VISUAL FIDELITY CRITERIA IN A 3D HOMOGENEOUS COLOR SPACE

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ABSTRACT

The performance of visual fidelity criteria for 2D color images is investigated leading to a meaningful numeric distortion measure of color differences. Suitable fidelity criteria are obtainable by formation of a metric in the 3D output space of a model of human color vision. Refinements to several model parameters are reported. A post-transformation is introduced which achieves a visually homogeneous 3D color space. The distortion measure applied in this space is investigated on the basis of recorded color photographs. Potential application areas are indicated.

ABREGE

La performance des criteres de fidelite visuelle pour des images 2D de couleur est recherchee, amene a une mesure significative par des differences de couleurs. Les criteres de fidelity convenables sont formes par une metrique dans l'espace 3D de sortie d'un modele de la vision humaine de couleur. Des ameliorations pour quelque parametres du modele sont rapportes. Une transformation a-posteriori est introduite pour cree une espace 3D visuelle de couleurs homogenes. La mesure de la distortions formee dans cette espace est examinee avec des photographies en couleur. Des applications potentielles sont indiquees.

KEYWORDS: Image Processing, color images, color space, color perception, model of human color vision, fidelity criterion, color distortion measure.

INTRODUCTION

The research work presented in this paper deals with the transformation of two-dimensional (2D) color images. The transformed image differs from the original one in its color composition. A numeric measure is sought which reflects the resulting color differences (i.e. distortion) by a single value. The fidelity criterion specifies analytically the calculation of this distortion measure. Visual fidelity criteria are investigated and further developed which give rise to distortion measures that grade color distortions in good agreement with the subjective average judgement of human observers.

Visual fidelity criteria find immediate applications in areas where color differences are to be associated with corresponding perceptual sensations experienced by human observers. This task arises in special areas of image processing such as source encoding for data compression, color reduction for image display with a finite number of simultaneous colors and color selection for pseudo-color processing. As well, related areas can benefit from visual fidelity criteria such as for the definition of palettes of color shades pleasing to the human viewer in cartography, in graphics design, and in graphics art where often contrasting colors are needed to create special effects.

An ideal fidelity criterion should account for the perceptual impact of uniform color stimuli, for the effects caused by the interaction of neighboring picture elements in an image, and for the powerful adaptation of human vision to varying viewing conditions. Thus, the development of adequate fidelity criteria will be based on models of human color vision. The model's analytic transformations map a given 2D color image into the model's output space which accounts for many of the human vision's properties. A metric formed in this output space can represent a good visual distortion measure. On this basis, fidelity criteria were developed for achromatic (gray level) images [1,2] and recently also for color images [3,4].

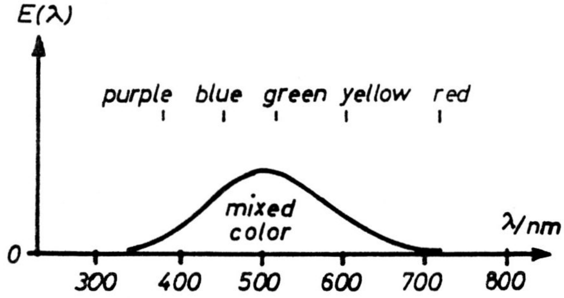


Figure 1 Spectrum of visible light

Unfortunately, the limited knowledge of psychovisual properties renders the underlying models of human vision inadequate in many respects. This work reports briefly on studies of the performance of known fidelity criteria. Conclusions are drawn from the outcome of these studies which lead to a visual fidelity criterion formed in a visually homogeneous 3D color space that exhibits improved performance for particular applications.

REPRESENTATION OF 2D COLOR IMAGES

In physical terms, color is defined by the energy distribution $E(\lambda)$ of light of different wavelengths as shown in Figure 1. On psychovisual grounds, color is tri-variant and can be expressed by a triplet $\underline{G}=(G1,G2,G3)$ in a three-dimensional (3D) color space spanned by the primaries G1,G2,G3 [5]. A 2D color image $\underline{G}(x,y)$ can be considered as a spatially ordered set of colored image points $\underline{G}(x,y)=[G1(x,y),G2(x,y),G3(x,y)]$, over an orthogonal x,y-plane. Thus, the image representation domain is established by the color space $\underline{G}$ in use. In the sequel the spatial coordinates x,y are omitted for convenience if no ambiguities can occur.

