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# Effect of Polarization on RGB Imaging and Color Accuracy/Fidelity

***Tarek Abu Haila[1,2], Reimar Tausch[1], Martin Ritz[1], Pedro Santos[1], Dieter W. Fellner[1,2,3]***
***[1] Fraunhofer Institute for Computer Graphics Research IGD, Germany***
***[2] Darmstadt University of Technology, Germany***
***[3] Graz University of Technology, Austria***

## Abstract

The use of polarization while trying to keep the digital color reproduction accuracy at its finest is very challenging due to how polarization is interacting and affecting the light spectrum itself and due to the quality of the used polarization materials. Our study on RGB imaging and color reproduction's fidelity with and without polarization shows that a cross circular polarization (on a camera lens and light source) will have a major impact on how a linear grayscale, whether it has a semi-glossy or matt finishing, would be reproduced in contrast to no polarization at all. A major loss in deep black shades in the case of a semi-glossy grayscale is unmistakable. In addition to a noticeable shift in both lightness and Chroma components regardless of the grayscale's finishing but depending rather on the used color target for correction. DE00 could not paint the full picture about color fidelity despite its low conformant reported values. Whereas, a closer visual inspection of the color components separately (lightness and Chroma) reveals color reproduction problems caused by polarization.

## Introduction and background

Color perception, in human beings, can be highly subjective and influenced by many factors that range from cultural and personal experiences to genetics, beside the contextual factors of the target color [1]. The same "subjectivity" applies for any imaging system that is, usually, more affected by its electronics components and their sensitivities in the first place. In addition to the image processing happening to produce and create the final look of the image (e.g. white-balance, demosaicking, noise reduction…etc.), not to mention all the other components that are aligned in-between between the imaging sensor and the imaged object (e.g. Lenses, filters, polarizers…etc.) [2] [3]. In addition to the fact that, color is not a primary characteristic of the object itself but rather is a secondary result of the object's reflectance interaction with the spectrum of the impinging light, which makes the selection of a light source, under which an object is being viewed, of utter importance in the chain of the color perception process (e.g. check metamerism effect). All of that puts color fidelity and accuracy in question when it comes to digitization and archiving. Digitizing cultural heritage artifacts, automotive industry, painting industry and architectural designs, just to name some, are among the highly demanding fields for such color accuracy reproduction.

Cameras, unfortunately, do not satisfy *Ives-Luther* condition [4], nor any other imaging system does. In other words, a camera sensor's response (device-dependent signals) has no linear transformation that links it directly to the CIEXYZ matrix of the human color matching function. Hence, a color transformation (aka. correction) needs to be carried out in order to align the color rendition, each camera model and camera sensor show, more with the human perception.

Color management system (CMS) is, usually, proposed to use when color accuracy is sought, along the process of color correction. It can ensure, with the help of a color target, that an imaging device is color calibrated and the produced images are color corrected. However, there are in the market many varieties of color targets that ranges in sizes and number of color patches from as little as 18 patches (e.g. Kodak's), 24 (e.g. SpyderCheckr) up to 140 (e.g. X-Rite SG) or even more in some cases (e.g. calibration targets for scanners). CMS aims to move color values from the imaging device-dependent color space (RGB) to a more device-independent color space (e.g. CIEXYZ, CIELAB) as a mediate universal language between input/output devices (e.g. moving a captured image from a camera to a display). A de-facto standard is already established in the field known as the *International Color Consortium (ICC)* [5] [6].

The main focus of the current research is, to find out how much the color fidelity and accuracy are affected throughout the process of color correction under polarization while conforming with the ISO standard geometry of $0^o/45^o$ for the camera and the light source in relation to the imaged object [7] [8].

Polarization phenomenon has, since long, been known and discussed from the physics optics' perspective [9], and its impact on the light spectrum and objects' reflectance is well-known and nothing new in that. *Coulson* showed how different natural surfaces affect the degree of the light polarization differently [10]. *Robertson* discussed further how polarization in measuring instruments such as a spectrophotometer, colorimeter and such has a significant and un-negligible effect on the measurement of the color reflectance [11]. *Wolff* even offered a good insight on the different applications polarization could have opened in solving some of the computer vision problems [12]. However, in terms of color imaging (RGB) there are, unfortunately, few to no publications that offer rather an application-related quantification and visualization of the direct effect of the use of polarization on color reproduction (e.g. Chroma change/shift, broken grayscale linearity…etc.) when color accuracy is sought while doing color correction/calibration for real life applications (e.g. cultural heritage digitization). For that reason, we took upon ourselves to disseminate such kind of knowledge and make the statistics and the observations more readily available and accessible to the community in a more comprehensible way especially to those who may not have the needed expertise and the background in color science or physics but rather have different backgrounds while working very closely with colors such as many professional photographers in the cultural heritage communities who are working in digitization and archiving domains and such. We believe that having the correct understanding of some of the color science aspects helps immensely in serving the goals and the needs of those people and helps in reaching more informative decisions in their career.

## Methodology

For this research we used the following components in two different setups. We had 1) a digital camera, 2) two external white light sources (Dedolight), 3) two circular polarization films for the lights, 4) one circular polarization filter for the camera *(B+W XS-Pro HTC Polfilter KSM MRC nano)*, and finally 5) the scanned color targets that are placed on the scanned surface opposite to the camera and directly perpendicular to its normal. Lights were fixed at nearly 45° angle following by that the ISO standard setup recommendations for cultural heritage digitization (0°/45°) [13]. The only difference between the two setups are the polarization components which, in one of the setups, were mounted in front of the respective elements (light sources and the camera lens). The setups are sketched out as in Figure 1 & Figure 2.

