Modelling Image Naturalness

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Abstract

Naturalness is one of important image appearance attributes to achieve a high-quality image, but few attempts have been made to quantify it. The current study introduces modelling image naturalness based on visual phenomena that had a large impact on perceived image naturalness. Psychophysical experiments were conducted under a dark surround. Twelve observers were asked to assess image naturalness using the categorical judgment method. Eight colour images were manipulated to produce variations by rendering lightness, chroma and sharpness. For modelling image naturalness, memory colours and four factors revealed to be important in the results of the psychophysical experiment were considered. A naturalness index determined from memory colours alone was not sufficient to predict perceived naturalness. The four key factors were however successfully modelled, based on parameters derived using the CIECAM02 colour appearance model and the CAM02-UCS uniform colour space for image naturalness.

Introduction

Various studies [1-5] have shown that naturalness is an important image appearance attribute for assessing high-quality images. Janssen [5] defined naturalness as the degree of correspondence between the visual representation of the image and a knowledge of reality as stored in memory. In colour reproduction, naturalness can be assessed by the mental recollection of the colour sensations previously experienced when looking at objects similar to those being appraised [4]. A mental recollection of the colours of familiar objects is often known as memory colour. Yendrikhovskij [3] demonstrated the usage of the memory colours of grass, skin and sky, for quantifying image naturalness. In his study, combinations of changes in hue and chroma were used to manipulate two test images. It was found that the images rendered by such changes led to a systematic reduction in perceived image naturalness, i.e. changing hue produced a more unnatural image appearance than only varying chroma or lightness. Janssen [5] also used memory colours of grass, skin and sky to predict image naturalness by computing the degree of matches in the u´, v´ and Y dimensions between an image considered and a set of natural images taken from Kodak Photo CD. Both these researchers demonstrated that the naturalness of an entire image could be determined from the naturalness predictions for the grass, skin and sky areas in the image. However, the validity of this result is dependent on the characteristics of the set of natural images in which the memory colour information for the grass, skin and sky was extracted.

The approaches applied to modelling image naturalness in the previous studies need to be re-evaluated using images differing in only one of three domains, lightness, chroma and sharpness. Additionally, a different memory colour set that was not used for the previous studies is required to verify the ideas of Yendrikhovskij and Janssen for modelling image naturalness. Other factors affecting image naturalness, besides memory colours, need to be found from which criteria observers judge images to be natural.

In advance of the present work, a large-scale psychophysical experiment was conducted by the authors in a dark surround [6]. Contrast, colourfulness and naturalness were established to be important perceived attributes affecting image quality. From the results of image-naturalness judgment, the images that appeared significantly unnatural could be categorised according to four characteristics: loss in colourfulness, loss of shadow-detail due to markedly increased lightness-contrast, washed-out appearance due to considerably decreased lightness-contrast, or too much sharpening. In other words, image colourfulness, image sharpness, reproduction of shadow-detail and non-existence of washed-out appearance are important factors contributing towards the perception of naturalness. Therefore, for modelling image naturalness in the present work, memory colours established by Tarczali's study [7] and the four important factors revealed in the previous psychophysical experiment [6] are considered.

Experimental Set-Up

Psychophysical Experimental Setting

All the psychophysical experiments were conducted under a dark surround. A 42-inch plasma display panel (Samsung PPM42H3) with 1024×768 pixel resolution was used to reproduce the images. The reference white of this display was 174 cd·m^{-2} with a correlated colour temperature of 8940 K. Eight test images were chosen including five natural scenes (Seashore, Park, Pier, Sheep and Harbour), one fruit (Fruits) and two portraits (Kids and Adults) [6]. Each image was stored in terms of CIE XYZ tristimulus values converted from the display RGB values using a 3D-LUT and tetrahedral interpolation. The CIECAM02 model was then used to process these images to manipulate the lightness (J) and chroma (C) values. For rendering sharpness, high-frequency emphasis filters were applied to the J channel. As a result, each of the eight test images led to 22 manipulated images. Twelve observers assessed image naturalness using a 9-point qualitative categorical scale. The category-scaling data of the observers were converted into equal-interval scale using Case V of Thurstone's Law of comparative judgments. Mean scale values were computed for each test image over all observers. Overall, all scale values of the eight test images fell within the 95% confidence interval from the mean scale-values of the eight images for most image manipulations. This indicates that the perceived image-naturalness appears not to be dependent on the test images used. Amongst the eight test images, six were used for developing the functions, and two images, Sheep and Park, were used for testing the model performance.

