A Comparative Study of Color and Contrast Enhancement for Still Images and Consumer Video Applications

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Abstract

The goal of color and contrast enhancement in general is to provide a more appealing image or video by adjusting the amount of saturation and lightness to achieve more vivid or realistic colors and to increase the visibility of details that may be obscured by deficient global and local lightness. We implemented and compared the performance of various color and contrast enhancement algorithms using image difference maps in all three dimensions of lightness, chroma and hue, derived from IPT, a uniform, perceptual color space. The comparative analysis includes four published methods, two proprietary algorithms commonly used in consumer video applications and a new proposed approach developed as part of our research. Functionalities of these algorithms are evaluated with regard to the working requirements for an algorithm to be suitable for a typical video processing chain in consumer systems. We also report the results obtained from two psychophysical experiments involving the proprietary and proposed algorithms. Several still images and videos are used in the Method of Paired Comparison experiments to compare overall image/picture quality of various algorithm outputs. Results show a consistently satisfactory performance of the new algorithm, with opportunities for further improvement.

Introduction

The main objective in color and contrast enhancement in video processing is to achieve the best possible combination of colorfulness and contrast in an efficient manner. Typically, the use of independent algorithms for color and contrast enhancement results in sub-optimal enhancement, and unwieldy combined tune-up. In order to be suitable for implementation in a consumer video processing chain, an algorithm: i) must be automatic, i.e. deal with all content types without external intervention ii) should integrate color and contrast enhancement functionalities, iii) must be adaptive to the overall image or video content, iv) must improve perceived lightness and saturation while maintaining the original hue, v) should not alter achromatic and highly saturated colors or produce color artifacts (e.g. blotchiness) and vi) must be suitable for implementation in real time on the required target platform (software or hardware). The ultimate goal of such algorithms is to achieve higher perceived image or picture quality.

Most of the published color and contrast enhancement methods were originally designed for digital color images. Many of these techniques can theoretically be implemented for video as well. Even though hardware implementation issues can impose serious restrictions for some methods, these are beyond the scope of this paper. In this research, we analyzed four published image enhancement methods that are based on very different approaches. Temporal processing issues were not specifically considered at this stage of our work.

The contrast enhancement problem requires adjustment of luminance in a suitable color space without changing the hue. However, due to the fact that the useful range of saturation decreases as one moves away from the medium luminance values, upon conversion back to RGB, it is possible to end up with illegal (out of gamut) colors which are typically corrected by clipping. This causes artifacts such as bright spots, washout regions, and loss of local contrast at the end regions of the range. Yang and Rodriguez proposed a method in which the saturation of an out-of-gamut color resulting from enhancement was clipped, instead of clipping the luminance [1]. This method was implemented in LHS color space. Saturation in the input image was first increased before applying the method. Note that this method ignores the interdependence of the color dimensions, namely, lightness, saturation and hue. In a very different approach, Colantoni, Bost and Tremeau [2] developed an image enhancement method based on the chromaticity diagram. They used λSY color space for colorfulness enhancement, where the three dimensions are the dominant wavelength (λ), saturation (S) and intensity (Y). In this implementation, a fractional luminance reduction was followed by increasing the saturation component to the maximum saturation corresponding to the adjusted luminance. An important limitation of the method is a potential for hue shift because of the curvilinear nature of the constant perceived hue lines in the chromaticity diagram. In a different application context, Tao and Asari [3] proposed a nonlinear image enhancement method that involved two independent processes, namely, adaptive luminance enhancement for dynamic range compression and adaptive contrast enhancement to preserve visual details. The color restoration in the final stage described in the paper was not considered suitable for an automatic algorithm and so, was not included in this implementation. Samadani and Li [4] proposed a method for lightening or darkening of an image where colors were directly adjusted by moving them along specific lightness-saturation curves while leaving the hue unchanged. The simplified version of the method was implemented in YCC space, which assumes for each hue, the saturation is a separable function of luminance and a scale parameter. The maximum saturation point determines the shape of the curve, which is a function of luminance, and implicitly, of hue. Note that Samadani's method involves lightness adjustment, but no color enhancement.