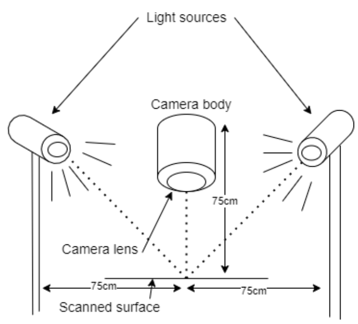


***Figure 1:*** *A Scheme of The Scanning Setup (Setup #1: Unpolarized)*

The camera, we are using is *PhaseOne iXG100MP* camera body with a 72mm lens. The light sources are Dedolight (D55). Regarding the used color targets, we used: 1) X-Rite SG (140 color patches), 2) SpyderCheckr (24 color patches) in addition to 3) (semi) gloss Munsell linear grayscale (MLG) (21 color patches) and 4) the SFR[1] target for a matt linear grayscale (20 patches).

Camera exposure was adjusted first based on a gray level patch, CIELAB(L*) ≈ 65 following by that the recommendations of the ISO standards [13] which we try to conform with as much as possible all along our workflow. Then, the color targets were captured in a raw format and processed as little as possible to preserve the actual camera raw data in order to carry out an accurate color calibration process [13]. We have converted the raw images into 16-bit tiff format while embedding either ProPhoto ICC profile or the camera profile itself depending on the used pipeline, linearizing the gamma curve and making sure that no input color profile or any form of color correction is tampering with the image data[2]. For color profiling we have implemented our own profiling pipeline that yields very comparable results to a well-known and widely-used commercial software in the market, namely *BasICColor input Pro*. Yet ours shows better statistics in most of the cases and reports lower DE00 (DeltaE2000) most of the time. Throughout this report we are making the comparison between the two methods of profiling, our pipeline and *BasICColor + CaptureOne (C1)* combination.

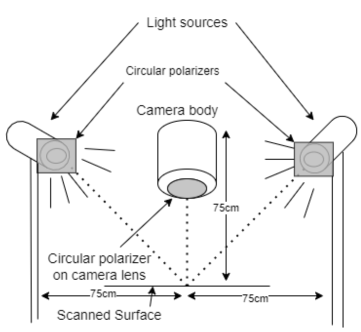


***Figure 2:*** *A Scheme of the Scanning Setup (Setup#2: Polarized)*

Our profiling pipeline, Figure 3, is described as following: after having captured the data in raw format, we convert them into 16-bit tiff using COPE converting engine from *PhaseOne* while setting the following parameters *(input profile: no color correction, output profile: ProPhoto, film curve: linear scientific).* Then, we extract the color values of each patch individually and convert them into CIELAB color space taking into consideration that D50 is the assumed illuminant. The extracted data are passed to *Argyll* to create the required ICC profile with the following parameters *('qm' quality medium, 'al' algorithm LAB cLUT, 'ua' if input profile then force absolute intent and 'R' to restrict the white, black and primary values)*[3]. Keep in mind that, in our pipeline we have skipped the step of doing WB on the raw images as it turned out that skipping it yielded better results than doing it. We noticed that WB in that case is being accounted for quite well in the process of color correction itself and better statistics overall were reported than if we did it during the conversion from raw → TIFF. On the other hand, WB was done as instructed when the other pipeline *(BasICColor+C1)* was in use to prepare raw data[2], whereas if it were to be omitted the results won't be as desired.

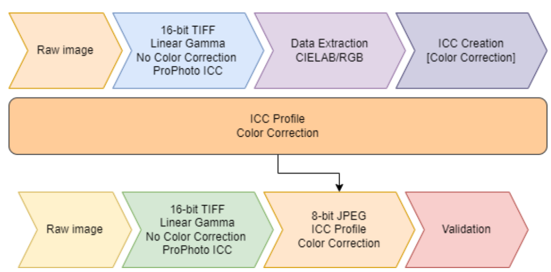


***Figure 3****: General Steps Of Our Implemented Pipeline*

After profiling, an ICC profile is generated that carries the color correction information, which is only valid and bound to the camera in-use and to the conditions under which the used images were captured. The profiling process was carried out on both color targets *(SpyderCheckr and X-Rite SG)*, then the resultant ICC profiles were applied on the other color targets. Color difference was calculated based on DE00 metric. When applying and presenting the statistics of *X-Rite SG*, only the common 24 color patches[4] were taken into consideration throughout this report except for Table 1. Table 1 shows the performance of the generated ICC profile/color correction when the ICC profile is being applied on the same input image that

[1] Slanted Edge Scanner Target with Grayscale SFR & OECF #2 – QA-62-RM.

[2] You may refer to PhaseOne Manual for more detailed steps on how to prepare your raw images for color profiling [16].

[3] The choice of the parameters was done heuristically.

[4] The common 24 color patches on X-Rite SG starts on E2 and ends by J5.

was used for generating the corresponding profile. Usually, such kind of information is not much of a value as the training and the testing datasets are identical. However, the data was used only as a first-step verification of their compliance with the ISO recommendations for the average and max values. After that, the ICC profile was applied on the other color target for validation, the results are shown in Table 2.

