Investigation of two Methods to quantify Noise in digital Images based on the Perception of the human Eye

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ABSTRACT

Since the signal to noise measuring method as standardized in the normative part of *ISO 15739:2002(E)*[1] does not quantify noise in a way that matches the perception of the human eye, two alternative methods have been investigated which may be appropriate to quantify the noise perception in a physiological manner:

- the model of visual noise measurement proposed by Hung et al[2] (as described in the informative annex of *ISO 15739:2002*[1]) which tries to simulate the process of human vision by using the opponent space and contrast sensitivity functions and uses the CIEL*u*v*1976 colour space for the determination of a so called visual noise value.

- The S-CIELab model and CIEDE2000 colour difference proposed by Fairchild et al[3] which simulates human vision approximately the same way as Hung et al[2] but uses an image comparison afterwards based on CIEDE2000.

With a psychophysical experiment based on just noticeable difference (JND), threshold images could be defined, with which the two approaches mentioned above were tested. The assumption is that if the method is valid, the different threshold images should get the same 'noise value'.

The visual noise measurement model results in similar visual noise values for all the threshold images. The method is reliable to quantify at least the JND for noise in uniform areas of digital images. While the visual noise measurement model can only evaluate uniform colour patches in images, the S-CIELab model can be used on images with spatial content as well. The S-CIELab model also results in similar colour difference values for the set of threshold images, but with some limitations: for images which contain spatial structures besides the noise, the colour difference varies depending on the contrast of the spatial content.

Key words: Signal to noise ratio, noise measurement, contrast sensitivity function, visual noise value, S-CIELab, CIEDE2000, CIEluv1976, just noticeable difference, OECF.

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Acronyms: JND: just noticeable difference, SNR: Signal to Noise Ratio, OECF: Optical Electronic Conversion Function, VN: Visual Noise, CSF: Contrast Sensitivity Function.

1. INTRODUCTION

Colour noise is a current phenomena in the image digital technology, it has many sources[4,5], and despite the constant improvement of the imaging digital technology, noise can not totally be avoided because of its inherent nature and its statistical, random characteristic. Being able to evaluate the noise using a quantisation based on the perception has become necessary.

2. SETTING THE CONTEXT

2.1. Signal to Noise Ratio Method

Until now the most current method to quantify noise has been the signal to noise ratio (SNR) measurement[1] . It describes the behaviour of noise in digital image capture devices, but this does not always match the perception of noise, as it is shown in the following example. The same two middle grey patches of the test chart OECF20 have been taken with the digital still camera: Panasonic® TZ1, only the ISO-sensitivity is different with sensitivity of 100ISO, which corresponds to Figure 1 and 400ISO, which corresponds to Figure 2.

Being submitted to the test of the signal to noise ratio[1] measurement, the noise values are very similar for both patches: for the sensitivity of 100ISO, the SNR is 27,9 and for sensitivity of 400ISO, the SNR is 29,1. But when looking at the patches it is obvious that for each patch the noise impression is different since the perception of noise is from a different kind: for the sensor sensitivity of 100ISO the noise is chromatic, with red and yellow nature, while for the sensor sensitivity of 400ISO the noise is achromatic, the variations take place as luminance differences.

The visual comparison of both patches clearly shows that the noise of the patch taken at 400ISO appears to be much stronger. A method which quantifies noise based on the “visual noise perception” would measure a greater noise value for the patch taken at a sensitivity of 400ISO than for the patch taken at a sensitivity of 100ISO. Both, the visual noise measurement[2] and the S-CIELab[3] models evaluate noise based on human colour vision. This is why they were selected to see if they could fullfill the expected requirements regarding the “visual perception of noise”.

2.2. Defining threshold images in terms of noise, a psychophysical experiment.

Before being able to investigate the two models, the term noise has to be defined. According to the Normative part of ISO 15739[1], noise is defined as "*unwanted variations in the response of an imaging system*"[1]. It means that the pixel value is not the one it should be regarding the environment light, the object colours and the camera setting. That is why noise can be also seen as a colour difference.

Two former diploma thesis[4,5] developed a software, which has been used as a tool to create images with a defined noise level. The software created images sets with noise based on a Gaussian frequency content and varying in amplitude for the different components L,C, and h, in the CIEL*a*b*1976 space. The added noise is measured as a colour difference ΔE.