A distortion measure is obtained by forming a metric in the image representation domain so that a function of the distance d between two image points $\underline{G}(x,y)$ and $\underline{G}'(x,y)$ (with same x,y-values) becomes a meaningful measure of the perceptual effect caused by the color difference. In order for the distortion measure to be ideal, it must be location independent within the space $\underline{G}$ (homogeneity) and its numeric value must be proportional to the color difference perception (linearity). The two factors, homogeneity and linearity, depend on the color space $\underline{G}$ under consideration. Due to the complexity of human color vision, only approximations to the ideal representation domain are known. Some standard color representation spaces are investigated in the following paragraph.

A conceptually pleasing approach to color representation is the luminance/chromaticity formulation (also known as HSL) in the 3D space $\underline{G}=(\phi,r,y)$. The luminance Y specifies the perceived brightness of a color, while the color's chromatic contents is further separable into hue ϕ and saturation r. A more technical approach is the RGB intensity representation of color in the 3D space $\underline{G}=(r,g,b)$, where each color is specified by the additive mixture of certain amounts r,g and b of three physically realizable primary colors red, green and blue. None of the above color spaces exhibit the desired homogeneity and linearity properties. In colorimetry, other artificially created 3D color spaces, such as the XYZ, UVW, PQS [5,6] and the augmented MacAdam's color space (MacAdam's η,ξ -chromaticity space augmented by log Y coordinate) [7] possess adequate visual homogeneity and linearity for small color differences which would make them a candidate for use with visual fidelity criteria. However, neither of these color spaces take into account spatial interactions of neighboring image points in the human retina, which play important roles in the human visual system [1] nor reflect the adaptation capability of human vision to varying observation lighting conditions.

The formidable task of developing an adequate image representation space which better reflects the way the visual system processes color informatin is summarized in the next chapter on the basis of a model of human vision.

MODEL OF HUMAN COLOR VISION

A model of human color vision describes the transformations which map a 2D color image, generally represented in the 3D RGB intensity color space, into a new 3D color image representation domain which emphasizes those image features ruled relevant for human visual perception. This output space of the model is called the human visual domain. If ideal, the latter 3D space exhibits the desired visual homogeneity and linearity and is ideally suited for the formation of a metric to obtain a meaningful distortion measure.

In this work, known models of human color vision [3,4] are used as tools to construct the human visual domain. A brief description of the model's configuration and operation are in order. Figure 2 illustrates the general structure of the model. The first stage represents a linear mapping of the RGB

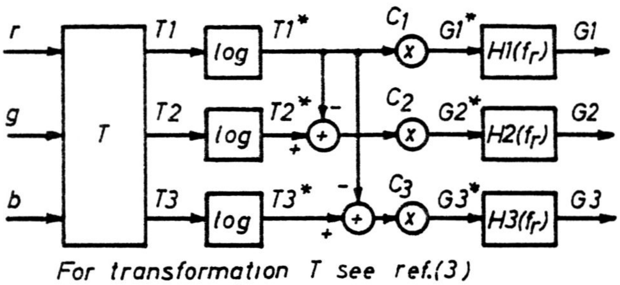


Figure 2 Model of human color vision

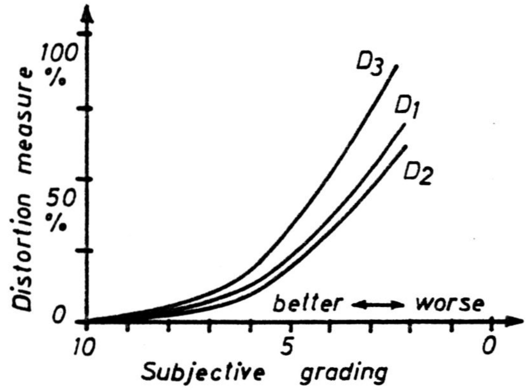


Figure 3 Subjective versus objective grading of color distortion

primaries r,g,b into the retina's tri-stimulus space $\underline{T}$=(T1,T2,T3) where T1 represents the luminance and T2, T3 specify the chromaticity of color implementing the opponent-color theory [8,9] along black/white (T1), red/green and yellow/blue (T2,T3) coordinates. The neural response to colored light stimuli is logarithmic on each coordinate, yielding the tri-variant neural color space $\underline{T}$*=(T1*,T2*,T3*) in the second stage of the model. The third stage of the model achieves independence between the chromaticity contents G2, G3 and the luminance G1 as required by Grassman's law [5].

