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Color Correction of Mars Images: A Study of Illumination Discrimination Along Solight Locus

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Abstract. *Geologists consider it crucial to work on faithful images of Mars. However, no color correction is yet done systematically on those images, especially due to the poor knowledge of the local martian weather. The weather is highly fluctuating and with the low gravity of the planet, it tends to set the conditions for varying amounts of dust in the atmosphere and ground illumination variations as well. Low discrimination of light variations by the Human Visual System is explained by Chromatic Adaptation (CA). Color images processing therefore often accounts for a step related to CA. This study investigates whether this step has to be applied to Mars images as well and is done through an illumination discrimination task performed on 15 observers for stimuli along daylight locus and solight locus (lights of Mars planet) generated through a 7-LEDs lighting system. This study gives outputs in agreement with other on daylight locus while showing low differences between results under daylight and solight.*
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1. INTRODUCTION

The surface of planet Mars has been studied for years by geologists seeking evidence of possible ancient life and to improve our understanding of crustal processes and climates variations. With this aim, Mars is steadily observed by orbiters developed by numerous space agencies worldwide: NASA, ESA, ROSCOSMOS, ISRO, UAESA, and CNSA, leading to recurring rover mission developments in order to perform closer surveys of different landing sites. *Viking* was the first spacecraft to land on Mars in 1975 and to provide color images of the planet's landscapes. The following ten years have seen the development of rover missions (able to move on the ground) such as *Sojourner* in 1996, followed by *Spirit* and *Opportunity* (Mars Exploration Rovers - MER) in 2003, *Curiosity* (Mars Science Laboratory - MSL) in 2011, and *Perseverance* in 2020, all providing images of the martian ground while visiting their landing sites surroundings. Although on Mars' surface, these rovers cannot provide an unlimited amount of scientific images. This is related to bandwidth limitations for interplanetary missions on one hand, and power availability of the rover on the other. Therefore any full-resolution image sent to Earth has to contain as much information as possible and the zone pictured has to be carefully selected for effective decision-making. In practice, this is performed through context images allowing planning for future (following days) navigation tasks toward zones of interest. In this context, it is crucial to show images that are as practical and meaningful as possible, and most of all, to ensure correct interpretations. This requirement expressed by geologists raises the need for color correction of images taken on Mars and motivates the need in investigating methods of (i) measuring the in-situ illuminant, and (ii) estimating how the Human Visual System (HVS) behaves in such an extra-terrestrial environment. This paper investigates partially the HVS using the results on the martian illuminant published in [1].

Images from cameras whose sensitivity functions are centered around 450 nm, 550 nm, and 600 nm - usually referred to as RGB cameras - may be color-corrected to become approximately colorimetric i.e. with pixel values

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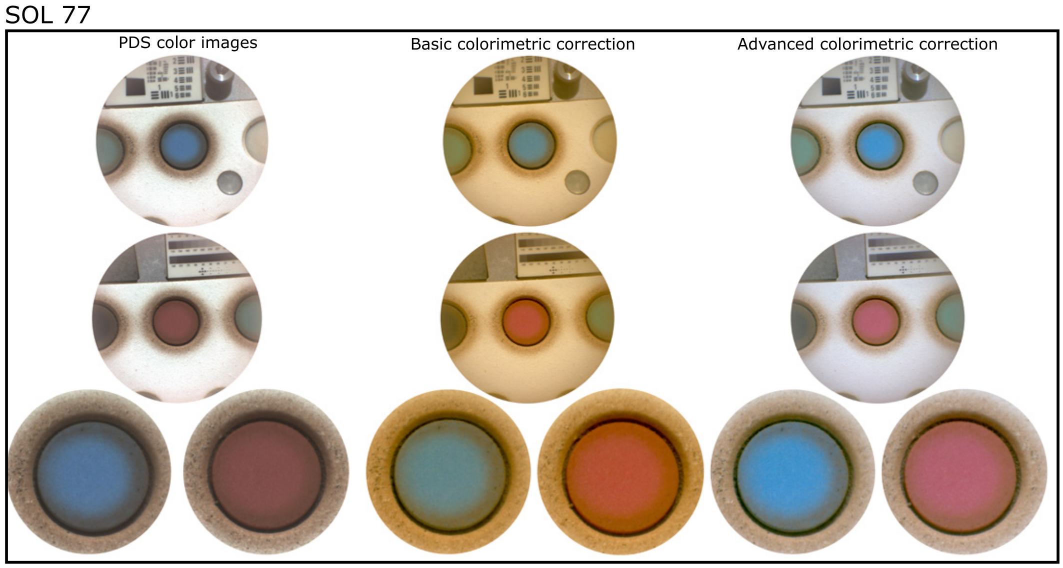

Figure 1. *Sol 77 (clear day) Planetary Data System* (PDS) color image versus *basic* and *advanced color corrected* images of the SuperCam calibration target pictured by the Remote MicroImager (RMI) onboard Perseverance rover. (PDS image reference: LRE_0077_0673772880_219ECM_N0032430SCAM07077_0050I6J01).