Modelling Image Naturalness

Lightness and chroma in each pixel of an image, and pixel-based colour differences at different image resolutions were computed using CIECAM02 (J, C and ΔE_{CAM02}) and CAM02-UCS (J', C' and $\Delta E_{CAM02\text{-}UCS}$) [8-9]. These were used to calculate a naturalness index based on memory colours, and to develop functions for determining changes in image naturalness caused by changes in the four key factors that were found from the results of the psychophysical experiment. Two of these factors, loss of shadow-detail and washed-out appearance, arose from images manipulated by the sigmoid and inverse-sigmoid lightness functions that generated the largest compression to dark and light areas in the test images respectively. It was found during the process of modelling image naturalness that one function was sufficient to explain changes in naturalness due to these factors. Thus, three functions were developed to reflect variations in image naturalness due to changes in image sharpness, image colourfulness, and both reproduction of shadow-detail and washed-out appearance. The functions were then combined to develop an image naturalness model.

All the image characteristics obtained using CIECAM02 (J, C and ΔE_{CAM02}) and CAM02-UCS (J', C' and $\Delta E_{CAM02\text{-}UCS}$), and scale values in the psychophysical experimental results were re-calculated in a relative scale by dividing those of each of 22 manipulated images by those of the original image. The ratio was thus 1 for the original image but not equal to 1 for the 22 manipulated images. These ratios were image independent. If the ratio was larger than 1, it indicates that an image presented on an imaging device (e.g. an existing display) appears more natural than that on another imaging device (e.g. a new type of display). As a result, the developed image naturalness model is image independent and can predict ratios of perceived naturalness of images viewed on an imaging device compared to those on another imaging device.

Results and Discussions

Observer Variability in the Experiment

Inter-observer agreement was computed using the coefficient of variation (CV) defined in Eq. (1). The resulting mean CV value of all observers was 25 for image naturalness. This was the largest CV value among those of the six attributes assessed [6]; indicating observers might use different criteria in the evaluation of image naturalness. For model performance, CV will be computed between the predicted and experimental image naturalness data and this will be compared with the inter-observer agreement.

$$CV = (100/\bar{y})[\sum(x_i - y_i)^2 / n]^{1/2} \quad (1)$$

where, x_i is individual observer data, y_i is the mean data of all observers, and $\bar{y}$ is the mean value of the y_i data set.

Considering Memory Colours

An absolute standard such as the concept of memory colours is a primary factor needed to judge naturalness in images, since an image having a green-face or pink-banana cannot be perceived to be natural. Three memory colours corresponding to the three familiar objects Caucasian-skin, grass and sky were chosen from Tarczali's study [7]. Table 1 describes memory colours for those in terms of CAM02-UCS $J'a'b'$. The memory colour is expressed using a 'colour centre' that was determined from the mean value of all observers participating in Tarczali's experiment, and 'standard-deviation' inside a bracket representing the variation of all the observers. Colour difference between the 'colour centre' and 'colour centre ± standard deviation' was computed for the three memory colours and is described as $\sigma(\Delta E_{CAM02\text{-}UCS})$ in Table 1. Hue-angle range corresponding to the 'colour centre ± standard deviation' is also given.

Table 1: Memory colours for Caucasian-skin, grass and sky in terms of CAM02-UCS *J'a'b'*.

	J'	a'	b'	$\sigma(\Delta E_{CAM02\text{-}UCS})$ (h)
Skin	88.40 (3.87)	6.10 (6.46)	9.02 (1.86)	7.76 (45° - 65°)
Grass	57.39 (5.85)	-22.62 (4.52)	17.14 (3.31)	8.10 (136° - 144°)
Sky	74.56 (7.69)	-14.96 (8.89)	-21.32 (2.93)	12.11 (229° - 249°)

(Note: Standard-deviation of the judgments of all the observers participating in Tarczali's memory-colour experiment of is given inside a bracket in terms of CAM02-UCS *J'a'b'*.)

