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Printing Image Re-Conversion Method for Adopting to Standard Dynamic Range (SDR) Images Converted from Twilight Ultra-High-Dynamic-Range (UHDR) Images

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Abstract

Printing display images normally proceeds well provided they comply with the SDR gamut supported by color management systems (CMS), like ICM used in Windows OS. Twilight vision, unfortunately, complicates this process, as it is quite difficult to convert images captured by UHDR systems given that their contrast ratios (CR) sometime exceeded 10^6:1 or so; SDR images have CR values of approx. 100:1. A typical example is the reproduction of lunar texture. Quite recently, we resolved this problem by employing just global tone mapping (GTM). Even with the use of GTM, emissive displays like LCD, not projection displays or printed matter, are strongly recommended to prevent image quality degradation. This study addresses the reasons why CMS fail to handle twilight vision material well and proposes enhanced GTM for printing emissive display images. The main point is the difference between the perception responses demonstrated in daytime and in twilight, even after the UHDR material is converted into SDR images. In other words, the key idea is to focus on the underutilized top and bottom margins of the reproduced SDR images. From another viewpoint, the most important result is the acquisition of super sensitivity. Our proposal enables high sensitivity even with the same sensor (increase is approx. 10 to 30 times).

Introduction

We start by summarizing our recent research results [1]-[3]. The well-known fact that people have quite different image preferences suggests the existence of individual differences in terms of visual perception in HDR environments.

Tone Mapping Operators (TMOs) are now being used to compress HDR into SDR images and many types of methods employing either Global- or Local- TMOs have been proposed. Current technologies assign equal importance to global- and local-TMOs, even though their basic mechanisms are quite different; the reason for this equivalence has not been adequately addressed up to now (e.g., refs. [4]-[5]).

To rectify the confusion, we first analyze the constraints of the human visual system accompanying eye movement and introduce a hypothesis and a demonstration. In conclusion, it is suggested that lightweight and switchable-predefined global TMOs, named NVPs (Normalized visual percept), part of our hypothesis, play an essential role in image compression at the first stage (i.e., alternative to real processing in the retina when viewing actual HDR scenes), resulting in the possibility of skipping subsequent local processing for image enhancement (i.e., that carried out only by the brain). A summary is shown in Fig. 1. It is also suggested, from the viewpoint of psychology, that top level perception cannot separate global from local processing results, even though the processes have diametrically different physical meaning, because our final perception is obtained after both processes are integrated for efficient scene understanding. Note that the result from the viewpoint of psychology was the same when local processing results included false or replaced information, analogous to “Where’s Wally?”. Another important result is that the concept of “dynamic range compression via global-tone-mapping” is itself a newly observed “visual illusion”, because we feel NVP-processed SDR images to be natural (i.e., perceptually true) when viewed in a room environment, if the reproduced color is locally varied (i.e., color change status is different part by part depending on luminance) from physically correct SDR images.

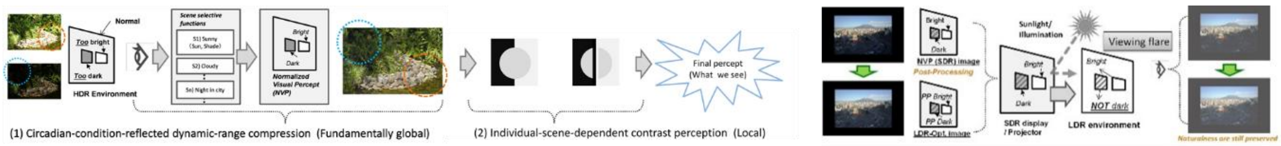
We briefly review the imperceptible illuminance effects yielded by the individual’s circadian rhythm as suggested by physiological research, because our previous study suggested that some of the characteristics of the human visual system dynamically change with the individual’s circadian pattern.

Finally, we conduct two psychophysical experiments based on the hypothesis that the human visual system employs several global TMOs at the first stage for information compression; these TMOs depend on individual-circadian-visual-features (ICVF) and other personal characteristics. The results suggest that (1) no participant could perceive actual-capture-time (ACT; i.e., this result suggests control is by reproduced luminance tone only), and (2) sensitive observers could discriminate reproduced images based on virtual-shooting-time (VST) which was induced by different types of Global-TMOs (surprisingly, they could discriminate 6 different images consecutively by utilizing only global-tones, not contents, even when given a five-choice response). We also discovered that VST-based luminance tone discrimination differed widely among people, but most were unaware of this functionality as evidenced by daily conversations. This suggests that the discrimination significantly differs with the individual, i.e., personal characteristics.