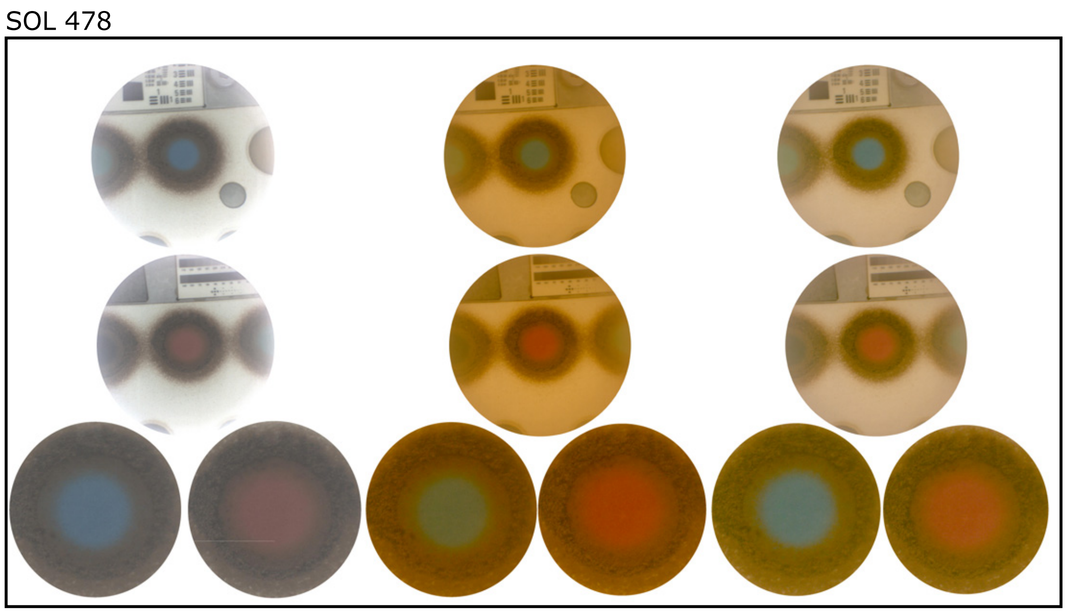

Figure 2. *Sol 478 (storm day) Planetary Data System* (PDS) color image versus *basic* and *advanced color corrected* images of the SuperCam calibration target pictured by the Remote MicroImager (RMI) onboard Perseverance rover. (PDS image reference: LRE_0478_0709372798_550ECM_N0261004SCAM08478_0010I9J01).

that are sensor-independent. Such values are expressed in a standard color space such as CIEXYZ [2] not related to the spectral sensitivities of the camera anymore, rather related to standard Color Matching Functions (CMFs) such as those of the CIE1931 observer [3]. In practice, this conversion from sensor-dependent to sensor-independent color spaces is not perfect, as the Luther-Ives condition is not fulfilled [4]. The advantage of colorimetric images is the power of comparison they offer [5]. For Mars images applications, it means any image from any camera could be compared to one another thus bringing invariant information on the colors of any object of the scenes that are imaged. Reaching colorimetric images requires an in-situ colorchecker with a large number of patches (or excellent knowledge of the camera spectral sensitivities) and the spectral power distribution of the illuminant of the scene. Then, as soon as *basic* colorimetric - as defined in [6] - values are recovered from the images, the question of displaying them occurs and so the question of *advanced* colorimetry - as defined in [6] - and in particular chromatic adaption. It has been shown through an illumination discrimination task (IDT) in [7] that discrimination of illumination changes is less

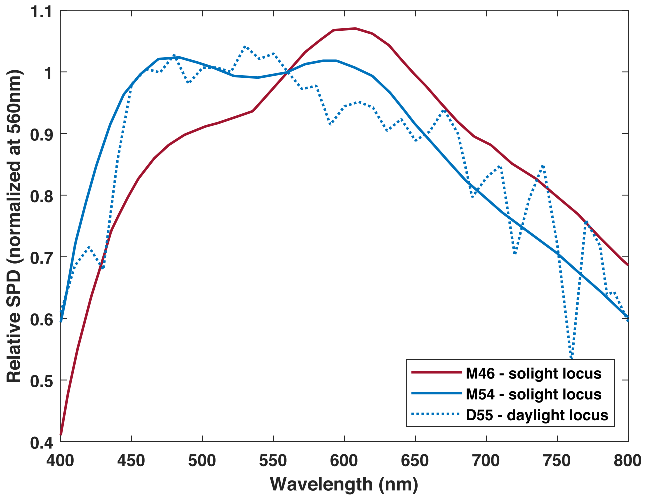

Figure 3. Relative Spectral Power Distributions (SPD) of two illuminants on the solight (Mars) locus, and one on the daylight (Earth) locus. Data are normalized for the value at 560 nm.

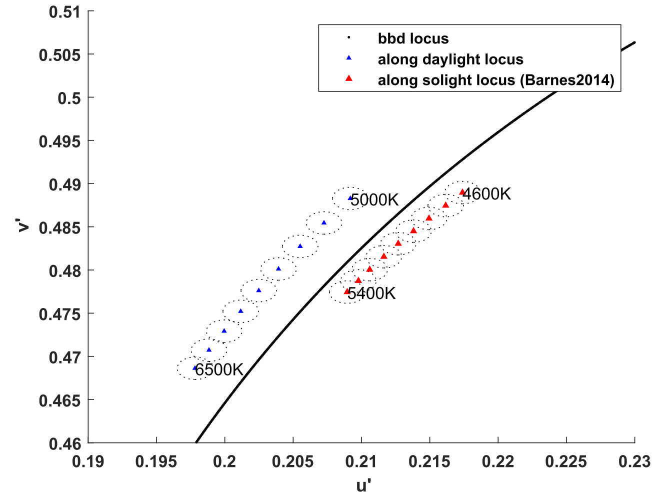

Figure 4. CIELUV chromaticity diagram showing the stimuli tested along the daylight locus (blue triangles) and along the solight locus (red triangles). The black line represents the blackbody (bdd) locus. The black dotted ellipses are the Just Noticeable chromaticity Differences (JNDs) at 50% probability (CIE TN 001:2014).

effective along the daylight locus than along an atypical locus, and in particular for bluer illumination changes. Assuming small discrimination indicates full adaptation from the HVS, while larger discrimination indicates HVS does not fully adapt, it demonstrates that surface color constancy is best for blue daylight illumination, and suggests chromatic adaptation occurs more easily for such stimuli. It brings us to wonder what insights this type of experiment could bring on chromatic adaptation on Mars.