To calculate naturalness-index, Eq. (2) was adapted from Yendrikhovskij's study [3] in which saturation s_{uv} in CIELUV domain was used.

$$N_i = \frac{\sum n_{ij} \exp(0.5(colour - difference_{ij} / \sigma(\Delta E_{CAM02-UCS}))^2)}{\sum n_{ij}} \quad (2)$$

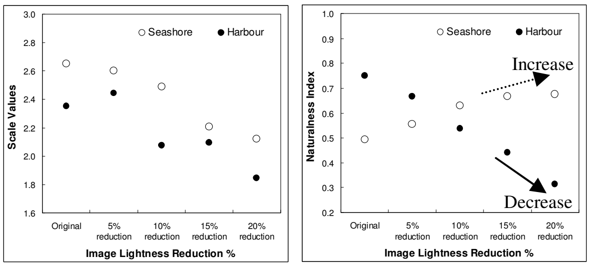
where, N_i is naturalness index, j indicates one of three familiar objects (sky, skin and grass), n_{ij} is the number of pixels belonging to one of the three objects in a test image, $\sigma(\Delta E_{CAM02\text{-}UCS})$ is obtained from Table 1, and $colour\text{-}difference_{ij}$ is the colour-difference value between the memory-colour centre in Table 1 and the colour of each pixel belonging to one of the three objects.

If the colour of any pixel belonging to sky is the same as the memory colour centre of sky in Table 1, the exponential component is 1. Therefore, as the colours of the sky, skin and grass areas in the test image are close to their associated memory-colour centres, N_i approaches 1. Note that the resulting naturalness index (N_i) is dependent not only on a test image but also on the data set of memory colours, that is the naturalness index value will change if a different set of memory colours is utilized.

The computed naturalness indices were compared with the experimental image-naturalness data for the eight test images × 22 manipulations. There was little correlation between them. To demonstrate the discrepancy between naturalness indices and experimental image-naturalness data, part of the comparison results is given here. Figure 1 shows the original images of Harbour and Seashore. Figures 2(a) and 2(b) plot score values of the experimental image naturalness and computed naturalness indices, against the original image and its darkened images by 5 - 20% lightness reduction, for each of Harbour (●) and Seashore (○) images. In the process of computing naturalness indices for these two images, cloud areas were screened by a mask. For both Harbour and Seashore images, as the images become darker, there is the same trend for the perceived naturalness (Figure 2(a)) but a different trend for the naturalness index (Figure 2(b)). The naturalness index for Seashore image increases while that of Harbour image decreases with decreased image lightness. Comparing naturalness indices between the two original images in Figure 2(b), the sky colour of the Harbour image is closer to the sky memory colour than that of the Seashore image, i.e. the higher naturalness index in the Harbour image than in the Seashore image. On the contrary, the Seashore original image is perceived to be similar or somewhat more natural than the Harbour image in Figure 2(a).

The reasons of this result could be due to the fact that the observers evaluated image naturalness using the whole image rather than the familiar objects in that image. This was also reported by Boust [10]. Another reason could be that a memory colour could be a representation of only part of an actual familiar object whose natural colour could have a considerable variation in lightness and saturation, compared with the entire colour of the object, for example when viewing sky [11]. Therefore, memory colours of familiar objects themselves may not be sufficient to describe image naturalness. However, a standard is necessary in the evaluation of image naturalness to avoid a case that an image having purple skin colour is evaluated to be natural. Hue angles in memory colours for familiar objects could define such a standard, but further studies using more memory colour data are required.

Figure 1. *Seashore image at the left side and Harbour image at the right side.*



(a) (b)

Figure 2(a). *Scale values of the experimental image naturalness and* ***(b).*** *computed naturalness index, against the original image and its four darkened image by 5 - 20% lightness reduction for each of Harbour and Seashore images.*