According to the ISO standards [14] the allowed tolerance for color reproduction is defined to be, for level A (i.e. the highest), DE00(Max) < 10 and DE00(Mean) < 4. Another recommendation concerns the weighting factor (SL)[5] of DE00 formula is to be set to unity during the color difference calculations for cultural heritage applications (SL is a weighting factor for the grayscale patches)[6] - unless it is mentioned explicitly in the report, by default weighted SL is used. ISO level B & C regarding color reproduction are defined to have DE00(Max) < 15 and DE00(Mean) < 5. What differs between the two are other factors such as ΔEab*, ΔL* among others [14]. In this report, we are limiting the study only to the main DE00 statistics.

## Results and Discussion

Table 1 presents the statistics of the generated ICC profile using the corresponding color target where it is being benchmarked against itself after color correction in the light of its ground-truth[7]. Two methods of profiling were used and listed in the following tables, one using our color management pipeline and the other is relaying totally on available commercial software that are, namely, *BasICColor Input Pro + CaptureOne (C1).* Our pipeline can generate an ICC profile almost always with less DE00 compared to what *BasICColor* could provide for the same raw image file.

Table 2 provides more practical statistics (our pipeline followed by Basiccolor+C1 pipeline separated by "/" symbole) for each of the generated ICC profile (Base-ICC) upon applying it on the other color target for both methods. We calculated the DE00 error once using the weighted SL parameter and once while setting it to unity (SL=1). It is noticeable that it is always the case that when SL=1 then DE00 gets a bit higher. In general, our pipeline seems to perform quite better than what the combination of *BasICColor + C1* could do despite the fact that in our pipeline we get a higher maximum value (outlier) than *BasICColor + C1* however we get pretty better AVG(90%) always. AVG(90%) is calculated by discarding the highest 10% of the calculated DE00 error after sorting them (i.e. discarding the outliers) and then averaging the rest.

***Table 1: DE00 Stats showing the performance of the generated ICC profile when being applied on the same color target used for profiling.***

Our Pipeline / Basiccolor+C1

| | SpyderCheckr | | X-Rite SG | |
|---|---|---|---|---|
| | Unpolarized | Polarized | Unpolarized | Polarized |
| avg | 0.51 / 1.26 | 0.67 / 1.25 | 1.06 / 1.72 | 1.22 / 2.33 |
| Max | 0.94 / 2.73 | 1.61 / 3.27 | 4.43 / 4.31 | 4.24 / 7.85 |

***Table 2: [Our Pipeline / BasICColor+C1] DE00 stats showing the validation performance of the generated ICC profile of one of the color targets when applied on the other. For SG CC the stats reflect only the common 24 patches' behavior.***

| | Weighted SL | | SL=1 | |
|---|---|---|---|---|
| | Unpolarized | Polarized | Unpolarized | Polarized |
| | X-Rite SG (Spyder base-ICC) | | | |
| avg | 2.80 / 4.10 | 4.82 / 4.77 | 2.99 / 4.51 | 5.32 / 5.25 |
| avg(90%) | 2.33 / 3.76 | 4.19 / 4.50 | 2.50 / 4.09 | 4.67 / 4.88 |
| min | 0.45 / 1.30 | 2.15 / 0.89 | 0.52 / 1.50 | 2.67 / 0.89 |
| max | 8.52 / 6.91 | 11.93 / 6.98 | 8.80 / 8.19 | 11.96 / 8.08 |
| std | 1.83 / 1.51 | 2.17 / 1.51 | 1.86 / 1.80 | 2.19 / 1.70 |
| | SpyderCheckr (SG base-ICC) | | | |
| avg | 2.63 / 3.12 | 4.64 / 4.87 | 2.78 / 3.31 | 5.17 / 5.54 |
| avg(90%) | 2.33 / 2.67 | 4.20 / 4.55 | 2.44 / 2.80 | 4.64 / 5.12 |
| min | 0.47 / 0.89 | 2.17 / 2.21 | 0.50 / 0.89 | 2.35 / 2.80 |
| max | 5.21 / 7.08 | 8.18 / 7.71 | 6.13 / 7.90 | 9.65 / 9.02 |
| std | 1.25 / 1.67 | 1.62 / 1.55 | 1.33 / 1.78 | 1.92 / 1.82 |

[5] All the stats assume weighted SL factor unless otherwise indicated.

[6] For more details about the color difference formula DE2000 please refer to [17].

[7] Ground-truth CIELAB values were measured spectrally beforehand using a Barbieri spectrophotometer LFP qb for all the used targets.

Table 2 shows acceptable results in general despite the fact that the numbers are doubling under polarization. In general, mean values are below 5 and maximums below 10 except that in our pipeline and using *SpyderCheckr* it maxes up beyond 10 and gets a mean around or a bit over 5 depending on the polarization state. All of that, in terms of numbers, may look fine and very compliant with the ISO defined thresholds. However, numbers don't tell much about the visual appearance and color perception unfortunately [15]. For that reason, we decided to have another color target to help in assessing more fundamentally the generated profiles' behavior and their ability of reproducing color neutrality and linearity in the first place. From which we may be more capable of having a better idea on how the correction visually may look like and what to expect. We used two linear grayscale targets for this task with two different finishings. Munsell Linear Grayscale (MLG) with a (semi) glossy finishing and the SFR target's grayscale with its matt finishing. Both targets consist of 20 gray patches linearly spaced (MLG has also 1 extra black patch; total 21 patches).