The last stage of the model introduces spatial interaction between neighboring image elements by independent linear spatial filtering of each image component. This operation introduces the edge awareness of human vision and explains many optical illusions. The resulting 3D space $\underline{G}$=(G1,G2,G3) is the human visual domain, and the transformed 2D image in $\underline{G}$ can be interpreted as the image scene perceived by the human brain.

STUDY OF MODEL PARAMETERS

Owing to the modelling of psychovisual phenomena of human color vision, the output space $\underline{G}$=(G1,G2,G3) of the model of human vision is expected to be best suited for the formation of visual fidelity criteria. Due to the limited knowledge of human color vision and the only recent development of models, some model parameters are not well established yet. It is therefore instructive to study the performance of distortion measures with parameter variations. Parameters addressed here are the scaling factors C1, C2, C3, the spatial chromaticity filter frequency transfer functions H_2(fr), H_3(fr) and the visual homogeneity of the output space $\underline{G}$.

An original image $\underline{G}(x,y)$ is color distorted by an additive white zero-mean noise field $\underline{n}(x,y)$. Given the original image and its distorted version $\underline{G}'(x,y) = \underline{G}(x,y) + \underline{n}(x,y)$ the distortion measure is computed as the arithmetic average (AVG) of a function of the distance $d(x,y) = \underline{G}(x,y)-\underline{G}'(x,y)$ over all x,y-image points. The following distortion measures are considered:

D1 = $(\mathrm{AVG}(d_e^2))^{\frac{1}{2}}$ root mean square Euclidean
D2 = $\mathrm{AVG}(d_e)$ Euclidean
D3 = $\mathrm{AVG}(d_a)$ Absolute

where d_e represents the l_2-norm and d_a denotes the l_1-norm of the distance vector $\underline{d}(x,y)$. For varying noise variances σ_n^2 the objective numeric distortion measures are computed and compared against the average subjective ranking and grading of the resulting color distorted images by eleven human subjects. This comparison establishes the basis for the performance evaluation of the fidelity criteria.

The spatial filters Hi(fr), i=1,2,3 of the model are adopted from [3]. While the achromatic filter response Hi(fr) has been studied extensively for gray level images (luminance channel G1) [2], the parameters of the two chromatic filters H2(fr) and H3(fr) vary in the literature [3,4,9]. It was found that no significant improvement of picture quality was noticed by average human observers if the cut-off frequencies of both low-pass filters were moved beyond fr=3 cycles/degree for the image on hand [10]. This suggests a possible reduction in chromaticity information from that pertaining to a cut-off frequency of fr=10 cycles/degree as suggested in [3]. The scale factors C1, C2, and C3 contribute to the visual homogeneity of the output space $\underline{G}$ achievable by this model. By variation of the scale factors, the set

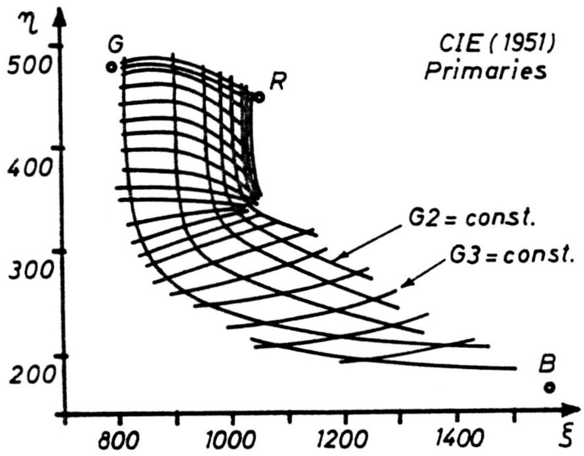


Figure 4 Distorted G2, G3-chromaticity grid in MacAdam domain

C1=1, C2=C3=2 was found to perform best for the image on hand [10], closely followed by the all unity set as suggested in [3]. The above new parameter set was adopted for further studies.