2. MARS IMAGES COLOR CORRECTIONS

Perseverance rover carries twenty-three cameras (https://mars.nasa.gov/mars2020/spacecraft/rover/cameras/) including five on *Supercam* mast. The *Remote Micro Imager* (RMI) is one on them, and is equipped with a calibration target [8] placed at the rear of the Perseverance's deck. Figures 1 and 2 show images of two specific *sols* i.e martian days, respectively *sol 77* and *sol 478*. For each, three types of images are shown: *PDS color images* i.e as published by NASA (https://planetarydata.jpl.nasa.gov/img/data/mars2020/mars2020_imgops/data_rmi_imgops/) [9], *Basic* colorimetric images i.e without chromatic adaption performed, and *Advanced* colorimetric images i.e with chromatic adaptation (Bradford [10]) performed. *Basic* and *Advanced* terms refer to [6] concepts now CIE vocabulary [2].

The *basic* colorimetric correction is applied through a Color Correction Matrix (CCM) computed as the minimum least square regression between the X, Y, Z tristimulus values and the R,G,B pixels values. The X, Y, Z tristimulus values were computed for the CIE1931 standard observer, M54, the martian illuminant from [1], and the 24 reflectances spectrum of the ColorChecker Classic. The R, G, B raw values were computed rather than taken from the image because no ColorChecker is available in situ - aside from 3 patches shown figs. 1 and 2. The same illuminant and reflectances as X, Y, Z computation were used, with the end-to-end spectral sensitivities of the camera system. After the CCM is applied to the raw image, and though no correction for chromatic adaptation is done, the XYZ to sRGB matrix optimized for D65 standard illuminant is applied to the image. This deviation from the usual way of doing is for illustration purposes only, as chromatic adaptation for Mars is the main aspect and unknown parameter of this study. Comparing *PDS color images* and *Basic* colorimetric image on figs. 1 and 2 first shows the relative high variations in colorimetry when the weather changes on Mars. *Sol 77* is known as a clear day whereas *sol 478* was a stormy day. These weather data are not yet published but eight-year climatology of dust optical depth on Mars was studied and published [11] showing how fast the variations of dust in the atmosphere may occur and alter the optical depth and so in-situ illumination. This methodology alone, poses several difficulties when color correction has to be performed on Mars images. First, the illuminant is varying fast and its spectral power distribution is not known at all time. Second, the end-to-end spectral sensitivities of the imaging system might be partially unknown as often measured with low resolution for some parts. Third, no color target is available except for the three red, green, blue patches, known to be insufficient for color correction computation [12].

The *advanced* colorimetric correction on both Figs. 1 and 2 uses the same CCM for *basic* colorimetric correction with an additional step performing chromatic adaption "*as on earth*". A Bradford adaptation [10] is applied with D65 as adapted white. It allows the visualization of colorimetric images assuming that the HVS performs chromatic adaptation the same way under daylight and under solight. This last uncertainty is another barrier when geologists require faithful images of Mars: there is no