These and many other published and patented methods reviewed as part of this research [5] do not meet the objective of enhancing color and contrast in an effective and coordinated manner. A novel algorithm proposed during this work addresses the need for a more complete color and contrast enhancement algorithm suitable for the video processing chain of consumer video systems. While the performance of the proposed algorithm is evaluated in this paper, full details cannot be disclosed due to the proprietary nature of the work.

Performance analysis of seven color and contrast enhancement algorithms

Four published methods for color and contrast enhancement were implemented to evaluate their performance as well as to determine the most appropriate enhancement strategy for the development of an integrated algorithm. Further, two existing color and contrast enhancement algorithms were provided by the research sponsor to be used as benchmarks in the development process. Thus, our performance analysis includes seven algorithms, i). **Proposed** (new algorithm developed as part of this research [5]), ii) **CH** (proprietary algorithm), iii) **Colantoni** [2], iv) **Samadani** [4], v) **Tao** [3], vi) **Yang** [1], and vii) **YO** (proprietary algorithm). The proprietary algorithms are based on traditional multi-module approach involving a cascade of methods to deal with local/global enhancement of color, contrast, and skin tone, and typical of consumer video applications. The proposed algorithm includes local and global adaptive, perceptual-based image processing designed for joint color and contrast enhancement in images and video. Implementation details of various algorithms are available in the first author's master thesis [5].

Performance analysis of various algorithms was conducted on several images on a case-by-case basis [5]. Here we chose one of those images for the discussion. This image, called *Veggies*, has several variations of color and contrast, as shown in Figure 1. While the red color of the tomatoes is the most prominent feature in the image, the broccoli, the corn and the cauliflower have significant contrast details that can be further enhanced. There is a slight yellow tinge on the cauliflower, which must not be enhanced to the extent that the cauliflower looks objectionably yellow. The gray background in the image must also remain achromatic during the enhancement process.

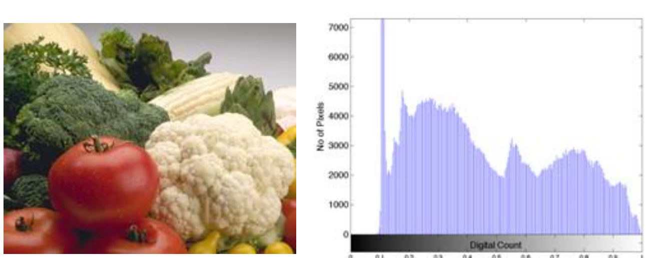

***Figure 1**. Test image Veggies and its intensity histogram*

In order to compare the performance of the algorithms in terms of perceptual attributes, the input and output image data were converted to IPT color space [6] to derive various image metrics. IPT color space was chosen since it is perceptually more uniform in terms of hue than many other color spaces, including CIELAB. While various image statistics including cumulative distribution function and intensity histogram were considered in the analysis, here we focus on the image difference maps in all three dimensions, namely, lightness (ΔJ), chroma (ΔC) and hue (Δh), computed for various algorithm outputs. Image-wise predictors of lightness (J), chroma (C) and hue (h) were computed by transforming the image data from the rectangular coordinates in the IPT space to a cylindrical coordinate system JCh [7].

From the histogram shown in Figure 1, it is evident that the input image has a good overall contrast, thus it is mostly local contrast, and not the global lightness, that needs to be enhanced. Figure 2 shows the lightness adjustment caused by different algorithms. This image difference map is indicative of global lightness adjustment as well as local contrast enhancement. Lightness differences are shown in absolute values. In each case, the 50^{th} and the 90^{th} percentile values of the lightness difference data, as well as the minimum and the maximum values are shown. In case of the proposed algorithm, 50% of the image pixels undergo a lightness reduction varying between -0.18 and zero, while for most of the other 50% pixels lightness increases only slightly, between zero and 0.2. Comparatively, lightness increases for most of the image in case of CH, as evident from the 90^{th} percentile value. Local contrast and edge enhancements are most prominent in case of the proposed algorithm, and to a lesser extent, in case of Tao's method. In our implementation of Samadani's method, the lightness was reduced to increase the perceived saturation while keeping chroma constant. Similar effect is achieved in Colantoni's method, which essentially moves colors toward the periphery of the chromaticity diagram. Lightness change in Yang's method also results from saturation enhancement.