In order to test the linearity of the model's output space G=(G1,G2,G3), noise of increasing variances is added to the color image represented in G. The resulting color distortion is measured objectively by the analytic distortion measures D1, D2, D3, and subjectively by human observers grading the distorted images. Figure 3 depicts the linearity performance of the distortion measures. None of the three measures under consideration reflects the desired linearity over the full range of color distortions [11].

In order to test the visual homogeneity of the model's output space G=(G1,G2,G3), loci of constant-length distance vectors d about a given color sample (constant distortion measure) are mapped into MacAdam's η,ξ -chromaticity space [12]. The η,ξ-space was derived experimentally on psychovisual evidence as a 2D chromaticity space which exhibits good visual homogeneity and linearity for small enough color changes in the order of "just noticeable" color difference thresholds for average human observers. As the luminance aspect of color is lost, only the two chromatic variables G2 and G3 of the models 3D output space G are involved in this investigation. However, due to the fact that luminance and chromatic phenomena are largely independent in medium-bright light levels, the homogeneity and linearity of the luminance coordinate G1 can be tested separately.

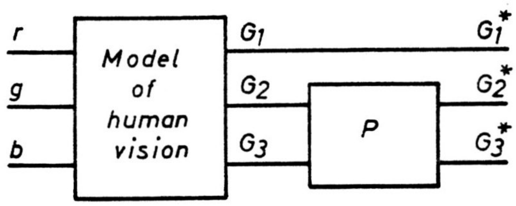


Figure 5 Post-transformation leading to visually homogeneous space G*

Convenient loci of constant-length distance vectors d are readily formed by mapping a rectangular grid in the G2, G3 chromaticity space in MacAdam's η,ξ -domain. The diagram in Figure 4 illustrates the outcome of this test. The deviation from the regular square-type grid structure indicates that the human vision domain G is not ideally homogeneous as far as chromaticity changes are concerned. The varying size of the "squares", enclosed by neighboring grid lines shows that a given perturbation affects blue colors slightly more than red and green. This result adds the desired quantitative factors to the qualitative conclusion in [3] that the human vision domain is fairly (but not ideally) homogeneous for small color difference variations. In addition, the treatment in this work introduces analytic qualifiers to this statement which can be exploited to arive at a almost homogeneous color space with regard to small chromaticity changes.

HOMOGENEOUS MODEL OUTPUT SPACE

The analytic nature of the test for visual homogeneity as outlined above also suggests a procedure to arrive at an improved 3D human vision domain G*=(G1*,G2*,G3*) which is almost homogeneous in the chromaticity plane G2*, G3*. A post-transformation is performed which maps the 3D representation space G=(G1,G2,G3) into the space G* as shown in Figure 5. The latter domain G* takes into account the varying thresholds of color difference perception of average human observers. The non-linear post-transformation P(G2,G3) can readily be expressed by geometric mappings which reshape the distorted grid of Figure 4 into an approximately regular grid. The result is illustrated in Figure 6. Homogeneity in both coordinates is achieved if the grid is of the

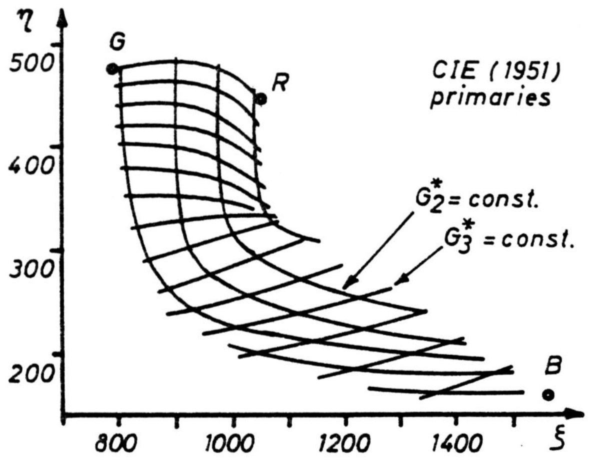


Figure 6 Reshaped G2*,G3*-chromaticity Grid in MacAdam domain

In order to limit the complexity of the post-transformation P, the transformation is subdivided into several subtransformations pertaining to mutually exclusive regions in the G2, G3-space where separability of P(G2,G3) into P'(G2)P"(G3) can be assumed.