Image Colourfulness

There was a strong positive linear relationship between image quality and image naturalness, however, another trend was also found that a more colourful image looked somewhat unnatural whereas it was perceived to have higher image quality [6]. Thus image colourfulness was considered to be one of the key factors affecting image naturalness and was modelled using two colourfulness predictors CIECAM02 M and CAM02-UCS M'. The colourfulness value in each pixel was averaged over all pixels in an image. This averaged colourfulness in the image was considered to be computed image colourfulness. Subsequently, the computed image colourfulness of each of the original image and 22 manipulated images was divided by that of the original image. The scale value of each of the original image and 22 manipulated images was also divided by that of the original image. All results were then averaged over the six training images in each of the original image and 22 manipulated images, resulting in 23 ratios. Figure 3 plots the 23 scale-value ratios of the experimental image naturalness against the 23 computed image-colourfulness ratios. The data are shown differently with respect to the three domains used in the image manipulations, lightness, chroma and sharpness. The image colourfulness in Figure 3 was calculated using CAM02-UCS M'. The result calculated using CIECAM02 M is not presented in Figure 3, because the relationship between the scale-value ratios and the image-colourfulness ratios computed either in CIECAM02 or CAM02-UCS is quite similar. The best fit function was found between the scale-value ratios and the computed image-colourfulness ratios only using data of the images manipulated in chroma domain. This is seen in the Figure 3 and is given in Eq. (3). Its correlation coefficient (R) was 0.94. The corresponding function developed in CIECAM02 space is given in Eq. (4) and its R value was 0.95.

$$N = \exp[3.68 - 3.71/x - 3.70\ln(x)] \quad (3)$$

$$N = \exp[2.75 - 2.78/x - 2.76\ln(x)] \quad (4)$$

where x is the computed image-colourfulness ratio in CAM02-UCS space (Eq. (3)) and in CIECAM02 space (Eq. (4)), and N is predicted perceived image-naturalness ratio.

For the images manipulated in the chroma domain in Figure 3, the predicted experimental image naturalness (curve in the figure) represents the psychophysical phenomenon previously mentioned: perceived image naturalness increases to a maximum then falls as image colourfulness increases.

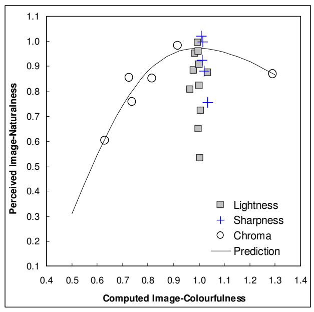


Figure 3. *Plot of the 23 ratios of the experimental image naturalness against the 23 ratios of the computed image colourfulness.*

Reproduction of Shadow-Detail and Washed-Out Appearance

The lightness value in each pixel was calculated using two lightness predictors CIECAM02 J and CAM02-UCS J'. The numbers of pixels having lightness values of less than 20, 30 and 40 were then counted. The reason of selecting the three lightness values (20, 30 and 40) was to find an optimum low lightness range that corresponded to typical reproduction of shadow-detail. The numbers of pixels having lightness less than 20, 30 and 40 in the original image were divided by those in each of the original image and 22 manipulated images. However, the scale value of each of the original image and 22 manipulated images was divided by that of the original image. Then all results were averaged over six training images in each of the original image and 22 manipulated images, resulting in 23 ratios.

The 23 scale-value ratios of the experimental image naturalness were plotted against the three sets of the 23 ratios of the number of pixels having the lightness (J or J') less than 20, 30 and 40. Three best fit functions were developed between the scale-value ratios and each of the three data sets only using data (J or J') of the images manipulated in lightness and sharpness domains. It was found that the experimental image naturalness could be predicted best by the reproduction of shadow-detail computed using the lightness range of 0 - 30, i.e. the highest correlation coefficient.

Figure 4 plots the 23 scale-value ratios against the 23 ratios of the number of pixels having the lightness (J') less than 30. The data set on the abscissa is considered to be the computed reproduction of shadow-detail. The data are shown differently with respect to the three domains used in the image manipulations, lightness, chroma and sharpness. The results calculated in CIECAM02 J are not introduced in Figure 4, because the overall relationship is almost the same between the scale-value ratios and each of the reproductions of shadow-detail calculated either in CIECAM02 or CAM02-UCS space. The best fit function is also seen in Figure 4 and is given in Eq. (5). Its correlation coefficient (R) was 0.91. The function developed in CIECAM02 space is given in Eq. (6) and its R value was 0.94.

$$N = \exp[1.60 - 0.31/x - 0.33\ln(x)] \qquad (5)$$

$$N = \exp[4.59 - 4.61/x - 4.11\ln(x)] \qquad (6)$$

where x is the ratio of the number of pixels having CAM02-UCS J' less than 30 (Eq. (5)) and having CIECAM02 J less than 30 (Eq. (6)), and N is predicted perceived image-naturalness ratio.