Figure 3 shows contour maps of the chroma difference between various algorithm outputs and the original. Output of Tao's algorithm is not included in the chroma and hue difference contour maps as the implementation does not involve color enhancement. The plots include the 50^{th} and the 90^{th} percentile values of chroma difference data, as well as the minimum and the maximum values. Absolute chroma values were normalized to unity before computing ΔC. For plotting the two contour levels, 90^{th} and 95^{th} percentile ΔC values corresponding to the proposed algorithm were used in all cases. If we consider the percentile values, algorithm CH increases the chroma more than any other algorithms. The values are similar for other algorithms except for Samadani's method, which does not show significant chroma enhancement, as expected. In this case, a change in chroma mainly results from the fact that the luma and chroma channels are not completely independent, so a lightness adjustment affects the chroma channels to some extent.

The contour plots enclose the image areas where significant chroma enhancement took place. For example, chroma enhancement on the cauliflower is quite strong in case of CH. In case of CH, YO and Colantoni's algorithm, most part of the green vegetables underwent significant chroma change, while for the proposed algorithm and Yang's, it is more subtle.

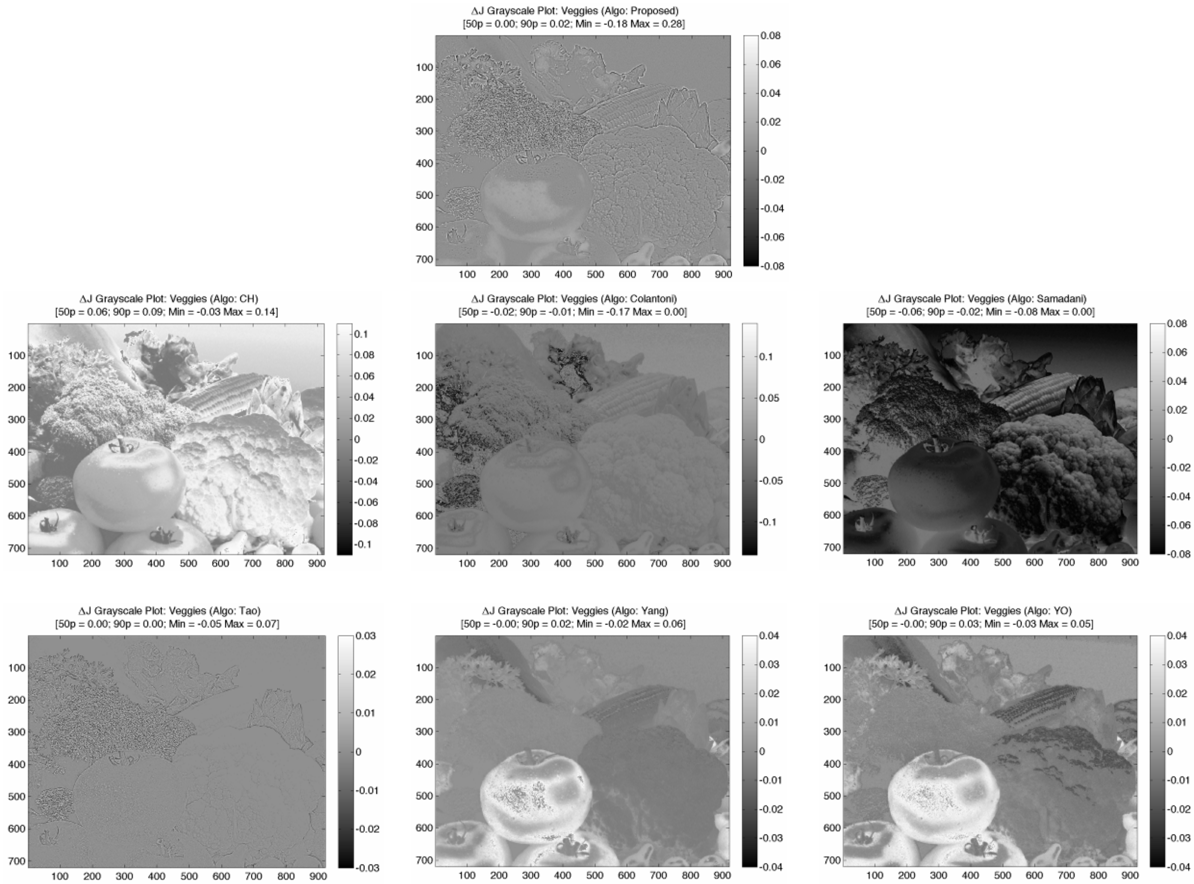

Figure 2. *Lightness difference (ΔJ) maps for different algorithm outputs*

For the contour plots of hue difference shown in Figure 4, the absolute hue differences were computed in degrees (between 0° and 360°). The hue difference map, as well as the percentiles, the minimum and the maximum values were obtained from a 5x5 low-pass filtered version of original hue difference data. The reason was to identify regions of significant hue difference and ignore individual pixel differences. It should be noted that the perceptibility of hue difference largely depends on the corresponding lightness. The same hue difference might be imperceptible for darker pixels, yet very noticeable for the lighter ones. Thus in Figure 4, the 50^{th} and