We tried to reproduce NVP (normalized visual percept) SDR images from HDR images and demonstrated some successful results in daylight. For application to various display images including printed images, characterized as low contrast environments, it is important that not only SDR but also LDR images be supported (See Fig.1 [6]).

Nighttime images are very problematic unlike daytime ones. It was found impossible to reproduce the twilight vision of humans, even though we could estimate the physically-accurate dynamic range. The bottleneck was the inability to reproduce true dark or black situations. Therefore, it was quite difficult to process SDR images, let alone LDR images [2][3].

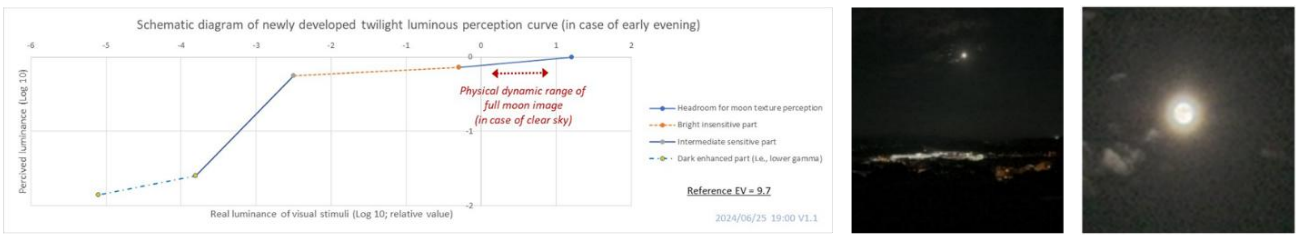
To escape this bottleneck, we had to think outside the box. The key idea was to assume that “the darkest part does not become 0, but has a finite pedestal”. In other words, the human observer perceives the darkest part as having a certain luminance.



(a) Concept of transformation from HDR scenes to normalized visual percept (NVP) in human visual system. SDR image is fairly good for recording NVP. It is assumed that human visual system executes scene dependent local processing after global processing (i.e., producing NVP) in earlier stage. Note that human observers cannot view reconstructed NVP image directly because processing is always active.

(b) Concept of transformation from SDR image (i.e., NVP recorded) to LDR image (e.g., image projected to screen or image printed on normal paper) by post-processing. Surrounding black/gray parts of images indicate minimum luminance yielded by different viewing flares.

Figure 1. *Our hypothesis of two-step human visual perception and schematic illustration of reconversion from SDR- to LDR- image.*



(a) Schematic diagram (b) Example (c) Enlarged moon

Figure 2. *Schematic diagram of visual perception in the early evening with sample reproduced image (See ref. [3]). This image is the combination of two 16-bit HDR images.*

As detailed in the next chapter, this idea made it possible to generate, for the first time, hyper realistic SDR (hSDR) /LDR images for nighttime situations.

Newly derived SDR/LDR GTM conversion curves for night

Experimental setup

A Nikon Z9 mirrorless camera was used to capture all original images. A Nikon Z-fc was also partially was used for confirmation. The images were recorded in Nikon-RAW format, which Nikon guarantees as attaining 14-bit resolution. The Nikon-RAW data were processed by "NX Studio" with a sensitivity correction of between approx. -3EV (Exposure value) and +5EV and written out as 16-bit TIFF files in sRGB space, for making conventional SDR (cSDR), for HDR-tone (HDRT) processed by Adobe Photoshop CS6, and for our proposal (hSDR).

An Epson SC-PX1V inkjet printer was employed for printing images, with ISO A4 size semi-glossy paper (KA420MSHR) or photo matte paper (KA450MM).

Difference in dynamic range between night (twilight vision) and day

Currently, we usually experience many artificial lighting situations at night, and can perceive the color of bright reflective parts and artificial lighting sources themselves even at night. However, we cannot perceive any color in darker or shadow parts. This is why we need to understand twilight vision more precisely. In addition, the features affected by the difference in MEQ (Morningness-Eveningness Questionnaire) [7], or the morning with its dim light melatonin onset (DLMO), have been the subject of many physiological and psychological studies as summarized in ref. [1].