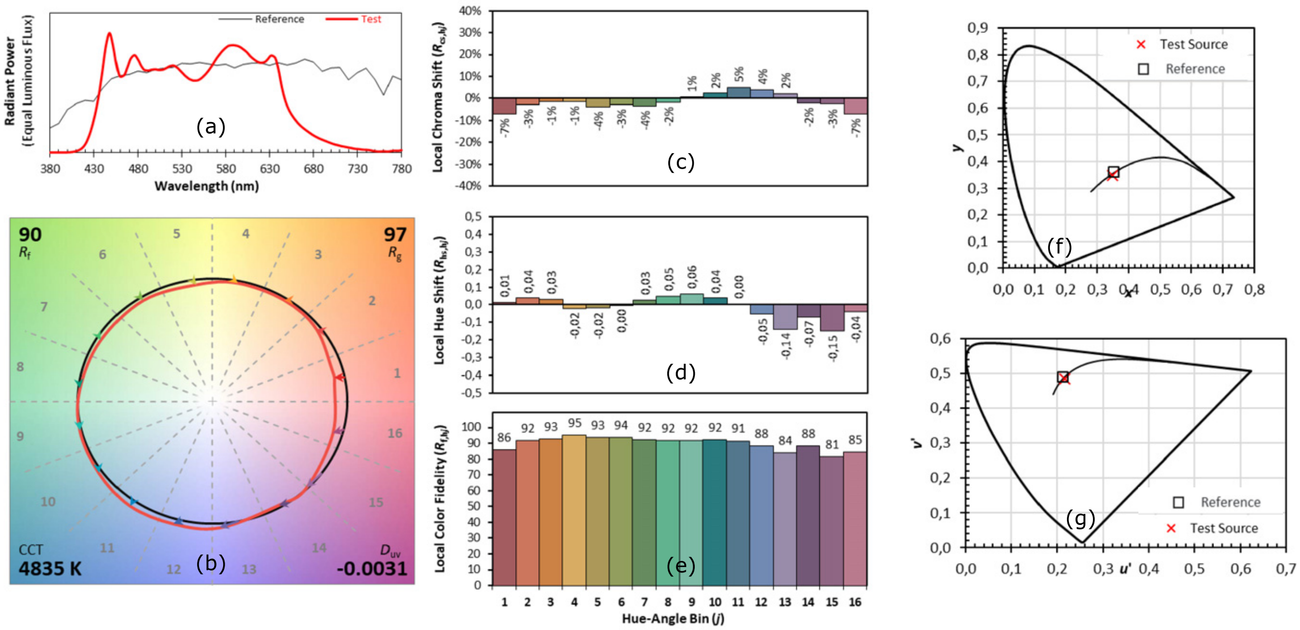

Figure 5. TM-30 plots for the Barnes 4800K CCT illuminant. "Reference" and "Test" in the figure refer to the stimulus to mimick through the multi-primaries system, and the resulting generated stimulus respectively. (a) Spectral Power Distribution of both test and reference stimuli. (b) Relative change in (a', b') between test and reference stimuli (averaged in hue bin). The red circle represents the distortion of the test stimuli compared to reference. (c) Chroma shift between test and reference for sixteen color evaluation samples. (d) Hue shift between test and reference for sixteen color evaluation samples. (e) Rf values for sixteen color evaluation samples. (f) Test and reference chromaticities in CIExy chromaticity diagram. (g) Test and reference chromaticities in CIEu'v' chromaticity diagram.

study concerning color perception on Mars. Note Bradford adaptation was applied with the same amplitude on images from *sol 77* and *sol 478*.

Figure 3 shows the D55 daylight standardized spectrum as well as two illuminants on Mars locus [1]: M46 (CCT 4600K, considerd as bad weather illuminant) and M54 (CCT 5400K, considered as clear sky illuminant). It highlights spectral differences between daylight and solight. Comparing all three types of images on Fig. 1 also shows how color-corrected images allow to better render real colors: the dust around the patches appears more *yellowish brown* (ISCC-NBS designation) as measured through multispectral radiometrically calibrated images by [13].

The aim of this study is to approach color constancy/inconstancy under Mars light compared to Earth light and therefore bring the first stone toward faithful color images for martian geologists. In this domain, the question is fundamental concerning the goal of the correction to apply: should we display Mars images in the way a human standing on Mars would see the scene, and therefore account for chromatic adaptation, or should we provide color constant images i.e with no dependency on the reflected light? An Illumination Discrimination Task (IDT) was therefore conducted. This method, first introduced by Pearce et al. [7], is approaching color constancy/inconstancy in measuring global lightning variations discrimination on a scene showing objects with invariant reflectances. The level of notice of the difference (i.e. discrimination), as a consequence of some HVS mechanisms, is described in the concept of *color appearance* and gives useful information on the occurrence or not of *chromatic adaptation* when Mars illumination is part of the viewing conditions of a scene.

3. EXPERIMENTAL CONDITIONS

Our study compares stimuli along the daylights locus to stimuli along the *solight* locus. The following four sections detail the multiprimary lighting system that is used, followed by the stimuli under study, and finally the observers who participated in the experiment.

3.1 *The Multiprimary Lighting System*

Multiprimary lighting systems allow immediate generation of customized color stimuli. The system used in this study for generating lights along the daylight locus [?] and the solight locus is composed of seven narrowband and broadband LED primaries. Each channel is addressed via an 8-bits digital signal and a very high refresh rate. Details about the system can be read in [14]. The weights to apply to each of the 7 channels are computed through a program previously developed (see [15]) based on maximizing the TM-30 Rf color fidelity scores [16]. As an improved version of the CIE Color Rendering Index (CRI - CIE 013.3-1995), TM-30 Rf score evaluates lightings through the way a set of 99 natural test samples render under it.

3.2 *The Stimuli*

Candidate Spectral Power Distributions (SPD) for potential future Mars standard illuminants were developed a decade

(a) Color Checker

(b) Rocks

Figure 6. Booth conditions. Reddish/brownish rocks are *pozzolan*, roughly simulating natural martian rocks.

ago [1] and have not been used, to our knowledge. They correspond to five different Correlated Color Temperatures (CCT): 5400K, 5200K, 5000K, 4800K, and 4600K along a locus determined in the same study and called here *solight*. These published data were interpolated in our study to use nine points on the described locus [1]. They are plotted in red in Figure 4 and listed in Table I as well as the $\Delta Eu'v'$ perceptual steps (euclidean distance) between the stimulus used as the reference for the IDT - here the point at 5400K - and the other stimuli.

Table I. Stimuli and perceptual steps ($\Delta Eu'v'$) with the references (6500K CCT on daylight, and 5400K CCT on solight).

(a) Solight locus		(b) Daylight locus	
CCT (K)	$\Delta Eu'v'$	CCT (K)	$\Delta Eu'v'$
5400	0	6500	0
5300	0.0019	6325	0.0034
5200	0.0039	6125	0.0066
5100	0.0057	5937.5	0.0097
5000	0.0076	5750	0.0126
4900	0.0094	5562.5	0.0153
4800	0.0112	5375	0.0179
4700	0.0127	5187.5	0.0204
4600	0.0143	5000	0.0227

For daylight locus, nine points were also selected equally distant (in CCT units) between 6500K and 5000K. They are plotted in blue in Fig. 4. These points are listed in Table I as well as the $\Delta Eu'v'$ perceptual steps between the stimulus used as the reference for the IDT - here, the point at 6500K - and the other stimuli. As depicted in Fig. 4 both studied loci proved to be at least one Just Noticeable Difference (JND) far from each other (black ellipses, 50% probability plotted following CIE TN 001:2014 equations) therefore confirming the motivation of comparing them.