The luminance channel G1 of the human vision model's output space G=(G1,G2,G3) is not affected by the post-transformation P, thus G1*=G1. Visual homogeneity in this coordinate can be assumed as the logarithmic transforms of the model satisfy Weber's law [5]. Proper choice of the scaling factors C1,C2 and C3 leads to visual homogeneity in all three coordinates of the improved human vision domain G*=(G1*,G2*,G3*).

The validity of the post-transformation P(G2,G3) is subject to the validity of the underlying psychovisual phenomena. MacAdam's η,ξ -chromaticity space was derived by color matching experiments using uniform areas of color of constant luminance. Thus, validity does not necessarily apply to natural color scenes with more random-like spatial distribution of color samples. As well, validity exists only at medium-bright light levels where Grassman's law holds true. Visual homogeneity and linearity of MacAdam's domain hold true for small enough color differences, thus local properties do not necessarily imply global properties.

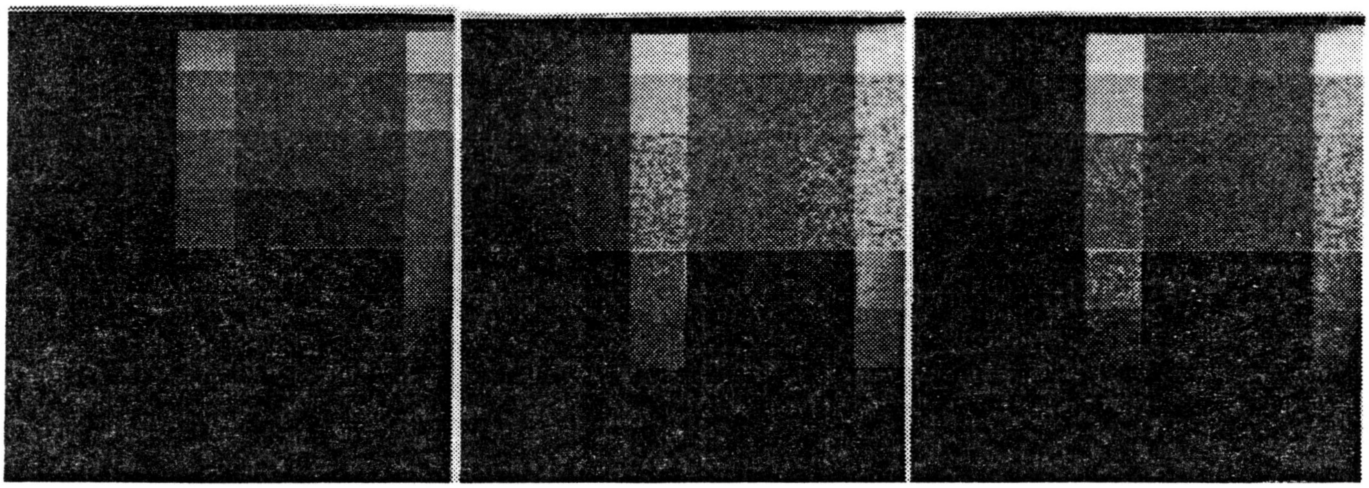
Finally, the transformation may be unreliable in the blue area of the chromaticity space where only few experimental tests are reported. Due to the separate treatment of luminance and chromaticity visual homogeneity in all three coordinates of G* domain is conditioned on the validity of Grassman's law which is true for medium-bright light levels where photopic vision is predominant. Adaptability of the human visual system to varying lighting conditions during observations is not reflected by the model shown.

Experiments are performed to test the actual improvement of the model after incorporation of the post-transformation P. Only a well structured image is used where validity of the procedure can be assumed. In this case the effects of the model's spatial filters Hi(fr), i=1,2,3 are negligible, except at visible boundaries of neighboring uniform image areas. The photograph in Figure 7a color cube in the RGB log-intensity domain approximately ordered by increasing luminances. This artificial image is contaminated with zero-mean additive white noise as outlined in the previous chapter. First, the contamination takes place in the original G=(G1,G2,G3) domain. The result is shown in the photograph of Figure 7b. The investigation reveals that green colors are more susceptible to noise contamination than red and blue colors. This can be attributed to the location dependency of "just noticeable" chromaticity differences, indicating some remaining visual non-homogeneity of the space G. Second, the noise contamination with equal noise variance is repeated in the G*=(G1*,G2*,G3*) domain. The recorded photograph appears in Figure 7c. It is apparent that the visible noise is now more evenly distributed over all color samples. Therefore, the expected improvement of the visual homogeneity of the G* domain is confirmed.