Figure 2 shows a simplified schematic illustration of our hypothesis [3]. From daily observations, we can assume that the tone curve of darker parts is similar to TC-5 (See refs. [1]-[3]) except for exposure value. On the other hand, it can be assumed that non-saturated (non-over) exposure values of highlights should be greatly extended compared with the daylight case, because human observers can perceive the texture of the brilliant full moon (e.g., ref. [8]). The problem is understanding how the human visual system can use global tone mapping to extend just the intermediate part.

Our previous study [2][3] used reliable demonstration data to show the possibility of connecting two parts by using only global tone mapping. Another objective of our previous study was to reveal the shape of the tone curve, i.e., NVP of twilight, more precisely, reflecting its dependence on illuminance fluctuation [3]. Note that the objective in this study is not to fully reveal the relationship between visual characteristics related to individuality as evidenced by circadian preference.

In this study, the variation is simplified to one situation, i.e., normal evening, because the objective is to enable the generation of printable images.

Conventional basic idea of reproduction techniques dependent on with- or without- moon, when employing emissive displays

Figures 3 and 4 show the schematic illustrations of both cases. The normal idea is to change the conversion characteristics in the latter case. In other words, it was usually thought to be important to enhance the effective range of SDR images, which is extremely narrow compared with UHDR real night environments. Figure 5 is a schematic illustration of the latter case in sRGB 8-bit space, where minimum and maximum values are 0 (A) and 255 (C), respectively. (B) shows the boosting of darker parts to replicate human twilight vision.

New challenge in reproduction techniques, independent of moon inclusion, for printed images (on semi-glossy paper or matte paper) or LDR images

Figure 6 is a schematic illustration of the newly developed, especially sharp boosting GTM curve (B) with lower-pedestal (A) and upper-margin (C) in sRGB linear space. This was obtained by a change in perspective. Note that the shape of (B) becomes sharper

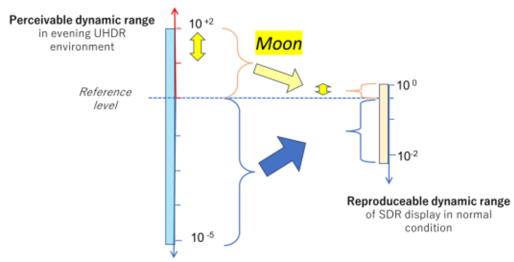


Figure 3. *Schematic illustration of dynamic range compression in case of existing moon.*

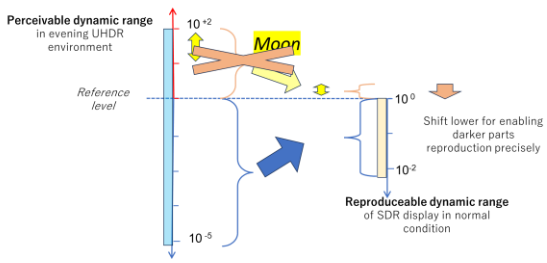


Figure 4. *Schematic illustration of dynamic range compression in case of normal scenes. Note that upper margin was truncated for enhancing effective dynamic range.*

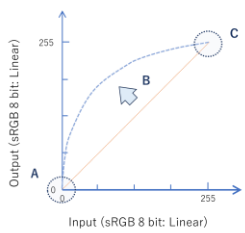


Figure 5. *Schematic illustration of GTM curve in sRGB linear space in case of previous studies [2][3].*

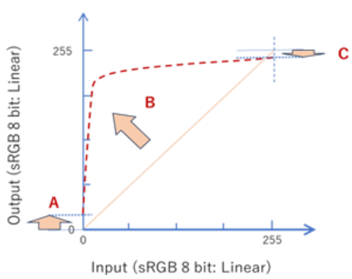


Figure 6. *Schematic illustration of newly developed especially sharp boosting GTM curve (B) with lower-pedestal (A) and upper-margin (C) in sRGB linear space. This was obtained by change of perspective.*

compared with that of Figure 5, in order to support human twilight vison perception more precisely.