***Table 3: [Our Pipeline / BasICColor+C1] DE00 of munsell linear grayscale reproduction used to validate the generated ICC profiles' behavior and capability.***

MUNSELL LINEAR GRAYSCALE DE00

| | Weighted SL | | SL=1 | |
|---|---|---|---|---|
| | Unpolarized | Polarized | Unpolarized | Polarized |
| MLG (SPYDER BASE-ICC) | | | | |
| AVG | 3.26 / 2.68 | 4.09 / 4.79 | 3.46 / 3.26 | 5.45 / 6.26 |
| AVG(90%) | 2.53 / 2.53 | 3.24 / 3.95 | 2.71 / 3.06 | 3.96 / 4.80 |
| MIN | 0.57 / 1.24 | 1.08 / 1.67 | 0.57 / 1.25 | 1.10 / 2.40 |
| MAX | 8.16 / 3.64 | 9.88 / 10.66 | 8.44 / 4.93 | 15.53 / 16.25 |
| STD | 2.37 / 0.74 | 2.49 / 2.48 | 2.42 / 1.02 | 4.11 / 4.06 |
| MLG (SG BASE-ICC) | | | | |
| AVG | 2.25 / 1.74 | 2.94 / 2.15 | 2.46 / 1.92 | 3.40 / 2.61 |
| AVG(90%) | 1.94 / 1.52 | 2.29 / 1.63 | 2.10 / 1.64 | 2.46 / 1.80 |
| MIN | 0.60 / 0.44 | 0.54 / 0.65 | 0.60 / 0.44 | 0.54 / 0.65 |
| MAX | 4.32 / 3.42 | 7.89 / 6.16 | 4.94 / 4.04 | 10.45 / 8.79 |
| STD | 1.09 / 0.76 | 2.06 / 1.58 | 1.24 / 0.93 | 2.80 / 2.39 |

***Table 4: [Our Pipeline / BasICColor+C1] DE00 of SFR linear grayscale reproduction used to validate the generated ICC profiles' behavior and capability.***

SFR LINEAR GRAYSCALE DE00

| | Weighted SL | | SL=1 | |
|---|---|---|---|---|
| | Unpolarized | Polarized | Unpolarized | Polarized |
| SFR (SPYDER BASE-ICC) | | | | |
| AVG | 2.52 / 3.60 | 2.09 / 4.57 | 2.66 / 4.26 | 4.98 / 5.18 |
| AVG(90%) | 2.25 / 3.23 | 1.71 / 4.19 | 2.38 / 3.90 | 4.50 / 4.68 |
| MIN | 1.66 / 2.12 | 0.18 / 1.59 | 1.73 / 2.18 | 2.25 / 1.73 |
| MAX | 5.21 / 6.22 | 6.97 / 7.38 | 5.51 / 6.92 | 8.30 / 9.00 |
| STD | 0.88 / 1.21 | 1.32 / 1.48 | 0.93 / 1.38 | 1.75 / 1.88 |
| SFR (SG BASE-ICC) | | | | |
| AVG | 2.80 / 2.45 | 2.34 / 2.04 | 3.00 / 2.65 | 2.87 / 2.31 |
| AVG(90%) | 2.50 / 2.16 | 1.93 / 1.64 | 2.68 / 2.36 | 2.39 / 1.80 |
| MIN | 0.40 / 0.95 | 0.84 / 0.29 | 0.46 / 1.04 | 1.35 / 0.29 |
| MAX | 5.36 / 4.54 | 7.30 / 5.90 | 5.78 / 4.57 | 7.81 / 8.27 |
| STD | 1.12 / 1.00 | 1.39 / 1.44 | 1.16 / 1.04 | 1.53 / 1.84 |

Table 3 and Table 4 show the performance of the generated ICC profiles (Base-ICC) using our pipeline / *BasICColor + C1* when applied on MLG and the SFR targets respectively. In case of MLG, SpyderCheckr24 shows very high error with a max close to 10 under polarization and it maxes up to nearly 16.0 if SL=1. *BasICColor + C1* look to have quite better max values when unpolarized SpyderCheckr is used as a base-ICC in comparison with ours. These numbers get much milder when X-Rite SG was used, instead, as a base-ICC. Looking at the AVG(90%) shows clearly that the behavior of all the used ICC profiles is ok (SG base-ICC performs clearly better) except for the outliers they all have which are reflected in the max values that may cause big color shift as a consequence which is also more accentuated under polarization.

To rule out or better understand the role of the finishing of the used target, we repeated the same experiment and checked the statistics however this time on the SFR target as it has a matt finishing unlike MLG. Table 4 shows the color difference (DE00) in a similar fashion to the previous table. Our pipeline yields better results when SpyderCheckr is used. When SG is, rather, in-use the differences between the two pipelines are minor whereas in the former case the differences are a bit more considerable.

Despite all these statistics, we still think that there is something missing to paint the picture fully and understand the ICC profile behavior better. The afore-presented statistics reflect the overall behavior of the ICC profile when all its components are taken into account altogether holistically. However, we think it is better if we can separate between the profile Chroma and the lightness to distinguish their individual impact. Only then, one can better understand how much compromise in the Chroma and in the lightness reproduction one is making when putting a certain ICC profile into action. Shift in Chroma could be observed more readily than changes in lightness while, of course, one would desire no shift to occur in either.