Under defined viewing conditions[4] (DIN 5035-7) about 30 observers were asked to select the threshold image with the just noticeable difference (JND) in terms of noise. By doing this for a variety of colours threshold images, which represent the same visual perception, have been defined. They are used to test the two models mentioned above. The assumption is that the different threshold images should be evaluated with the same 'noise value' using the visual noise measurement model or the same colour difference using the S-CIELab Model.

3. AN ALGORITHM DESCRIBING THE HUMAN VISUAL SYSTEM

3.1 A new approach: an algorithm describing the human visual system.

Based on the cognition of the human visual system[7,8], a model has been developed and can be implemented as an algorithm. This algorithm is used in both the visual noise measurement model, described in *Annex C* of *ISO 15739:2002(E)*[1] as well as in the paper of Hung et al[2], and the S-CIELab model, described by Fairchild et al[3]. Although the two models were originally designed for different purposes, the implemented human visual algorithm is similar. The main idea is to filter the image data using the opponent space and contrast sensitivity functions to simulate the perception of the image by the eye before the quantisation of the noise content. There are differences between the methods in the implementation of different contrast sensitivity functions and the transformation matrix from the RGB image space to the opponent colour space.

3.2. Structure of the implemented algorithm of the human visual system

As it is described in the paper of Hung et al[2], the human visual system can be simplified in the followings steps (the model is valid for photopic viewing conditions and normal vision): 1) First an object is observed through the optical system of the eye. 2) Second the electromagnetic radiation reflected by the object are detected by the photoreceptors: L, M and S cones for photopic vision.

The detected signals are then processed by the visual neural system. This can be simplified into two steps although they both occur simultaneously during the neural processing: 3) First the detected signals are transferred into the opponent colour space, into three coordinates: the luminance channel A, the red-green channel C1, and the yellow-blue channel

C2. 4) Second, each image signal in the opposite colour space is filtered by each corresponding contrast sensitivity function. 5) Finally, the processed signals reach the brain, where the actual sensation of colour occurs. This can be best described by the three coordinates: lightness, chroma and hue.