Figure 7 schematically illustrates a newly developed GTM curve with lower-pedestal (A) and upper-margin (C) in logarithmic luminance space. The left-hand side shift of the developed curve (B), i.e., the same as push-process in film developing, shows the

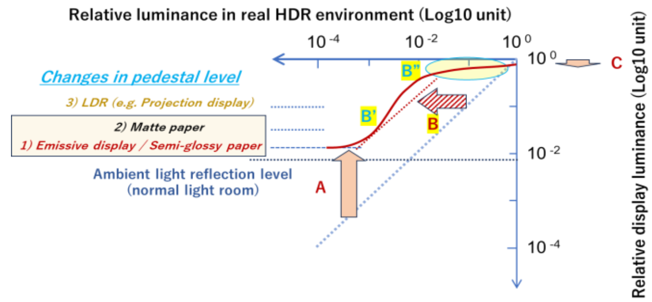


Figure 7. *Schematic illustration of newly developed GTM curve with lower-pedestal (A) and upper-margin (C) in logarithmic luminance space. The left-hand side shift of obtained curve (B), i.e., the same as push-process in film developing, shows the exposure gain by boosting.*

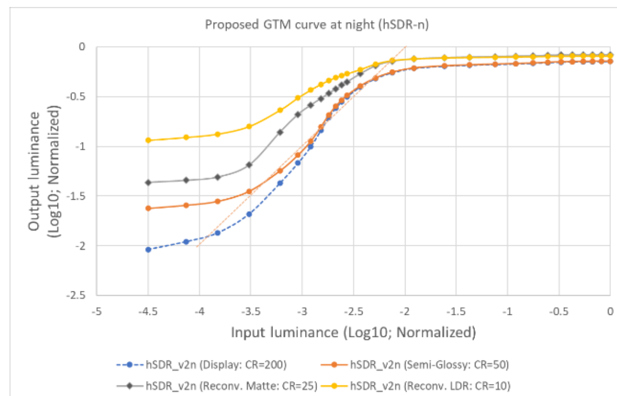


Figure 8. *Newly proposed hSDR GMT curves for night in various ambient reflection conditions (hSDR-n).*

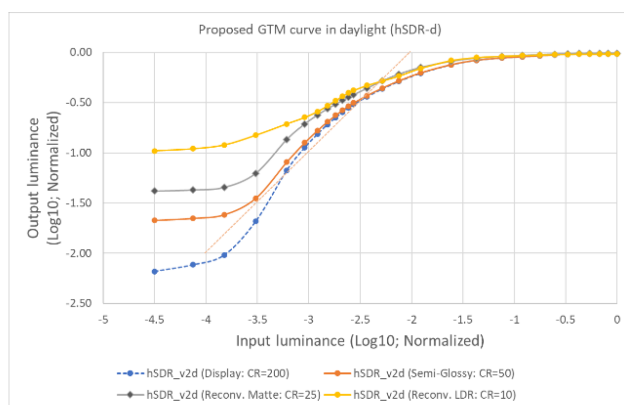


Figure 9. *Our proposed hSDR GMT curves for daylight time in various ambient reflection conditions (hSDR-d; Current version).*

exposure gain by boosting. The value of lower-pedestal (A) can be changed to suit the print materials as illustrated in the figure. The slant (B') shows contrast enhancement in darker area if $\gamma > 1$. The slant (B") shows the glare of highlight from light sources because $\gamma \ll 1$.

The quite important result is that the boosting increase was estimated to be approx. 30 times (5EV=2^5 ～ 6EV=2^6; See experimental results in Figure 12). In other words, the difference in exposure level between the original HDR image with our hSDR conversion and SDR images with proper exposure reached approx. 5 or 6 EV in these cases. Note that our proposed reconstructed images also keep the perceptual reality of highlight glare.

Newly derived GTM curves for night and comparison with those of day

Figure 8 shows the newly proposed hSDR GMT curves for night in various ambient reflection conditions (hSDR-n). Note that original curve of Display and Semi-glossy printing condition are the same reconstructed image except for the difference in actual contrast ratio in real environment. The other two curves for matte paper and LDR were re-generated from original hSDR-n (i.e., for Display and Semi-glossy printing). These curves were obtained by the first author's empirical retouching by repeatedly applying the "tone-curve" tool in Adobe Photoshop CS6.

Figure 9 also shows our proposed hSDR GMT curves for daylight time under various ambient reflection conditions (hSDR-d). Current version is simplified without consideration of the effect of circadian rhythm.