## Lightness, Chroma And Polarization[8]

We try to split the color components and convert them into CIECLh color space (derived from CIELAB) so that it is easier to visualize and understand what is happening to the lightness and the Chroma components separately. Looking at the lightness component in Figure 4 and Figure 5[9] of MLG and the SFR targets respectively two observations come to light. In both cases whether applying the color correction on a matt or (semi) glossy grayscale finishing the SpyderCheckr does seem to increase the lightness level noticeably especially when polarized which will result in colors having a washed-out look upon correction (i.e. colors gaining more lightness). Observing MLG reproduction in specific, one notices that it is never the case that the lowest part of the curve matches or comes even close to the ground-truth which corresponds to the first few deep black patches, the lowest corrected value is always starting way above its ground-truth counterpart (i.e. actual black is becoming less black in comparison, it is gaining more lightness into it), in addition to the fact that these first few black patches are getting all flat hence no distinction would be observable anymore on the final corrected image among them (i.e. lost information/losing shades).

Moving to observe the Chroma shift behavior CIELCh(Ch) that is illustrated in Figure 6 and Figure 7 for MLG and the SFR targets respectively, we notice that despite the aforementioned statistics, we can observe now how each ICC profile is influencing and affecting the grayscale reproduction and breaking its “assumed” neutrality. We notice how each of the two methods (our pipeline and *BasICColor + C1*) tend to shift the Chroma in different directions across the hue circle and there seems to be no general trend here. For instance, correcting for a matt grayscale (SFR target), our pipeline shows a Chroma shift rather toward the yellow region regardless of the used color target for most of the points. On the other hand, *BasICColor + C1* pipeline tends to let the Chroma shift populates only the left-half of the hue circle. In case of SpyderCheckr, for instance, the Chroma shift is a bit messy spreading over the blueish/greenish gray till reaching the yellowish gray while in case of X-Rite SG the Chroma shift concentrates more in the yellow/greenish region. Looking at MLG, *BasICColor + C1* pipeline, again, shows that the Chroma shift is dominating only the left-half of the hue circle, in case of SpyderCheckr the shift concentrates near the greenish gray region while in case of X-Rite SG the Chroma shift tends to spread out more with few outliers that go deep in the cyan region and the greenish/yellowish region. Our pipeline correction shows more outliers in case of X-Rite SG that go deep in the blue/cyan region as well as in the deep green when polarized, while in case of SpyderCheckr the outliers shrink to only one or two points that go deep in the green region. Apart from that, most of the points tend to concentrate near the center however in different gray directions.

All in all, regardless of the used method or software and regardless of the finishing of the used target (matt vs. (semi) glossy) and the number of the color patches it contains whether it is only 24 or 140, Chroma shift seems to be inevitable consequence of the color correction process and polarization could accentuate the effect to make it more dire. It may not carry any significance to some people in certain domains as the shift, in some cases, minimal and unobservable while affecting only certain shades. However, it is something that would raise big concerns among the cultural heritage folks in their attempts to preserve historical artifacts in a digital format with little to no alteration in surface color to the possible extent. One needs at least to be aware of the color changes that are inflicting the digital replica especially when such replica may be an asset of a virtual museum or if the digital replica were to be used for research and analysis purposes (e.g. think of digitizing Rembrandt’s The Night Watch).

[8] Figures for this section are provided in the annex.

[9] The stats for SFR target start at point #2. 21 point measurements were taken including the central gray tile on the target (#1) but was discarded later as it is not relevant to the linear sequence of the gray patches.

## Conclusion

We have, in this paper, demonstrated and showed the statistics of two different pipelines, one fully commercial while the other we have implemented using different open-source tools for color profiling. We have put two common color targets under the test to generate accordingly the corresponding ICC profiles with and without cross-polarization in place with geometry 0˚/45˚. In addition to applying the generated ICC profiles on a different color target, we have applied them as well on two different grayscale targets (MLG and the SFR) that have two different finishings. We have shown with numbers how the reported error in terms of color difference (DE00) is always increasing when polarization is in-use in contrast to no polarization regardless of the used color target and number of color patches. We have shown, as well, how much Chroma shift is being introduced regardless of the target in-use and the polarization state. Lightness reproduction regardless of the target proved to be highly affected and would have undesired/irreversible effects on the deep levels of blacks/grays when a (semi) glossy target is being used (e.g. MLG) given the nature of how polarization interacts with such sort of materials. Polarization is breaking deep black levels linearity making multiple deep black values rather flat, hence losing shading nuances. In addition to the fact that when SpyderCheckr is used for correction the whole grayscale linearity reproduction shifts higher in lightness but only when polarization is in place regardless of the grayscale finishing, which would lead to undesired washed-out/drab colors when this kind of ICC profile would be put in-use (corrected colors will be prone to lose their luster). The color neutrality correction of either of the grayscales regardless of the situation and the used color target does not seem to be guaranteed, a color tint / Chroma shift is very likely to be introduced nevertheless, rendering the grayscale not to be neutral anymore (greenish/yellowish hue tint could be observable on some gray patches). We advise to be more careful when reading color correction stats and try to look at the correction rather visually to assess the correction acceptability and suitability to the intended application. Numbers may be as low as desired on average however they would not paint the full picture clearly on how the color correction would be perceived. Another point to take into consideration is polarization. It may be indispensable to certain applications the use of polarization, however one needs to pay more attention to what could happen to the deep black/gray levels that seem to be highly affected and losing their linearity when the surface finishing interacts strongly with polarization (e.g. glossy surfaces). In addition to that, certain gray levels may transform their Chroma into more greenish/cinder shades (or other shades depending on the polarizer's quality) and one must be aware of that when rendering a scanned digital object.