A TM-30 analysis was done on one of the Mars illuminant displayed. Figure 5 show the results including at the top left, Spectral Power Distribution (SPD) of the analysed illuminant (4800K CCT from [1]) in black as well as, in red, the SPD of the generated light with the 7-LEDs lighting system. Fig. 5 also shows some *Rf* values related to the light generated, the mean *Rf* value over the 99 Color Evaluation Sample (CES) [16] is 90 (the higher the better, maximum is 100).

Through the multiprimary (7-LEDs) lighting system described earlier, the nine stimuli on each locus were projected into a booth whose compartment was painted with a nonselective gray of about 45% reflectance. Two conditions were selected for the booth (Figure 6): either with a Classic ColorChecker or without it. For each booth condition, the observer was asked to "*Select the test illuminant which is the closest to the reference illuminant first shown.*" The time sequence was the following: reference illuminant (either 6500K on daylight locus, or 5400K on solight locus) for 2 seconds, then the light was off for 0.4 seconds, test illuminant #1 for 1 second, light off for 0.4 seconds, and finally the test illuminant #2 for 1 second. This was intentionally the same time sequence as in [7] for comparison's sake. For each task, at least one of the two test illuminants was the same as the reference illuminant. Each task (full-time sequence 2 s–0.4 s–1 s–0.4 s–1 s) was repeated ten times randomly for statistical analysis. The total time for each observer was 40 minutes, divided into two sessions of 20 minutes: one for performing the tasks on daylight locus, the other for performing the tasks on solight locus. To avoid a bias induced

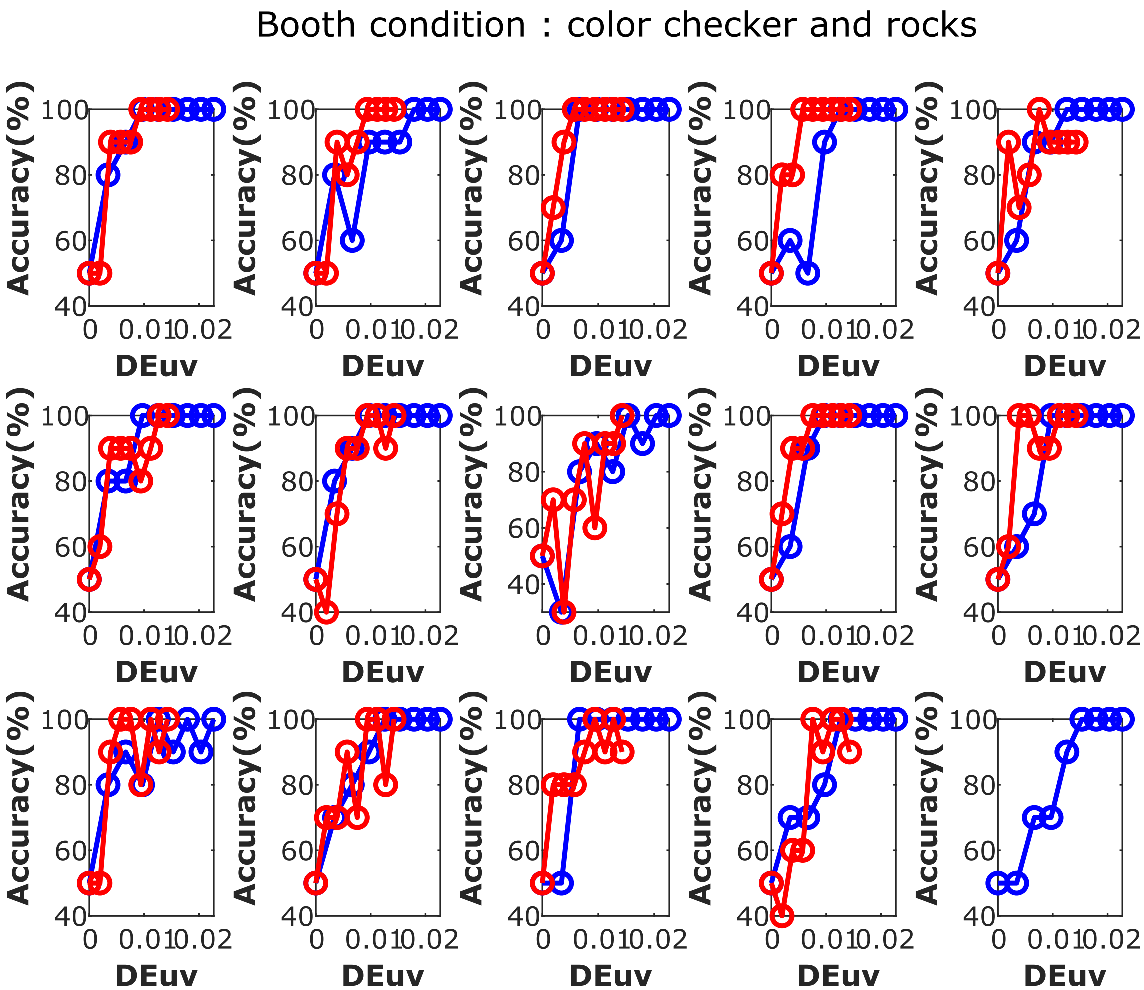

Figure 7. Individual illumination discrimination results for the booth condition: *with the ColorChecker*. Each box stands for an observer to the IDT. Blue lines refers to the IDT results along daylight locus. Red lines refers to the IDT results along solight locus.

by the order of presentation of the loci, half of the observers began with the daylight locus, and the other half began with the solight locus.