Figure 10 shows sample images of both hSDR-n and hSDR-d. Authors hope that readers of this manuscript would be satisfied with the image quality from the view point of natural perceptual tone. It is suggested that (1) brighter parts in daylight were wider than that of at night and it becomes nearly complete saturation at reference exposure level, and (2) darker level of daylight image contains enhanced detail compared with that of night image, but the pedestals remained (See also histograms).

Comparison to local tone mapping (LTM)

General features of LTM

Figure 11 shows the demonstration of difference in reproduced SDR images from HDR environment by different tone mappings [1]. Upper part of Panel (a) shows SDR images with different exposure levels. They are just for reference here. Four different SDR images show that the environment of the experimental scene was enough HDR environment because any of four images could not reproduced complete scene.

Panel (b) shows enlarged images: comparison between our proposed image reconstructed by only employing GTM and example image taken by iPhone SE2 employing LTM. Basically, you can confirm the difference in color reproduction by checking captured images of the color chart [9]. First, the reproduced tone (both perceived brightness contrast and color saturation), especially bright parts, of our proposed method was a little lower compared with the reference online image of it [9]. The reason is our perceived γ is lower than 1 [1]. On the other hand, the color saturation, especially in case of vivid colors, in iPhone SE2 image is generally higher than the online image [9], and looks like fluorescent color. Furthermore, you will be able to imagine the color differences of the other parts based on this difference.

It is clear that the reproduced image looks good if annotation was not provided. Therefore, it is considered that LTM is suitable for art pictures in some cases, rather than realistic or natural photographic images.

Special features of LTM at night

Figure 12 shows two kind of different situations for preliminary subjective evaluation of images printed on Matte paper: (a) representative of bright city (headlight glare), and (b) dark

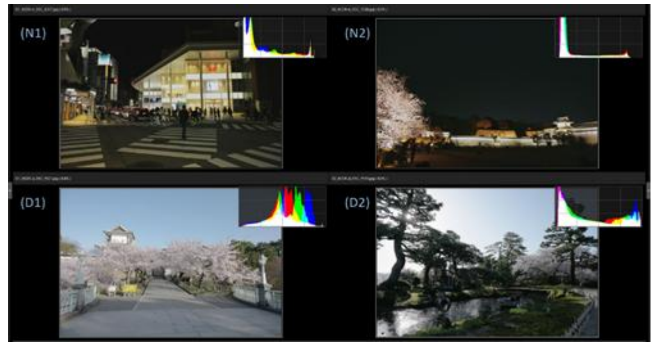
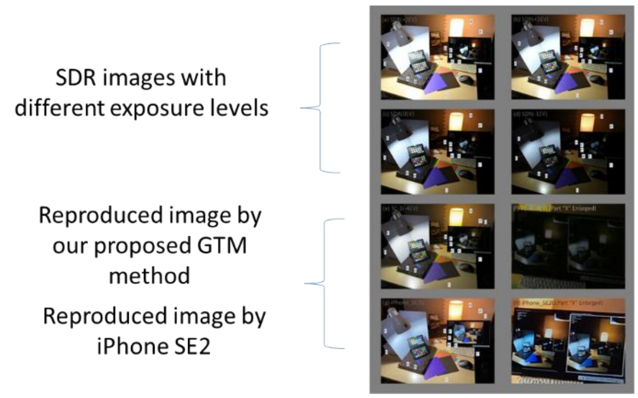
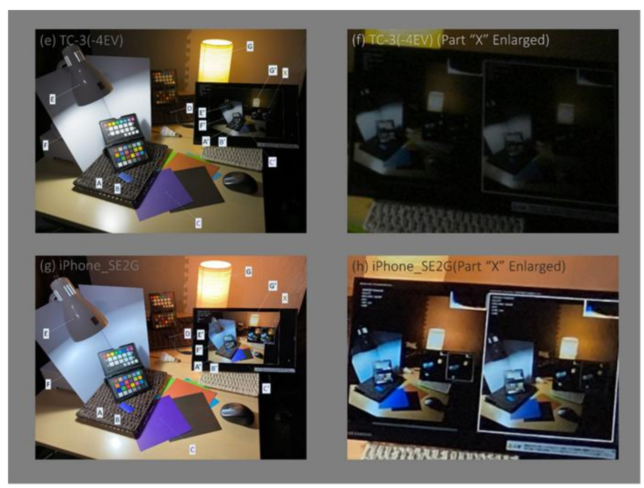


Figure 10. *Difference in actually used dynamic range between night and day.*



(a) Wole comparison



(b) Enlarged image: Comparison between our proposed image reconstructed by employing only GTM and example image taken by iPhone SE2 employing LTM.