The type and the quality of the polarizer in-use are also in question. Our future experiments would include the assessment of a wider set of high-quality polarizers that are popular among professional photographers and already in the market to study the Chroma/lightness shift more systematically and under the light of the desired accuracy and fidelity when digitizing cultural heritage artefacts. In addition to our intention to carry out a more comprehensible analysis on what is happening in actuality to the light wavelengths and how they are being affected by different types of polarization to cause such Chroma/lightness shift using spectral measurements as a next step.

## Acknowledgment

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# Annex

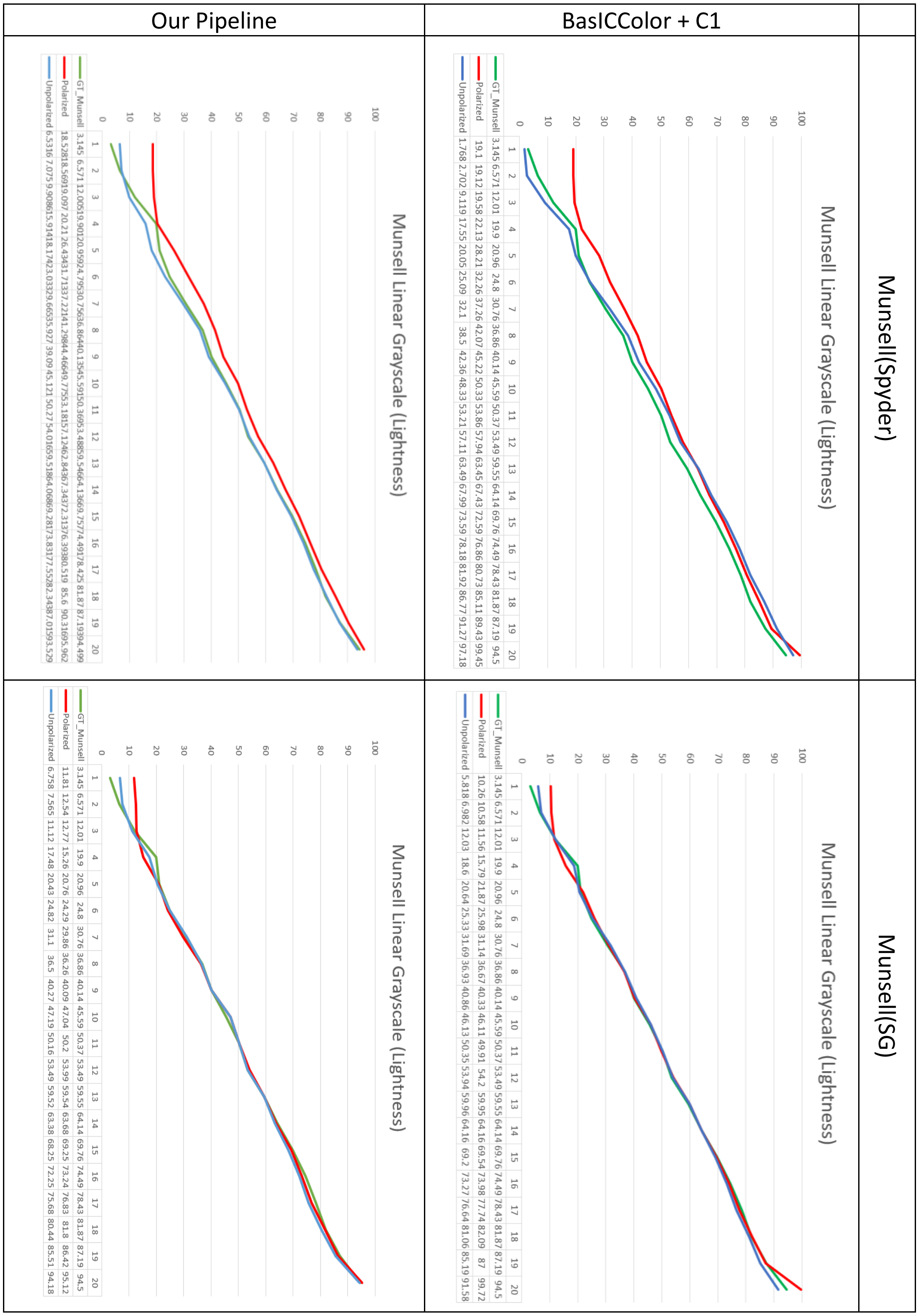



***Figure 4:*** *Munsell linear grayscale lightness CIELAB(L*) reproduction upon applying the generated ICC profile of the corresponding color target indicated inside the parentheses. Ground-truth (green), polarized (red) and unpolarized (blue).*