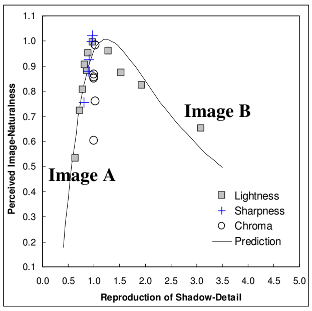


Figure 4. *Plot of the 23 ratios of the experimental image naturalness against the 23 ratios of the number of pixels having lightness J´ less than 30.*

Figure 5. *Image A (manipulated by lightness sigmoid function) at the left side and Image B (manipulated by lightness inverse-sigmoid function) at the right side.*

In Figure 4, Image A dictates the image manipulated by a lightness sigmoid function with the largest compression applied to dark areas in the test image amongst the 22 manipulations. The Image B dictates the image manipulated by inverse-sigmoid function with the largest compression applied to light areas in the test image amongst the 22 manipulations. Figure 5 shows examples of Image A and Image B using Seashore test-image. The dark areas in Image A are much darker than those in the original image (Figure 1), leading to a loss in shadow-detail. The dark areas in Image B are much lighter than those in the original image (Figure 1), leading to a washed-out appearance. For the computed values of the reproduction of shadow-detail (the abscissa), Image A shows the least value but Image B shows the largest value. The perceived image-naturalness values (the ordinate) for Image A and Image B, however, are both lower than those for most of other manipulated images. This means that unnatural images are perceived not only for the images in which shadow-detail could not be distinguished well, but also the images losing much contrast and washed-out appearance. The developed function having an inverted U-shape can take into account this phenomenon: as the computed reproduction of shadow-detail increases, the perceived image naturalness reaches a maximum then decreases again.

Image Sharpness

As image sharpness increases, colour differences between neighbouring pixels in the areas of an image containing edges may increase, improving edge detail. Therefore, averaged pixel-based colour difference (ΔE_{CAM02} and $\Delta E_{CAM02\text{-}UCS}$) in an image was selected as a variable to be representative of image sharpness. Observers however cannot notice the pixel-based colour differences in a high resolution image. Hence pixel-based colour differences were calculated using five different image resolutions: 1024×768, 512×384, 256×192, 128×96 and 64×48 in the horizontal × vertical direction of the display studied. Changes in experimental image naturalness due to changes in image sharpness could be predicted best by the pixel-based colour difference computed in 128×96 (4 cpd at 2 m viewing distance) image resolution.

At each pixel in an image of 128×96 resolution, averaged colour difference between the centre pixel and its neighbouring pixels was calculated. This pixel-based colour difference was averaged over all pixels in the image. Then, the averaged pixel-based colour difference of each of the original image and 22 manipulated images was divided by that of the original image, leading to 23 pixel-based colour-difference ratios. The scale value of each of the original image and 22 manipulated images was also divided by that of the original image, resulting in 23 scale-value ratios.

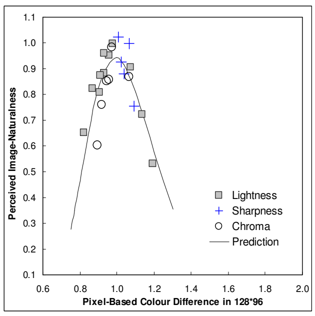


Figure 6. *Plot of the 23 ratios of the experimental image naturalness against the 23 ratios of the pixel-based colour-difference computed at 128×96 image resolution.*

Figures 6 plots the 23 scale-value ratios against the 23 ratios of pixel-based colour difference computed at 128×96 resolution and in CAM02-UCS space. The data are shown differently with respect to the three image manipulation methods, lightness, chroma and sharpness. The results calculated in CIECAM02 space are not introduced in Figure 6, because the overall relationship is very similar between the scale-value ratios and pixel-based colour-difference ratios calculated either in CIECAM02 or CAM02-UCS. The best fit function is seen in the Figure 6 and is given in Eq. (7). Its correlation coefficient (R) was 0.80. The function developed in CIECAM02 space is given in Eq. (8) and its R value was 0.89.

$$N = \exp[28.48 - 28.54/x - 28.82\ln(x)] \tag{7}$$

$$N = \exp[39.30 - 39.32/x - 39.93\ln(x)] \tag{8}$$

where x is the pixel-based colour-difference ratio at 128×96 image resolution computed in CAM02-UCS space (Eq. (7)) and CIECAM02-space (Eq. (8)), and N is predicted perceived image-naturalness ratio.