APPLICATION AREAS

The availability of a good visual fidelity criterion which measures color differences in good agreement with the average human judgement leads to immediate applications in various special research areas. The requirement common to all of these areas is the need to associate a set of colors with a corresponding set of visual sensations invoked by the colors or the color differences.

In source encoding for data compression, an original color picture is to be transmitted at a low information rate which causes a permissible color distortion. The fidelity criterion measures this distortion and permits minimization of the average picture distortion following information theoretical approaches [13]. For the display of natural color scenes on modern RGB-based color monitors only a



(a) (b) (c)

Figure 7 Color photographs (256x256 picture points, viewing distance 65cm=viewing angle 6°) recorded with CELCO precision display on Polaroid type 59 film. (a) Original color palette, (b) Color palette contaminated in G-space, (c) Color palette contaminated in G*-space.

simultaneous colors) is available. The fidelity criterion aids in the required color reduction by specifying rules for the selection of the visually optimal set of reproducing colors. These rules lead to a visually equi-distant quantization of the monitor's color space (RGB cube) so that a change from any given reproducing color sample to its nearest neighbor(s) invokes the same color difference perception [7,14].

The design of special color palettes also benefits from the availability of a good visual fidelity criteria in other areas related to image processing. In cartography the reproducing colors of a map should be equally well distinguishable from one another without dominant colors suppressing the perception of others. A set of meaningful color difference distortion measures will assist in this color selection. In computer graphics and graphics art one or more dominant colors are often desirable to highlight certain graphical information and clearly distinguish it from less relevant graphic contents. The perceptual difference sensation of dominant colors with regard to other colors of the set can be measured by the fidelity criterion and estimation as to the visual dominance can be made.

The fidelity criterion defined in the 3D homogeneous color space G* is particularly well suited for color images containing regions of uniform color contents as occuring most frequently in computer graphics and graphics art. In these cases it will provide an improved visual color distortion or color difference measure. For natural color scenes where the spatial interaction between picture points plays an important role, the fidelity criterion defined in the 3D color space G is applicable, although the space G is not ideally homogeneous in a visual sense.

SUMMARY AND CONCLUSION

The research presented in this paper addresses the performance of visual fidelity criteria for 2D color images. The ultimate objective is the development of a criterion which grades color distorted images in good agreement with the subjective judgement of average human observers.

The fidelity criterion prescribes the rules for the calculation of a numeric distortion measure. The latter is obtainable by formation of a metric in the 3D image representation space. The choice of a suitable representation space is found crucial for the good performance of fidelity criteria. Standard 3D color spaces are shown to be unsuitable as they do not reflect many of the visual phenomena. Recently developed models of human color vision lend themselves naturally as a basis for image representation domains since they process colored light stimuli similarly to the human visual system. Suitable fidelity criteria are obtainable by forming the distortion metric in the output space of the model of human vision, called the human visual domain. Several refinements of the model's parameters are reported in this work affecting the spatial chromacticity filters and scale factors of the three color channels.

By way of subjective color distortion evaluation by human observers, the non-linearity of several common distortion measures applied in the 3D human vision domain is shown. The visual homogeneity of the human vision domain is tested with the aid of MacAdam's , -chromaticity space and found to be non-ideal. A post-transformation is suggested to overcome this problem. Subjective evaluation of color-distorted graphic color images reveal the achievable improvement.

The limitations of the approaches adopted in this research are pinpointed and shown to be subject to the lack of detailed knowledge of physiological and psychovisual aspects of human color vision. It is shown that the improved fidelity criterion in the 3D-homogeneous color space G* as developed in this work is particularly suitable for structured images containing extended regions of uniform color.

The availability of a good visual fidelity criterion for color images which provides a perceptual measure of color differences should prove beneficial in many areas where color stimuli and their associated visual sensations are addressed. This includes image processing, color display, color graphic art and cartography.

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