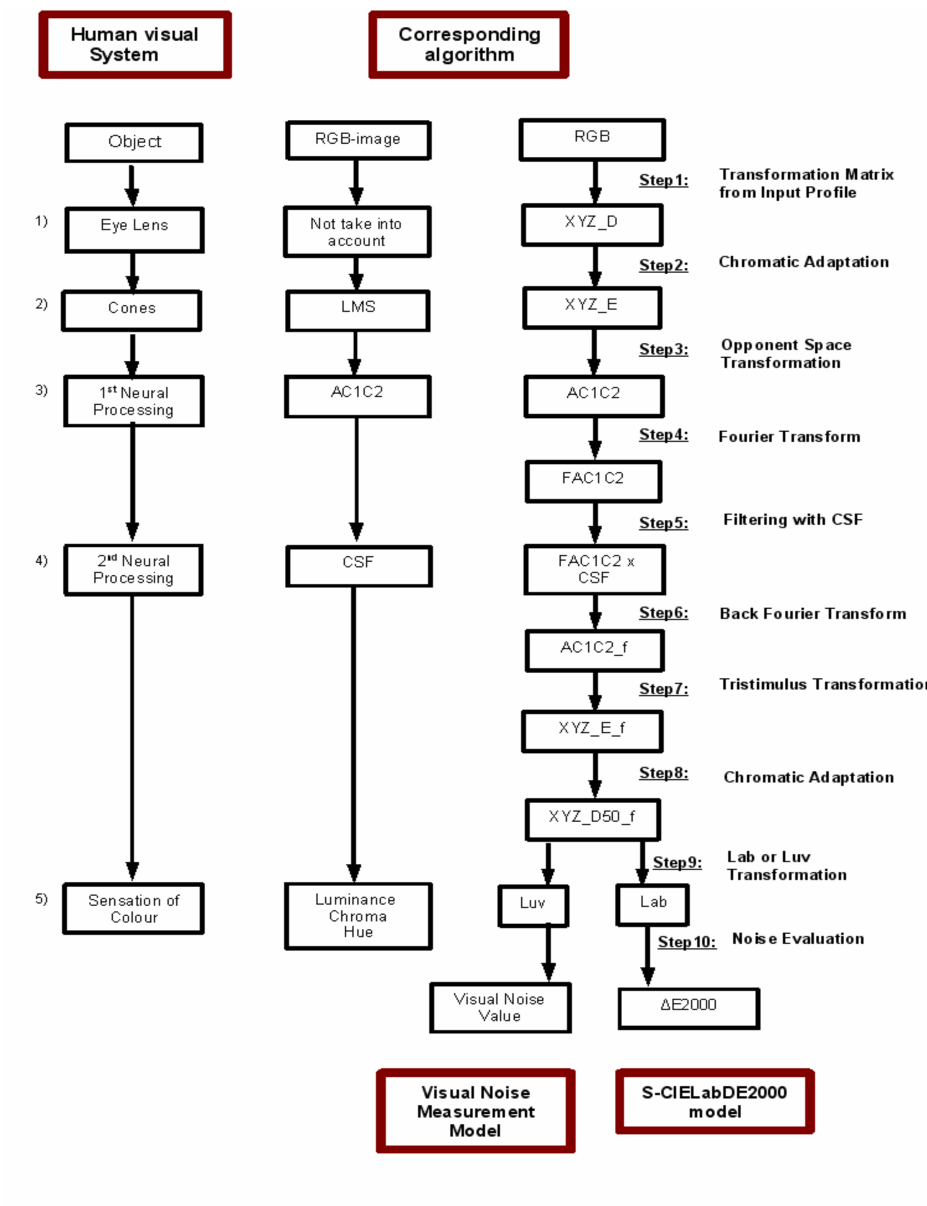


Fig 3 : Scheme of the implemented human visual algorithm[2]

In the context of this research[6], the algorithm following the steps described above has been implemented in Matlab®. Relating and referring to own results, the Matlab® implementation would use the contrast sensitivity function proposed by Fairchild[3] and the opponent space transformation matrix used by Hung[2].

4. DATA/MEASUREMENTS/EVALUATION

4.1. Visual Noise Measurement

4.1.1. The Evaluation: Standard deviation over a uniform patch.

After having filtered the image data with the implemented algorithm of the human visual model, the colour values, which in this case are the tristimulus values Xd_f, Yd_f, and Zd_f, (corresponding to step 8) can be used to determine the visual noise value from the visual noise measurement model.

The tristimulus values are converted into the uniform CIEL*u*v*1976 colour space[10] (Step 9). At last the visual noise (VN) value[1,2] can be determined, and is defined as the weighted sum of three standard deviations of the digital values along the L*, u* and v* axes from the CIEL*u*v*1976 colour space:

The weights for each axes has been determined with an empirical approach to fit the visual experiences by giving some coefficients[2]. These coefficients seem to match the human visual colour discrimination behaviour. Namely, the eye recognises differences in luminance better than in chroma, as well as differences in the red-green channel than in the yellow-blue channel.

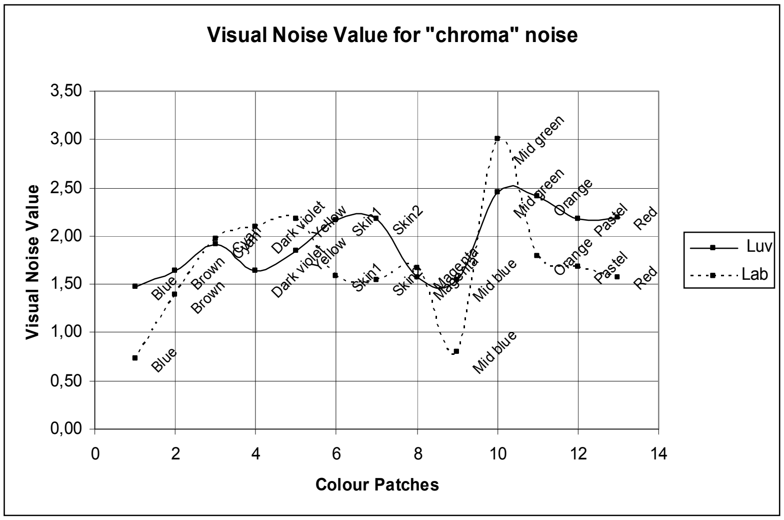
Although it was not recommended in the *ISO 15739:2002(E)*[1], in this research the visual noise value is also determined as the weighted sum of three standard deviations of the digital values along the L*, a* and b* axes from the CIEL*a*b*1976 colour space (with L* having the same coefficients, a* and u* as well as b* and v*), since there is no recommendation from the CIE to prefer one over the other colour space[11, 12].