A New Image Naturalness Model

The above newly developed functions were combined with different weights in order to give the least difference between the visual and predicted image-naturalness data. This is introduced in eqns. (9) and (10) for CAM02-UCS and CIECAM02 spaces respectively.

$$N = 0.53RSD + 0.83IC + 0.54IS - 0.85 \tag{9}$$

$$N = 0.72RSD + 0.73IC + 0.35IS - 0.76 \tag{10}$$

where *RSD*, *IC* and *IS* are representatives of the reproduction of shadow-detail (and washed-out appearance), image colourfulness and image sharpness respectively, and N is predicted perceived image-naturalness ratio.

For the six training and two testing images, the reproduction of shadow-detail, image colourfulness and image sharpness were first predicted using eqns. (3), (5) and (7) for CAM02-UCS space, and using eqns. (4), (6) and (8) for CIECAM02 space. Perceived image naturalness was then predicted by Eq. (9) for CAM02-UCS space and Eq (10) for CIECAM02 space. The coefficient of variation, CV, was calculated between two sets of the predicted and experimental image-naturalness data. In calculating the CV value, the three data sets corresponding to the three image-manipulation domains were considered both independently and combined. Table 2 shows the computed CV values for the two testing and six training images. The CV values written in bold-font were calculated using all data sets.

For the two test images, the CV value is smaller in CAM02-UCS (14) than in CIECAM02 (19) when all manipulated images are considered together. There is however almost no difference for the six training images, i.e. 5 both in CIECAM02 and in CAMUCS. More test images and psychophysical data are required to make a final decision as to which colour space is the better choice for modelling image naturalness. All the CV values are however smaller than the mean CV value for the inter-observer agreement (25), indicating perceived image naturalness can be well predicted by the image naturalness models developed both in CAM02-UCS and CIECAM02 spaces. Additionally, it has been demonstrated that the four key factors found from the psychophysical experimental results could model image naturalness reasonably well for images varied in any one of lightness, chroma and sharpness domains.

Table 2: Summary of the CV values computed between the data sets of the predicted and experimental image-naturalness for the six training and two testing images.

Colour Space	CIECAM02	CAM02-UCS
Testing Images	**19** L (24) C (17) S (6)	**14** L (17) C (15) S (7)
Training Images	**5** L (5) C (3) S (5)	**5** L (5) C (4) S (7)

(Note: L is lightness manipulation, C is chroma manipulation and S is sharpness manipulation.)

To examine the relative contribution of the three factors, *RSD*, *IC* and *IS*, on the perception of image naturalness, the seven combinations of the three factors were used for modelling image naturalness: one model having all three factors, three models having two factors, and three models having one factor. The coefficient of variation was calculated between the predicted and experimental image-naturalness data for each of the seven models. It was shown that *IS* (image sharpness) and *IC* (image colourfulness) are more influential visual factors on the perception of image naturalness than *RSD* (reproduction of shadow-detail and washed-out appearance).

Conclusion

Image naturalness was modelled in the present work. It was found that a model using memory colours did not perform well in predicting perceived naturalness; contrary to the previous studies [3,5]. However, an absolute standard needs to be embedded into model of image naturalness to provide basic colour information for familiar object colours (for example, a red apple, a yellow banana and green grass etc.). For such a standard, hue angles of memory colours of familiar objects are recommended but this needs to be further verified by including more diverse memory colour data.

Besides such a standard, the important criteria used by observers in the psychophysical experiment were found and were applied to modelling image naturalness. These could be classified into four factors [6]: reproduction of shadow-detail, non-existence of washed-out appearance, image colourfulness and image sharpness. These factors were revealed from 2208 observations made by 12 observers against the 22 manipulated images of individual eight natural images, which were viewed in a dark surround. It is noted that the eight images were manipulated to provide to observers images having large, but realistic, variations in lightness, chroma and sharpness domains. As a result, the four key factors used for modelling image naturalness may provide a general basis, together with memory colours, that are applicable to the perception of the image naturalness in real situations.

The four factors were successfully modelled for image naturalness, based on lightness, chroma and pixel-based colour differences that were computed in CIECAM02 and CAM02-UCS spaces. However, the aim of the present work was to verify some ideas applicable to the computation of image naturalness, thus the derivation of a comprehensive image naturalness model will be published in near future.

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