Figure 11. *Demonstration of difference in reproduced SDR images from HDR environment by different tone mappings.*

suburb (Fireworks). A total five reconstructed images were prepared for subjective test in each scene (i.e., Proposed hSDR, SDR 1(relatively lower), SDR 2 (+1EV compared with SDR 1), HDRT 1

(a) Bright city (Headlight glare)

(b) Dark suburb (Fireworks)

Figure 12. *Images for preliminary subjective evaluation printed on Matte paper: Total five reconstructed images were tested in each scene.*

(using original HDR image same as hSDR), and HDRT 2 (over exposure)). You can find that the LTM images reproduced by employing Photoshop HDR-tone (Default setting) are highly impacted by exposure level. It is suggested that artifacts are possible in the case of LTM image processing at night including light sources.

In particular, the over saturation of dark parts yielded strange artifacts, e.g., in the case of HDRT 1, orange colored building in the upper image and the green bright rice field in the lower image. With regard to HDRT 2, the upper image is not so bad but the lower image still looks strange.

Preliminary subjective assessment

Requirement for observer

Our previous studies [2] confirmed that subjective test results strongly depended on the sensing ability of each subject. Therefore, we choose a special participant (S1) with high skill for this study. First, his major was mechanical engineering, and he was able to render real perspective scenes at a glance. Second, his peripheral vision worked well as confirmed by another experiment. Third, he was not familiar with image processing. Therefore, his judgment was expected to be less affected by the local result of image processing.

Observer's task

First, S1 was asked for his impressions of each image printed on semi-glossy paper (ISO A3 size). Then, the first author explained the real situation about perceptual tone (both brightness and color) of each part of the image. S1 was also allowed to ask for more detail if he felt his understanding was incomplete.

After that, S1 was asked to compare two images from various viewpoints (it was a dummy task). Paper size of matte paper was ISO A4, where illumination condition was approx. 750 lx, T = 4600K, with a LED lamp (Ra 93) in addition to ceiling LED lights. He was allowed to hold the material freely, where he was asked to change two images' left-right location at least once in order to avoid location artifact. Then, S1 was asked to evaluate two images by using a five-grade quality scale. This sequence was repeated ten times other than the trial. Therefore, each image yielded four evaluation results.

Experimental result

S1 gave the score of 8/10 to samples (a) and (b) when he viewed both on semi-glossy paper. Therefore, we judged our proposed method to have sufficient quality.

Figure 13 shows the subjective evaluation results of images printed on matte paper after processing by two-way ANOVA. Two-way Anova revealed the main effect depending on image in the case of HDR2. In addition, it was suggested that (1) HDR1 always yielded the lowest score with no distribution, (2) above two (i.e., ANOVA result and (1)) agree with a preliminarily discussion of the strong dependence of LTM artifacts on exposure level in the "Special features of LTM at night" section, and (3) the results for proposed method were stable and highest (all 8 scores were the same as 4 even though none attained the maximum score of 5).
Therefore, it was suggested that images printed on matte paper were of high quality.

In case of SDR image, the brighter image was judged as perceptually natural.

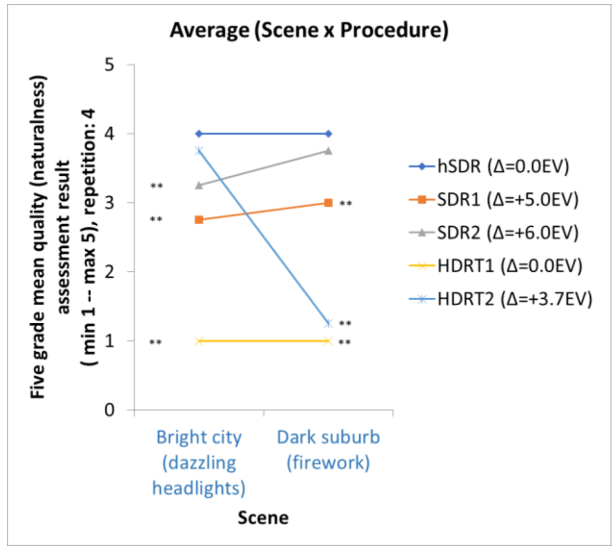


*Figure 13. Subjective evaluation result of printed image on Matte paper by employing two-way ANOVA: ** shows significant difference (p < 0.01) between proposed hSDR and other methods.*