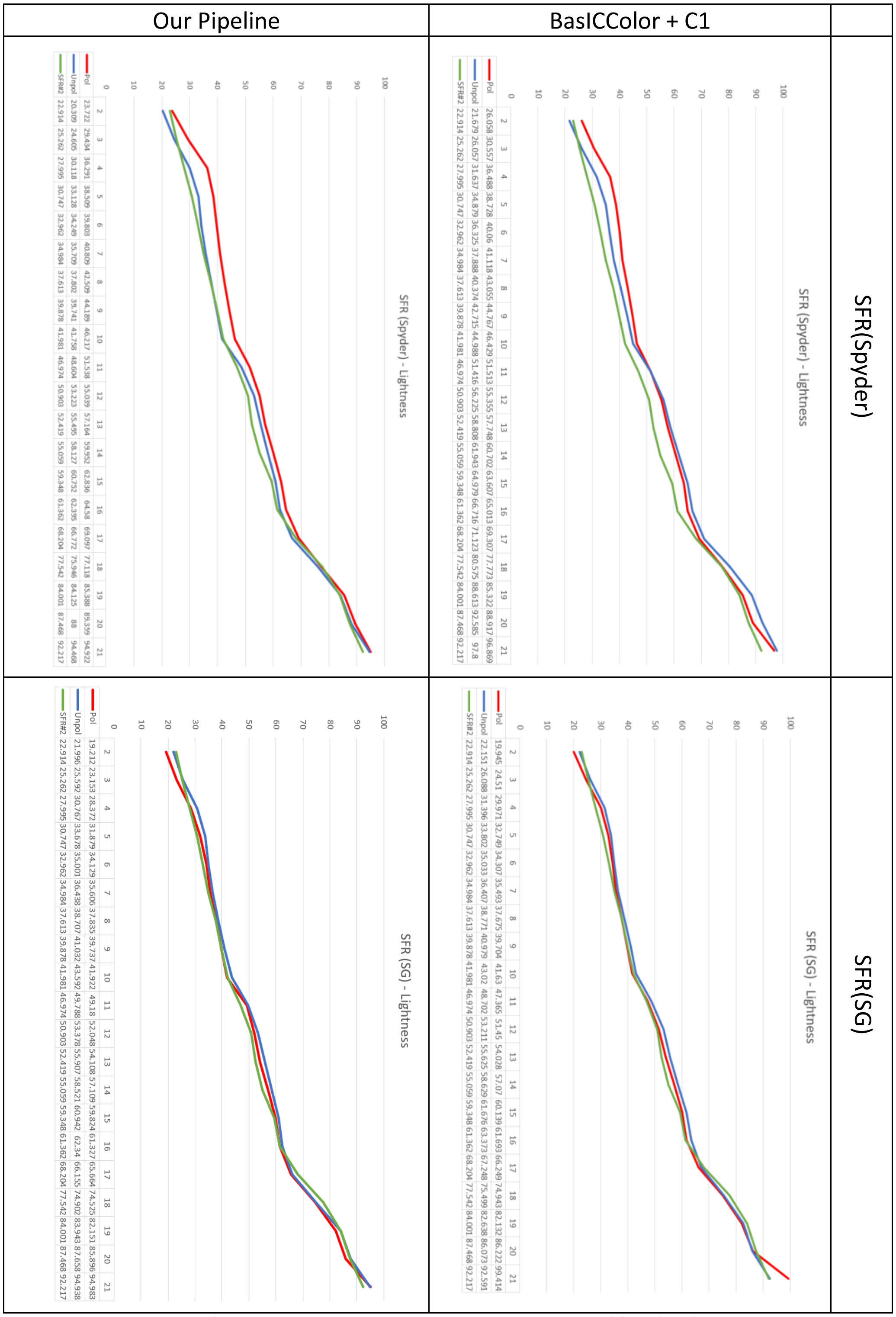



***Figure 5**: SFR linear grayscale lightness CIELAB(L*) reproduction upon applying the generated ICC profile of the corresponding color target indicated inside the parentheses. Ground-truth (green), polarized (red) and unpolarized (blue).*

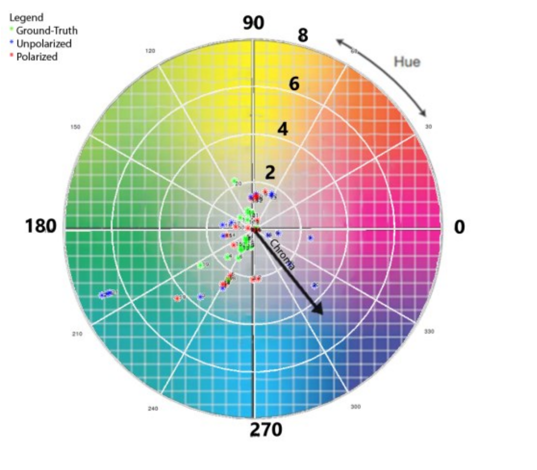
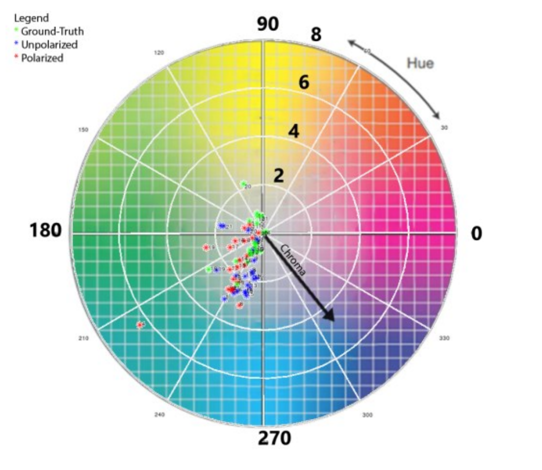
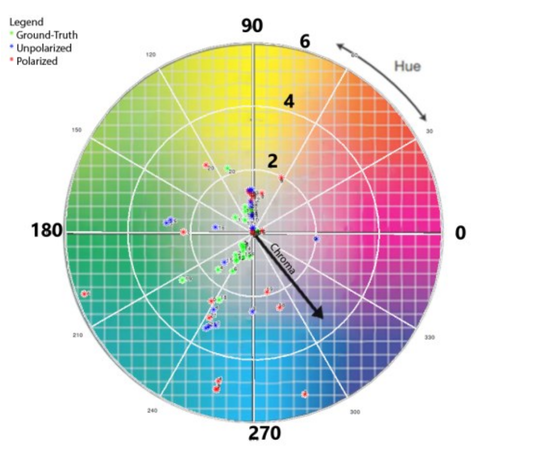
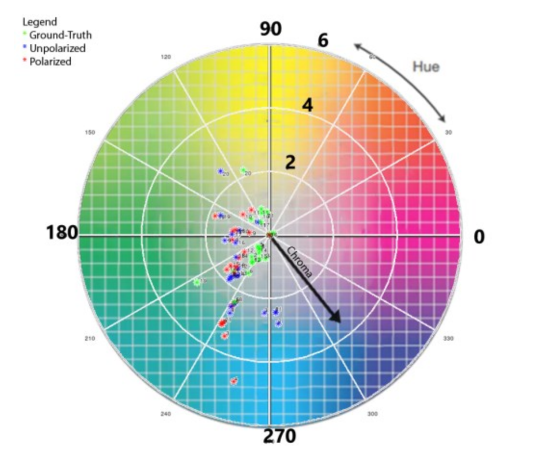
| | Our Pipeline | BasICColor + C1 |
|---|---|---|
| Munsell(Spyder) |  |  |
| Munsell(SG) |  |  |