the 90^{th} percentile values of hue difference are more indicative than the maximum value. Lower the percentile values, the smaller is the overall hue shift resulting from image enhancement. The hue shift is evidently less for the proposed algorithm and for Yang's method, than for CH, YO or Colantoni's method. Also, note that for the latter methods, the hue shift occurs over wide contiguous areas, both on the vegetables and on the gray background, indicating that hue shifts in these areas are real and cannot be attributed to low-pass filtering. Interestingly, in case of Samadani's method, while chroma change resulting from lightness adjustment was minimal, the hue shift is rather significant. This is possibly related to the choice of the YCC color space for processing, since this color space is not uniform in terms of perceived hue. However, a part of the hue shift occurs in darker areas of the image, so the change may not always be perceivable.

Psychophysical evaluation of three algorithms

Psychophysical experiments were performed on still images as well as on video test sequences. Many of the algorithm implementations discussed in the previous section were not integrated algorithms, focusing either on lightness adjustment, or on color enhancement, or simply contrast enhancement, but not all at the same time. Thus, it was not appropriate to include these algorithms in a single psychophysical experiment, as the end-results were very different. The experiments discussed in this paper involve only three of the seven algorithms discussed, two Intel-proprietary algorithms CH and YO, and the proposed algorithm. All three algorithms attempt to enhance both color and contrast of the input images or videos.

A 22" flat-panel Apple Cinema® LCD controlled by a PowerPC G5 Mac computer and with a maximum resolution of 2560x1600 pixels was characterized and subsequently used in all psychophysical experiments. The display white point and gamma were set to native values. A Matlab based software tool with a graphical user interface previously developed by the author was used for designing and executing the experiments as well as for analyzing the results.