3.3 *The Observers*

Fifteen observers participated in this illumination discrimination task. Fourteen of fifteen were experts and all of them affirmed to have normal color vision. The mean age was 34 years old and ranged from 24 to 59. All participants were seated at the same distance of the booth (1 meter). The height was not adjusted so the 45° view is not held for all of them but the ColorChecker and the rocks in the booth were fixed. The observers were also asked to stare at the white patch when the ColorChecker was in the booth (Fig. 6-a), and at the center rocks otherwise (Fig. 6-b).

4. RESULTS

Figures 7 and 8 (a figure per booth condition as titled) show individual results of the illumination discrimination task i.e. the accuracy averaged on ten repetitions at each stimulus tested. Red curves are for results along *solight* locus, whereas blue curves are for results along the daylight locus. In these plots, high accuracy shows the ease of the observers to discriminate the tested illuminants, whereas low accuracy shows the difficulty of discrimination. Fig. 7 shows thirteen individual results as two observers didn't manage to perform the second part of the study. Observer #15 experienced a failure of the automatized stimuli generating system while performing the *solight*/ColorChecker task so the results were simply withdrawn as seen in Fig. 7.

Figure 9 show global results averaged over the observers with error bars. The same color coding is kept: blue lines for IDTs along daylight locus, red lines for IDTs along solight locus. Both booth conditions are differentiated by dotted lines (*with ColorChecker*) and full lines (*no ColorChecker*). Due to the low number of observers in the dataset, the standard error on the sample variance needs to be accounted for in the error bars. For a centered distribution of standard deviation σ, its value is given by $Var(Var(X)) = 2^{*}\sigma^{4} : (n-1)$ where n is the number of samples (> 0). In our case, this accounts for up to $\sim$10% of the computed value, which which could be withdrawn from the standard deviations on Fig. 9. The global (averaged over observers) results for conditions no *ColorChecker/daylight*

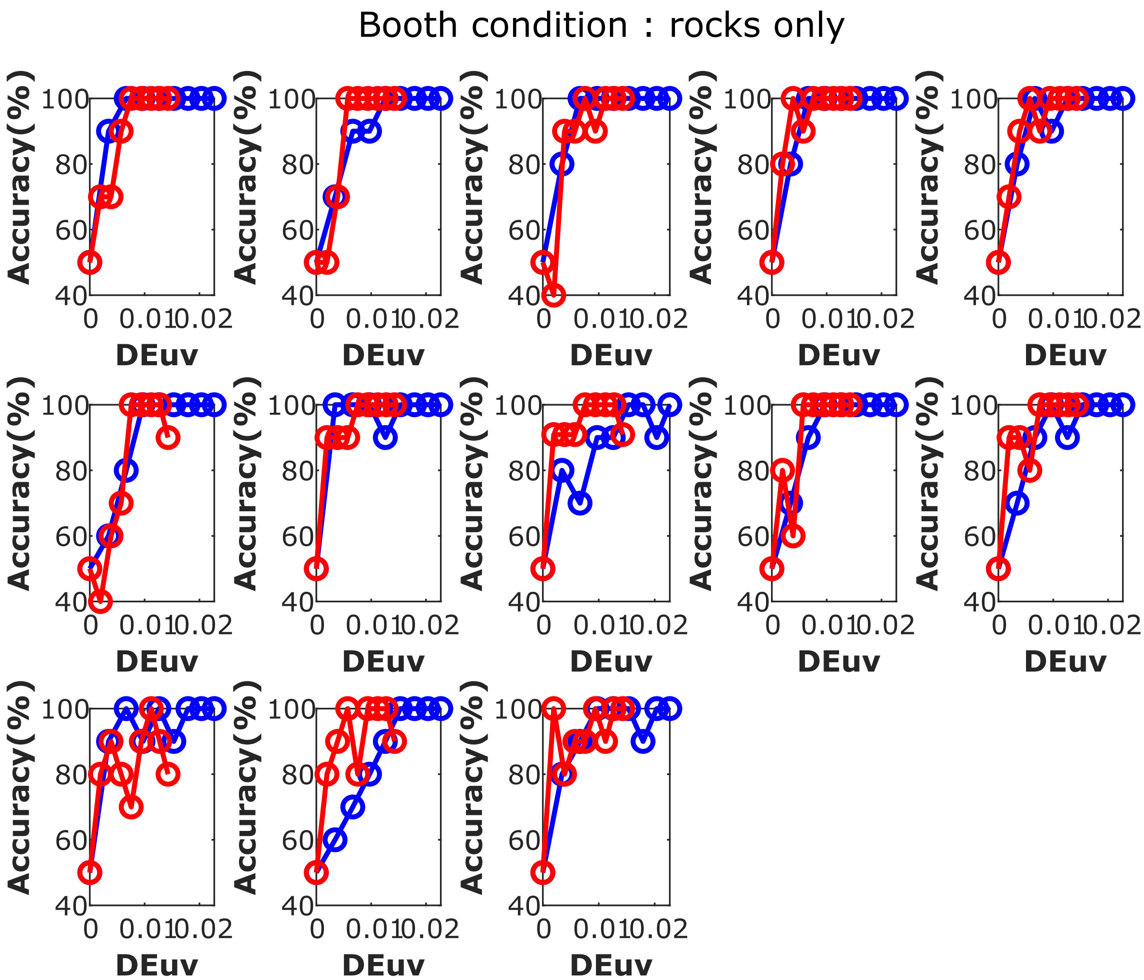

Figure 8. Individual illumination discrimination results for the booth condition: *without the ColorChecker*. Each box stands for an observer to the IDT. Blue lines refers to the IDT results along daylight locus. Red lines refers to the IDT results along solight locus.

and *ColorChecker/solight* almost perfectly overlap. The results for *no ColorChecker/solight* are slightly more accurate, while the results for *ColorChecker/daylight* show lower accuracy and therefore lower illumination discrimination ability. It conversely demonstrates that chromatic adaptation is better optimized for the *ColorChecker/daylight* condition with small adaptation difference for the solight locus tested.