Discussions and limitations

The main point addressed here is considering exposure level dependency of HDR-tone. One hypothesis is the difference in climate between humid Japan (strong scattering and unclear dark) and dry US (clear dark). To confirm this, we prepared images taken in San Jose in May, 2022, when the climate was very dry.

Figure 14 shows the first comparison example of reproduced tone between HDR-tone and our proposed method with different exposures. The location was the wide street in front of the San Jose convention center. Note that hSDR-n curve was employed for image (a3), whereas hSDR-d curve was employed for image (b3). The reason for this selection was the presence of strong artificial lighting. Dark parts were well reproduced in (a2). On the other hand, (a3) looks natural but somewhat dark. It is suggested that images (a2) and (a3) had both advantages and disadvantages. However, (b2) exhibited many artifacts, especially the yellow or pale orange color of street lights, see the upper right of the image, changed to highly saturated orange or red. This effect was completely different from the processed Japanese images. On the other hand, (a3), our proposed method with 8 times (+3 EV) over exposure well reproduced the true HDR with good brightening effect and less hue rotation.

Figure 15 shows another example. The location was a downtown crossing in San Jose. Both samples demonstrated a similar relationship between HDR-tone and our method.

It is clear that more precise subjective tests are needed. We may also investigate climate effects, especially humidity or PM2.5, in order to check the effects of scattering.

Conclusions and future works

We proposed a new printing method for night images. The key idea in reproducing SDR images was to utilize the top and bottom margins. Our method becomes it possible to employ a wide range of print material including semi-glossy, matte, and normal paper. From another viewpoint, the most important result was the super sensitivity offered by our method. It attains high sensitivity (10 to 30 times higher) even with the same sensor.

More precise subjective tests are needed to elucidate human visual perception at night in more detail.

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Authors also would like to thank the special subject S1 for his cooperation and giving may comments on picture quality.

Figure 14. *Comparison of reproduced tone between HDR-tone and our proposed method with different exposures (1): Wide street in front of San Jose convention center in May (i.e., air was quite dry). Note that hSDR-n curve was employed for image (a3), whereas hSDR-d curve was employed for image (b3).*

Figure 15. *Comparison of reproduced tone between HDR-tone and our proposed method with difference exposures (2): Down town crossing in San Jose in May (i.e., Air was quite dry). Note that hSDR-n curve was employed for image of (a3), whereas hSDR-d curve was employed for image of (b3).*

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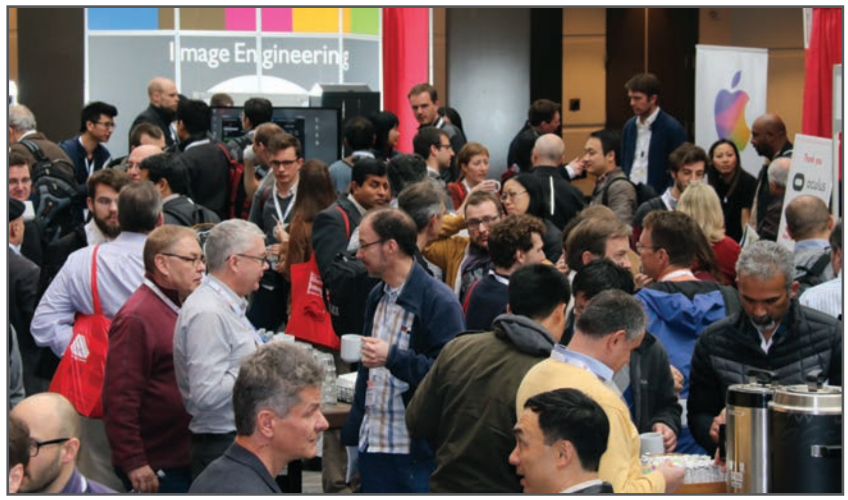

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