4.1.2. Measurements: uniform colour patches as test images.

The visual noise value is evaluated as a standard deviation, which implies a comparison of each single pixel value to the mean value of the patch. This is why the test images can only be uniform colour patches. The patches used to evaluate the models mentioned above have been defined in the research of the former diploma thesis[4] and were named: brown, cyan, dark grey, dark violet, yellow, skin1, skin2, light grey, magenta, mid- blue, mid-green, orange, pastel, and red.

The experiment shows that over the 30 observers, the variance to determine the threshold image for noise input in the luminance channel is very low (0,04): all observers chose almost the same threshold. But for noise input in the chroma and hue channel, first the observers themselves show more difficulty and reluctance to determine the threshold, and the threshold differs much more among the observers with a variance in a range of 2 to 10 depending on the colour and the channel of the noise input.

The following graph 1 reports the visual noise value measured for threshold images determined in terms of noise input for colour difference in the chroma channel. It can be observed that the colour patches all obtain similar values (only green and blue behaves as small outlier).



Graph 1: Reports the measured visual noise value for each colour patch,once for the visual noise value determined with the CIEL*u*v* and once with the CIEL*a*b* formula.

Similar results have been obtained for noise input in the luminance and hue channel. In the following table 1, the mean value of the visual noise value has been calculated and reported for the set of the colour patches for each noise input channel. It can be observed that the luminance channel gets the smallest visual noise value and that chroma the highest, but that in general the determined visual noise value for all threshold images are very similar regardless of the channel used to add the noise (acceptable standard deviation over the channel).

Noise Input as ΔE	VN with Luv	VN with Lab
ΔL	1,42	1,36
ΔC	1,95	1,69
Δh	1,76	1,56
Mean value	**1,71**	**1,54**
Standard deviation	0,27	0,17

Table 1: Mean value of the visual noise value for the threshold images.

4.2. S-CIELab2000: S-CIELab and CIEDE2000

4.2.1 Evaluation: CIEDE2000 Colour difference

In the S-CIELab Model, after the image data has been filtered by the algorithm of the human visual model (step8), the colour difference CIEDE2000[3,13] is calculated. Two images are needed in order to be able to determine a colour difference: a “noisy” and a “noise-free” colour. The colour difference for each pixel of the image is computed and which can be regarded as an error image: the "image of the noise pattern". The obtained error image is reduced to a statistical single number to represent the overall perceived difference[3], which can be the mean value, median, standard deviation, variance or error maximum depending[3] on the purpose of the evaluation or the art of the colour difference.

This allows to evaluate complex images. In the former diploma thesis[5] a set of images containing vertical rectangular patterns varying in frequency and contrast have also been used to add noise and the observers were asked to determined the threshold images.

4.2.2 Measurements: comparison of a “noisy” and a “noise-free” image.

4.2.2.1. Measurements of uniform colour patches.

At first the same set of uniform colour patches has been evaluated with the S-CIELab Model and the ΔE2000 colour difference without filtering. Table 2 reports the mean value, standard deviation and variance of the evalutaion of the uniform colour patches with first the ΔE2000 colour difference without filtering and then with the statistical evaluations of the S-CIELab Model: mean value, variance, standard deviation, median, and maximum error.