5. DISCUSSION

Our results agree with [7] pointing out that the discrimination of illumination is less effective along the daylight locus than along an atypical (orthogonal) locus. They especially show that illumination discrimination variations follow the trend of the most common lights i.e. bluish, then yellowish, reddish, and finally (less common) greenish. As they demonstrate that the Human Visual System (HVS) is adapted to typical environments, our study shows that the observers didn't experience an important difference in illumination discrimination being under Earth's bluish illuminant or under Mars slightly reddish illuminant. This is true for the reduced loci used from [1] in our study. Mars illuminants used in our experiment were developed

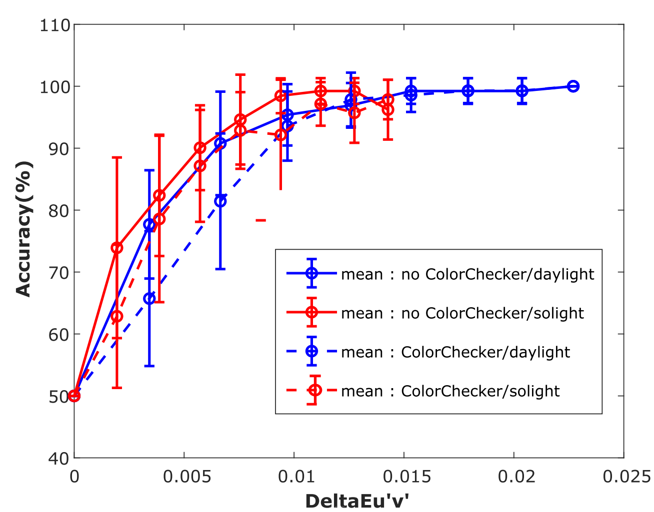

Figure 9. Averaged results of all participants. Accuracy is over the illumination discrimination tasks (nine on each locus) repeated ten times each.

from a Principal Component Analysis (PCA) based on fifty measures on Mars through radiometrically calibrated

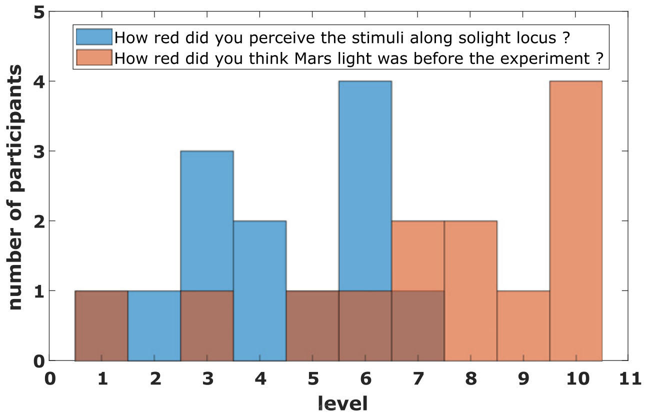

Figure 10. Results of a qualitative survey among 13 participants.

multispectral images of two rovers (*Spirit* and *Opportunity*) [1]. To stay in the range of the Mars illuminants measured data, it was decided to focus the study on a reduced locus. An extension may be considered in forthcoming investigations currently at the stage of collection of more illuminant SPDs from all RAD-calibrated images available for all rovers on Mars.

Our overall results, considering a reduced locus, demonstrate that *solight* was perceived in a similar way as *daylight*. Indeed, the observers clearly stated that the illuminant displayed as *the martian* was "less red than expected". Through a quantitative study whose results are shown in Figure 10, they were nearly 70% to answer above (strictly) 6 to the question "*Between 1 and 10, how red did you think Mars light was before you did the experiment?*". They were nearly 85% to answer below (strictly) 7 to the question "*How red did you perceive the stimuli along solight (Mars) locus ?*".

Overlapped JNDs in *solight* locus (see Fig. 4) do not look to affect the results as the first four stimuli concerned (CCT 5400K to 5100K) show accuracies higher than for the *ColorChecker/Daylight condition*.

The expertise in color sciences of most of the observers may be part of the explanation for the result observed for the *ColorChecker/Daylight* condition. The ColorChecker Classic is an object very often stared at by such scientists, making this condition even more typical. Together with the large error bars, this suggests performing the experiment with more observers and with different expertise. However a sample of fifteen observers is already larger than several other IDTs repo in the literature [7, 17].

Similar results in illumination discrimination suggest comparable HVS abilities to chromatic adaptation on Mars and on Earth. Therefore the same processes might be applied to Mars and Earth images i.e. bringing colors toward a rendering under D65 illuminant (roughly, beyond the scope of this paper). This could bring geologists closer to what they would see if standing on Mars. However, more aspects of color appearance [18] should be studied such as the impact of the chromaticity of the scene [17] as Mars landscapes show an homogeneous distribution of reflectance in the visible spectrum [19].