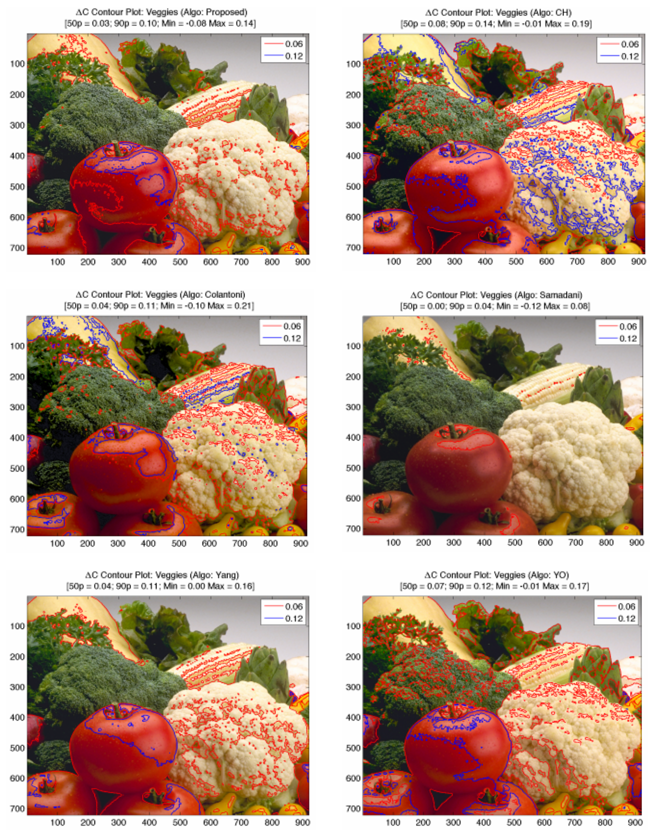

Figure 3*. Chroma difference (ΔC) contour maps for different algorithm outputs*

Fifteen still images with a resolution of 920x720 pixels were included in the first psychophysical experiment, as shown in order in Figure 5. A second psychophysical experiment was performed on four video test sequences, with 7.5-10 seconds durations and a resolution of 854x480 pixels (Figure 6). For the video experiment, individual frames had to be compressed before generating the movie clips to resolve playback issues. All images and video sequences were run through the Lookup Tables obtained from display characterization before displaying on the LCD screen. The experiments were performed in a completely dark room. The observers maintained a distance of around 30 inches from the screen. A total of 25 color normal observers participated in each psychophysical experiment involving still images and the video test sequences. While both naïve and experienced observers were included in the experiments, no observer was familiar with the algorithms or the technology variables.

The method of paired comparison was used in both experiments. The trials were presented in a unique random order chosen by the software. The relative position of the images/videos on the display screen was also randomized. In the second experiment, movie clips were played using QuickTime® player embedded in a web browser. The same pair of samples was presented only once. There were 90 observations in the first experiment and 24 in the second, requiring 20 - 30 minutes on an average in each session. The task of the observers was to select one of two images/movies displayed on the screen, based on the highest overall image/picture quality. They were instructed to ignore noise in the video experiment.

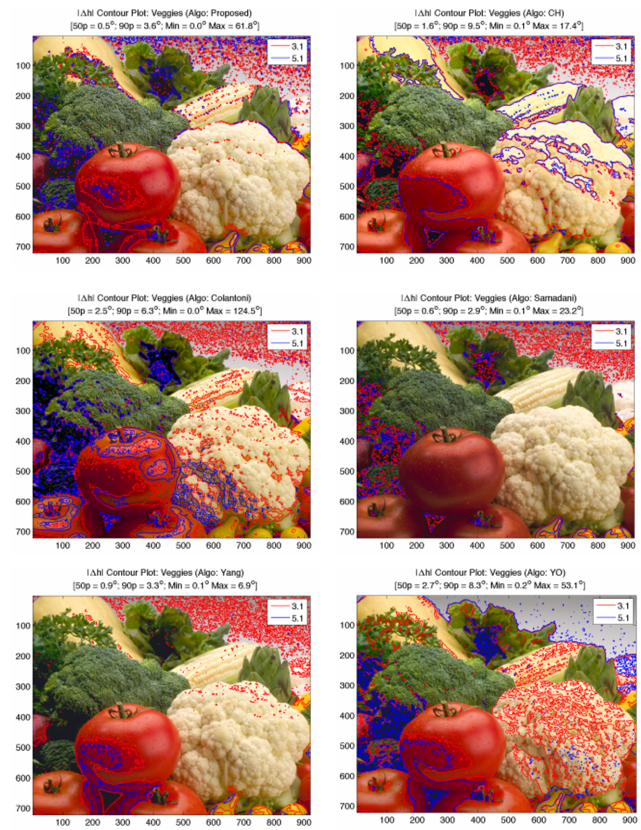

Figure 4*. Hue difference (Δh) contour maps for different algorithm outputs*

Data from complete pair wise comparisons were analyzed using Thurstone's Law of Comparative Judgment Case V [8] in order to create an interval scale of overall image preference. An analysis of the experimental data led to separate interval scales for each test image and video. Thus, there were 15 interval scales from the first experiment and 4 interval scales from the second experiment, as shown in Figure 7. Each bar corresponds to one version of the image (three algorithm outputs, or the original). Here, CH and YO are the proprietary algorithms, NA is the new algorithm and OR is the original. Evidently, not a single algorithm was preferred for all these images. For many images, difference in the interval scale values for two or more algorithms is statistically not significant. Smaller is the overlap between two error bars, the more statistically significant the corresponding interval scale difference is. As expected, the algorithm outputs were preferred over the originals for most of the test images. Note that image 7 is a low contrast version of Veggies (image 6).