Noise Input	For all threshold images	ΔE-2000	S-ΔE-2000				
			Mean value	**Variance**	**Std dev**	**median**	**Maximum error**
ΔL	Mean Value	**0,58**	**0,71**	**0,20**	**0,42**	**0,61**	**3,05**
	Variance	0,02	0,03	0,02	0,02	0,02	0,91
	Std dev	0,14	0,17	0,13	0,13	0,15	0,95
ΔC	Mean Value	**1,86**	**0,77**	**0,22**	**0,44**	**0,67**	**3,39**
	Variance	0,53	0,06	0,04	0,04	0,04	1,97
	Std dev	0,73	0,25	0,20	0,19	0,20	1,40
Δh	Mean Value	**2,72**	**0,94**	**0,41**	**0,62**	**0,80**	**4,47**
	Variance	0,48	0,06	0,04	0,03	0,04	1,02
	Std dev	0,69	0,24	0,20	0,17	0,20	1,01

Table 2: mean value, variance and standard deviation of the threshold images for the ΔE2000 value and the S-ΔE2000 mean value, variance, standard deviation, median and maximum error.

The results showed that the statistical evaluation with the normal ΔE2000 colour difference and the maximum error approach do not lead to satisfiying results. The values differ to much between the patches. The evaluation with the mean value, median, standard deviation and variance statistical leads to similar results for all patches with a small standard deviation (around 0,2) and variance (around 0,04).

4.2.2.2. Measurements of colour patches with rectangular patterns varying in frequency and contrast.

An extended experiment has been conducted with the colours: cyan, red, mid-blue, light grey, and mid-green. For each colour a rectangular frequency pattern of either 4, 6 or 10 pixels was added at a contrast level of either 3, 10 or 22%. So there are 9 different patterns of contrast and frequency for each colour. In table 3, for the colour mid-blue, the median value of the colour difference of the difference image over the 9 patterns has been calculated. The values for the others colours re are not reported here, but they behave similar to the reported one.

frequency in pixels pro cycles	**contrast in %**	noise input ΔL	S-ΔE200 median	noise input ΔC	S-ΔE200 median	noise input Δh	S-ΔE200 median
4	3	0,78	1,14	8,32	0,92	4,28	1,08
6	3	0,78	1,14	8,95	0,98	4,60	1,15
10	3	0,72	1,14	8,07	0,89	4,13	1,08
4	10	0,9	1,24	9,68	1,11	4,87	1,29
6	10	0,97	1,55	10,39	1,21	5,14	1,37
10	10	0,82	1,23	8,79	1,00	4,48	1,20
4	22	1,22	2,17	11,58	1,79	5,68	2,03
6	22	1,11	2,14	11,19	1,63	5,13	1,78
10	22	0,95	1,85	10,18	1,51	5,33	1,91

Table 3: median value as statistical value of the colour difference over the pixels for mid-blue for noise input in the luminance, chroma, and hue channel for each of the 9 patterns of contrast and frequency.

For all three kind of noise, the median value of colour difference is actually increasing with increasing contrast. Namely, it is increasing to a ΔE = 1 unit count from 3% contrast to 22% contrast and remains almost constant depending on the frequency pattern (decreasing with increasing frequency, with sometimes a maximum at 6 pixels pro cycle, while the highest variation occurs for higher contrast).

5. RESULTS

The investigation of the two models is based on threshold images which all should lead to the same noise perception (in this case JND). The assumption was that a valid model which quantifies noise based on visual perception should lead to more or less the same result for all threshold images.

5.1. Visual Noise Measurement

The visual noise measurement model shows good results: the set of the threshold images were evaluated as having a similar visual noise value regardless of the kind of noise input (in the luminance, chroma or hue channel).

There are no major differences between the implementation of visual noise value formula from the CIEL*u*v*1976 or CIEL*a*b*1976 colour space. Both lead to satisfying results. The choice of the CIEL*u*v*1976 colour space can be preferred, since the visual noise formula has been implemented for the use of this colour space.

It also performs better than the signal to noise ratio quantification method: for the grey patch taken at a sensitivity of 100ISO (figure 1), the visual noise value is 2,65 and for the one taken at sensitivity of 400ISO (figure 2) the visual noise value is 3,70, despite both being evaluated with the same value when measured with the signal to noise ratio.

The limitation of the model is that it only evaluates the noise for uniform colour patches. That is why the S-CIELab model has also been investigated for quantification of noise as a colour difference.

5.2. S-CIELab Model and CIEDE2000

The S-CIELab model also quantifies noise based on visual perception and shows satisfying results. The median statistical should be used to quantify noise and to report a single number for noise in a uniform patch. A further investigation with a set of complex threshold patches varying in pattern frequency and contrast shows that the colour differences were increasing when the contrast increases, while remaining constant for the different frequency patterns.