6. CONCLUSION

The illumination discrimination ability of the Human Visual System (HVS) proved to be optimized for typical environments in an earlier study [7]. The study conducted in this paper reports similar outcomes while showing small differences between results under daylight and solight. It suggests that some of the Mars illuminants tested here are experienced as typical by the observers as they show similar ability to discriminate illuminations along both loci. This implies, for the reduced part of the loci tested, that Mars images might be corrected from chromatic adaptation in a similar way to what is done for Earth scene images. However further data is under collection and study in order to determine the extent of the Mars illuminants; from blue sunsets to dust storms. Pending on future results on this topic, another illumination discrimination task with more non-expert observers and stimuli more sparsed on a longer loci is perhaps required. Assuming the crucial need for color-corrected images for geologists of Mars exploration missions, and taking into account the data transmission limitations in space imaging, Spectral Filter Arrays (SFA) stand as very promising solutions [20, 21].

REFERENCES

1. D. Barnes, "Mars rover colour vision: Generating the true colours of mars," *Paper presented at 12th Symposium on Advanced Space Technologies in Automation and Robotics* (United Kingdom of Great Britain and Northern Ireland, 2013).
2. Cie, "CIE 015:2018 Colorimetry, 4th Edition," Technical Report, International Commission on Illumination (CIE), (2018).
3. J. Guild and Joseph Ernest Petavel, "The colorimetric properties of the spectrum," *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character* (The Royal Society, London, 1931), Vol. 230, pp. 149–187.
4. J. Vazquez-Corral, D. Connah, and M. Bertalmó, "Perceptual color characterization of cameras," Sensors **14**, 23205–23229 (2014).
5. M. D. Fairchild, D. R. Wyble, and G. M. Johnson, "Matching image color from different cameras," Proc. SPIE **6808**, 122–131 (2008).
6. W. Günther and W. S. Stiles, *Color Science: Concepts and Methods, Quantitative Data and Formulae* (John Wiley & Sons, 2000), Vol. 40.
7. B. Pearce, S. Crichton, M. Mackiewicz, G. D. Finlayson, and A. Hurlbert, "Chromatic illumination discrimination ability reveals that human colour constancy is optimised for blue daylight illuminations," PloS One **9**, e87989 (2014).
8. J. A. Manrique, G. Lopez-Reyes, A. Cousin, F. Rull, S. Maurice, R. C. Wiens, M. Madsen, J. M. Madariaga, O. Gasnault, and J. Aramendia, *et al.* "Supercam calibration targets: Design and development", Space Sci. Rev. 216, 127 (2020).
9. O. Gasnault, C. Virmontois, S. Maurice, R. Wiens, S. Le Mouélic, P. Bernardi, O. Forni, P. Pilleri, Y. Daydou, W. Rapin, and P. Caïs, "What supercam will see: The remote micro-imager aboard perseverance," *52nd Lunar and Planetary Science Conf.* (USRA, Houston, TX, 2021).
10. G. D. Finlayson and S. Süsstrunk, "Performance of a chromatic adaptation transform based on spectral sharpening," *Proc. IS&T/SID CIC8: Eighth Color Imaging Conf.* (IS&T, Springfield, VA, 2000), pp. 49–55.
11. L. Montabone, F. Forget, E. Millour, R. J. Wilson, S. R. Lewis, B. Cantor, D. Kass, A. Kleinböhl, M. T. Lemmon, M. D. Smith, and M. J. Wolff, "Eight-year climatology of dust optical depth on Mars," Icarus **251**, 65–95 (2015).
12. A. Alsam and G. Finlayson, "Integer programming for optimal reduction of calibration targets," Color Res. Appl. **33**, 212–220 (2008).

[13] J. F. Bell, D. Savransky, and M. J. Wolff, “Chromaticity of the martian sky as observed by the mars exploration rover pancam instruments: Chromaticity of the martian sky,” J. Geophys. Res. Planets **111** (2006).

[14] Y. Yuan, M. J. Murdoch, and M. D. Fairchild, “A multiprimary lighting system for customized color stimuli,” Color Res. Appl. **47** (2021).

[15] M. J. Murdoch, “Dynamic color control in multiprimary tunable led lighting systems,” J. Soc. Inf. Disp. **27**, 570–580 (2019).

[16] Y. Ohno, A. David, K. Houser, M. Wei, M. Royer, K. Smet, and L. Whitehead, “Development of the IES method for evaluating the color rendition of light,” Optics Express, [online] (2015).

[17] A. Radonjić, B. Pearce, S. Aston, A. Krieger, H. Dubin, N. P. Cottaris, D. H. Brainard, and A. C. Hurlbert, “Illumination discrimination in real and simulated scenes,” J. Vis. **16**, 2–2 (2016).

[18] M. D. Fairchild, *Color Appearance Models* (Wiley, Hoboken, NJ, 2013).

[19] M. S. Rice, C. Seeger, J. Bell, F. Calef, M. St. Clair, A. Eng, A. A. Fraeman, C. Hughes, B. Horgan, S. Jacob, and J. Johnson, “Spectral diversity of rocks and soils in mastcam observations along the curiosity rover’s traverse in gale crater, Mars,” J. Geophys. Res.: Planets **127**, e2021JE007134 (2022).

[20] E. Cucchetti, E. Robert, A. Delahaye, M. Boutillier, C. Latry, K. Mathieu, N. Théret, and C. Virmontois, “Image quality of spectral filter arrays for planetary rover applications: From demosaicing to color correction,” *Proc. IS&T CIC30: Thirtieth Color and Imaging Conf.* (IS&T, Springfield, VA, 2022), pp. 205–212.

[21] P.-J. Lapray, X. Wang, J.-B. Thomas, and P. Gouton, “Multispectral filter arrays: Recent advances and practical implementation,” Sensors **14**, 21626–21659 (2014).