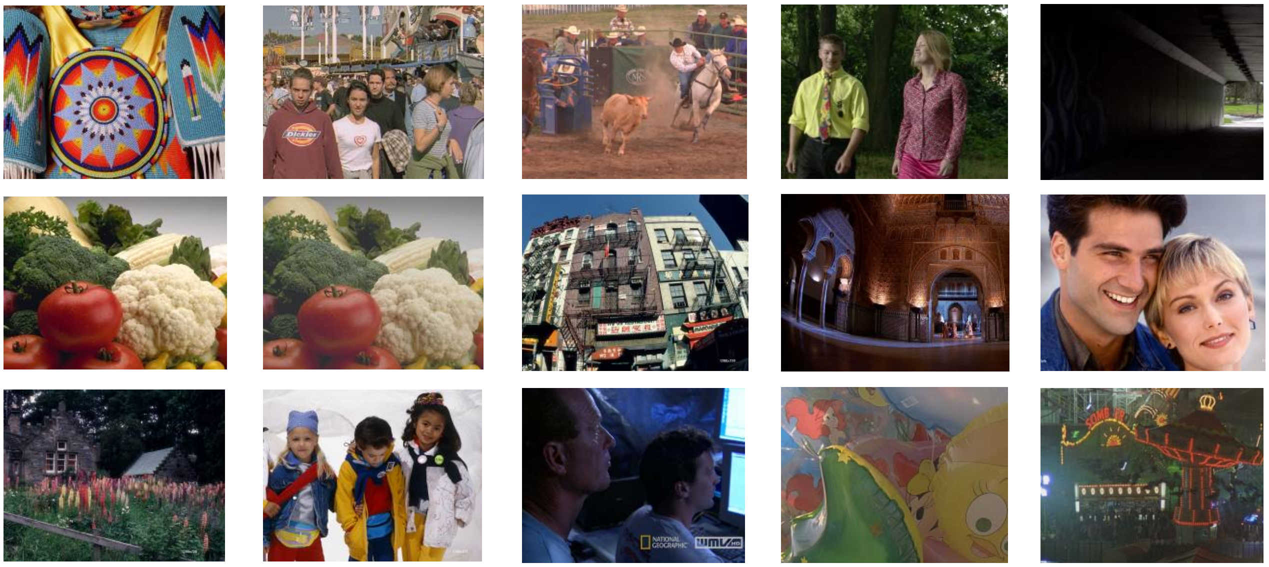

Figure 5. *Fifteen still images used in the first experiment*

Avia *Calendar* *Vintage Car* *Couple*

Figure 6. *Video test sequences used in the second experiment*

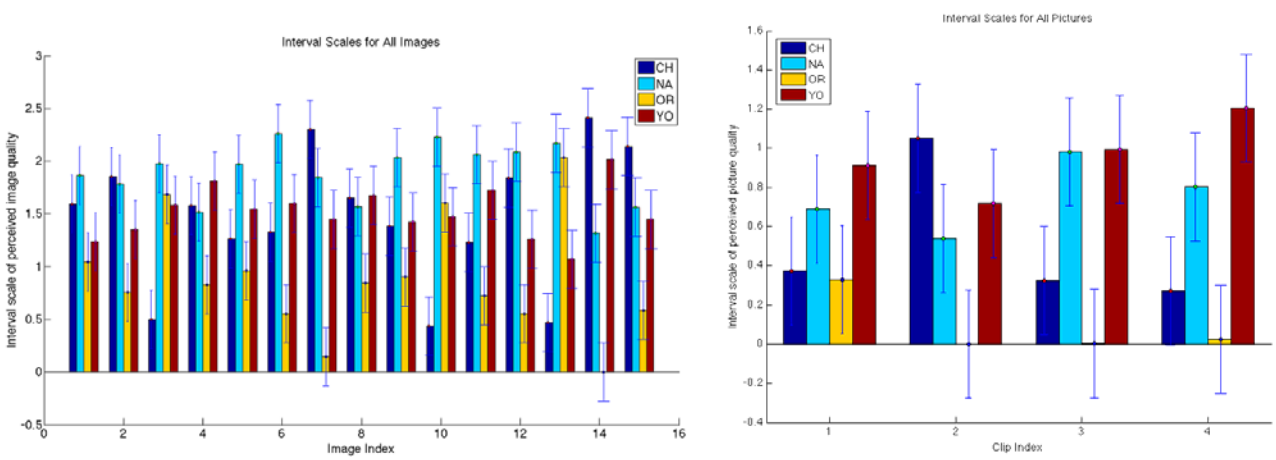

Figure 7. *Interval scale plots of the observer data from the still image experiment (left) and video experiment (right)*

Even though algorithm YO output was not ranked #1 for any image while CH output was ranked #1 thrice, the overall ratings for the two algorithms were comparable, as the performance of CH was significantly worse for several images. Enhancement by algorithm CH was perceived too strong in some cases. The bull in Rodeo (image 3), the skin tone in Faces (image 10), the men's faces in the dark room in National Geographic (image 13) –content such as these looked somewhat unnatural with strong saturation enhancement. However, CH worked better than the other algorithms when the input images were low contrast (image 7) and/or inherently noisy (image 14 and 15). Perceived noise was less after enhancement.

Overall, the new algorithm has performed consistently well. Adaptive contrast enhancement was judged favorably in most of the cases. NA ranked #1 for four test images. It performed significantly worse compared to the other algorithms only once (test images 14), as opposed to 4 and 3 times in case of CH and

YO respectively. One of the drawbacks of the new algorithm is the noise amplification in case of inherently noisy images (e.g. image 14 and 15), resulting from the contrast enhancement process. In some cases color enhancement of certain colors, for example skin tone and green vegetation, was not found optimal.

In case of the second experiment on video test sequences, the differences in the interval scales of perceived picture quality for the three algorithms are not statistically significant. Outputs of all three algorithms did better than or similar to the original. This is more obvious for algorithms NA and YO, whose performances were consistent and similar for all four clips. CH worked particularly well for the second clip (Calendar). In this case, a high boost in the saturation of low-chroma image content was judged favorably by observers. The results from this experiment did not indicate marked superiority of the new algorithm. Although no major temporal artifacts were noticed in the outputs of any of the three algorithms, it is not clear whether other confounding factors (e.g. compression blur/noise, or motion) played a role in the evaluation. A more comprehensive video quality experiment would require better resources in terms of video processing and playback capabilities.

