{\min} = 0.05 \text{ cd/m}^2$, $u = 4 \text{ cycles/deg}$), one obtains the set of curves depicted in Fig. 9.

Discussion and Conclusion

The graphs in Fig. 9 provide two important notions related to observers in a given age range. The first is the maximum number of JNDs that they will perceive in a display. The second is the shape that the display function should have to provide perceptually linear behavior. With respect to the number of JNDs, let us reference for example a display device

Fig. 9 Set of proposed grayscale display functions at different ages. DICOM's GSDF is reproduced in black

capable of covering the full luminance range used in the DICOM specifications $[0.05 \dots 4000] \text{ cd/m}^2$. In this case, a simple examination of the numerical data permits to relate age and number of perceivable JNDs as presented in Table 1, second column. The third column of the same table shows the number of JNDs for a real-world medical display having a luminance range $[0.5 \dots 1000] \text{ cd/m}^2$. Barten's model predicts 1023 JNDs in the same luminance range. However, it should be noticed that in ref. [8] the author states that his model is valid for “an observer with good vision and with an age between 20 and 30 years.” The proposed model shows that the performance of observers only slightly worsens in the 35–44 age group before undergoing further deterioration. The results in Table 1 can be easily recalculated for a display having different $L_{\min}$ and $L_{\max}$ values.

Standardization and consistency of visualization are the primary goals of the DICOM PS 3.14 proposal. Linearity of perception is its second important goal within the consistent proposal. Indeed, a GSDF was selected by which the numerical values of the image to be displayed (“P values”) are approximately linearly related to human perceptual response [5] (p. 10). The proposed set of display functions aim at the same result: to provide observers in different age groups with a linear relationship which is not available from GSDF. Specifically, it should be noted that the slope of all the higher-age display functions is larger than the one found for the GSDF particularly at low luminance values. Thus, according to the proposed model, an observer older than 44 would fail to perceive low-contrast details in dark areas when reading a GSDF-mapped image.

This may be better understood by way of an example. A person in the age group 55–64 with a presentation luminance field in the range of 0.05 to 4000 cd/m^2 using a DICOM-calibrated display can perceive 474 levels, instead of the 1023 levels predicted for a young subject. Moreover, for the same person, the displayed luminance steps represent a different fraction of a JND at different background luminance, destroying linearity. The graphs in Fig. 10 were derived numerically from the GSDF and the proposed display function for the various age ranges. The figure shows the fraction of JND that corresponds to a single level change in the display. It is clear that the observer between 55 and 64 years old needs approximately four steps to observe one JND at low luminance, while in bright areas less than two steps are sufficient.

Table 1 Age and predicted number of JNDs for an ideal and a real-world medical display device

Age JNDs	Ideal JNDs	Real
35–44	965	739
45–54	677	503
55–64	474	340
65–74	312	215
75+	189	126

Fig. 10 JND fraction perceived at different ages, per unitary DICOM JND step

If a more suitable age-related mapping was adopted instead, each luminance change would represent 0.46 JNDs for the same observer, uniformly in the entire range. A similar situation can be evinced for the other age groups in Fig. 10; obviously, the nonlinearity error is less marked for younger users.

Since aging effects are widely variable among subjects, “effective” age can deviate significantly from “numerical” age. To address this variability, it would remain important to devise visual assessment tools to accurately estimate effective age.

We are aware that a wide range of dedicated experiments is needed to validate our model. However, the model we propose represents a step towards the goal of providing each user with an optimized visualization environment.

The modified model we have derived is consistent with experimental data collected from a large number of observers having different age (e.g., in refs. [25] and [26]). The model indicates that the perceived quality of the displayed image can be significantly degraded. In other words, relying on DICOM GSDF guarantees only an objective consistency of image visualization and not a subjective perceptual uniformity. Since the latter remains relevant to diagnostic visual tasks, this article provides initial insights into possible improvements.

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