The latter does not match the expectations, and maybe shows the limitation of the accuracy of the model to quantify colour differences in terms of noise for complex images. But it is interesting to see that investigating the colour difference of the uniform colour patches, the model achieves similar colour difference values for all threshold images.

The median value seems to be the most appropriate value in order to describe the observed visual noise. However, this may be only be valid for the present case and for the same specific Gaussian noise. For another kind of noise, another statistic value may perform better. This require further research.

5.3. Implemented algorithm of the human visual system

For both models, the quantification of noise in a visual manner is only valid for uniform colour patches. And still there are some slight variations over the quantification of noise for the threshold images: they do not get exactly the same noise quantification. This can be due to the limited accuracy of the measurements. But it can also be that the used algorithm may not perfectly describe the human visual system, which is complex and always adapting itself to the changes of its environment. There are many factors, that are still uncertain. During the investigation the two main factors seems to be the transformation matrix from the tristimlus to the opponent colour space coordinates and the contrast sensitivity function.

5.3.1. Transformation matrix form the tristimulus values to the opponent colour space coordinates.

There are different matrices proposed to transform the colour coordinates from the tristimulus values into the opponent colour space values. There is no standardised recommendation which one performs best.

5.3.2. Contrast Sensitivity Function

During the investigation, it has been observed that the use of the contrast sensitivity proposed by Fairchild[3] leads to more even results for the threshold images. But it is important to mention the following:

First, the contrast sensitivity function has not been standardized yet. As shown in different studies[14], the contrast sensitivity function changes its shape in terms of many parameters (amplitude of the wave, the wave shape (sine, square,...), object luminance, surround luminance, border condition (frame, background), observing distance, field size, direction of the gratings (vertical, horizontal...)...). So the contrast sensitivity function should be used and defined for specific parameters depending on the environment and the context.

The graph 2 show the contrast sensitivity functions (CSF) used by Fairchild[3], while the graph 3 shows the contrast sensitivity function used by Hung et al[2].

Second, how to implement the contrast sensitivity function in the algorithm is uncertain. Especially how to handle the DC-component of the fourier transform of the image is still an issue that can be discussed. The DC-component contains essentially the mean value of the image channel and, „*for simple patches, this mean value is the value of the patch itself*“[3]. Until now in both models it has been normalised to 1 at 0 cycles per degree in order to keep the main information of the image[3]. The normalisation of the DC-component to 1 may not match the actual filtering occurring. It could be suggested to apply the filtering in a different way: being in the frequency domain of the opponent colour signals (step 4), first the DC-component could be substracted, so it is set to zero. It could be then filtered with the contrast sensitivity function having an amplitude set to zero for the component zero cycles-per-degree. The DC-component could be added back afterwards.

To conclude, both models lead to similar noise values for all the threshold images with uniform colour patches and therefore performs as expected. Though it is limited to uniform colour surfaces, the algorithms used to simulate the processing of colours in the human visual system seems to be valid.

6. CONCLUSION

Two colour models have been investigated in order to quantify colour noise in a physiological manner: the visual noise measurement model and the S-CIELab model. Both are based on the simulation of the human visual system. The algorithms have been implemented in Matlab® In both cases the image is filtered in a very similar way, the analysis of the filtered images is different but leads to comparable results.

The visual noise measurement model quantifies the noise using a single value, which is the sum of the weighted standard deviations along the L*u*v* axes of the CIEL*u*v* 1976 colour space. This implicates that noise quantification can only take place for uniform colour patches.

The S-CIELab model calculates the colour difference of CIEDE2000 between a "noised" image and a "noise-free" image, which have both been processed through the algorithm of the human visual system. The colour difference represents actually the “image of the noise”, so the model should be able to quantify noise images with differently contrasted frequency patterns.

Only for the quantification of noise in uniform colour patches both models lead to satisfying results regarding the assumption made for the threshold images. There is no doubt that a better and more precise understanding of the human visual system would improve the algorithm used. Consequently, this could improve the quantification of noise matching the visual perception. However, these new approaches have been the most successful compared to the former methods used so far.

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