Conclusions

The comparative performance analysis and psychophysical experiments presented in this paper demonstrate the challenges involved in designing an automatic color/contrast enhancement algorithm that will consistently produce pleasing results for various image/movie content. To summarize our research findings, following are some key aspects relevant for the development of an effective color and contrast enhancement method for images and video applications:

1. The choice of color space is critical: Image/video processing in a perceptually uniform color space helps in achieving visually pleasing results, while minimizing color artifacts and the need for additional color correction methods.
2. An ad hoc approach is detrimental: It is preferable to achieve moderate enhancement for a wide variety of image content than superior enhancement in some cases and unacceptable results in others.
3. Color attributes are interdependent: As lightness of a given color is increased, the corresponding maximum attainable saturation increases up to a certain value, then it decreases; the relationship is dependent on the hue.
4. Lightness adjustment should be globally adaptive: An input image/video that is mostly dark should be lightened to an appropriate level, while an image/video with high lightness should be darkened.
5. Color enhancement should be content dependent: Often times, a strong chroma enhancement can lead to a loss in detail, unrealistic colors, and in some cases, an out-of-gamut color (depending on the corresponding lightness and hue).
6. Contrast enhancement should be locally adaptive: A strong contrast enhancement may be objectionable in some cases (e.g. people's faces or uniform backgrounds), while in other cases it may help accentuate the details.
7. Certain colors may need special processing: Skin tone or memory colors like natural green and blue sky may need special detection and enhancement.
8. Noise should not be amplified: If noise detection and suppression module does not precede color/contrast enhancement in a video processing chain, the algorithm must incorporate noise reduction filters.

Acknowledgments

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