*Figure 6: CIELCh(Ch)[10] based on CIELAB – Munsell linear grayscale*

[10] Each point in all three states (ground-truth, polarized, unpolarized) on the lattice has a number to track its shift more clearly – higher resolution images can be requested directly from the author if needed.

<table>
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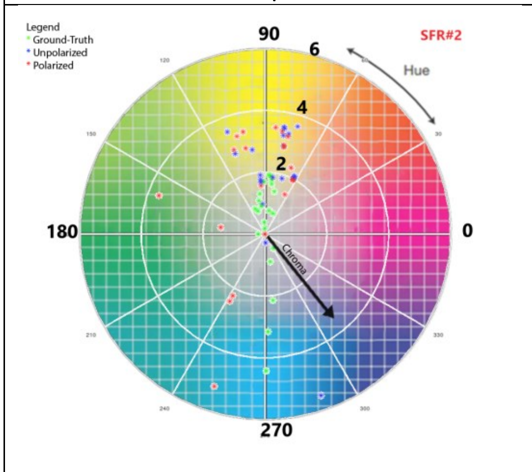
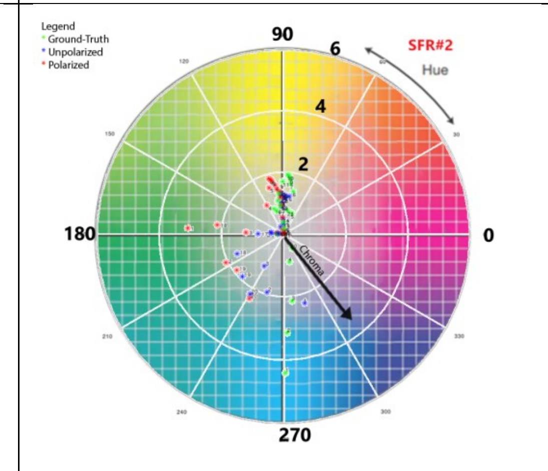
<tr><td>
</td><td>
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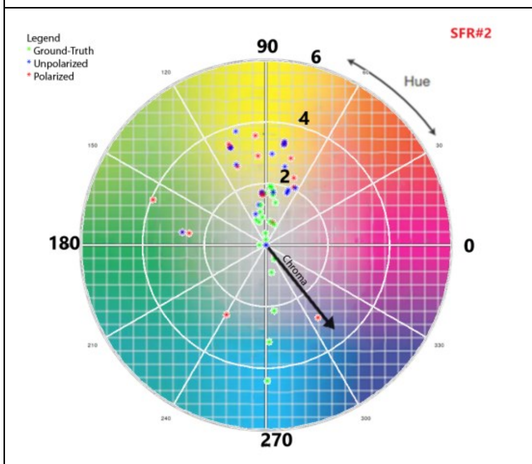
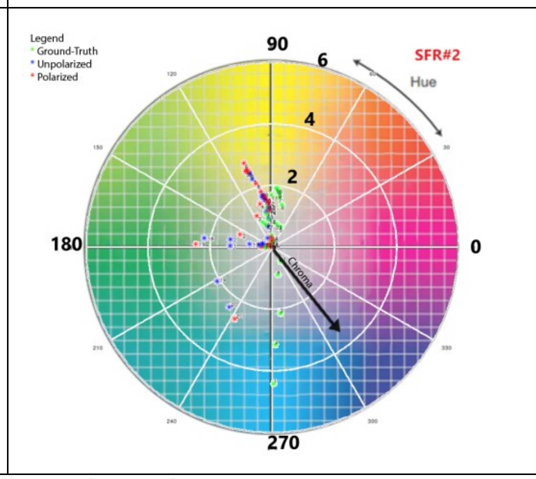
<tr><td>
</td><td>
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***Figure 7**: CIELCh(Ch)[10] based on CIELAB - SFR grayscale*

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## Author Biography

*Tarek Abu Haila obtained his bachelor in Informatics Engineering with Artificial Intelligence major (B.Sc.) at the end of 2015 and then did his master degree (M.Sc.) between 2017-2019 in Color Science under the European Erasmus+ joint programme namely Color in Science and Industry (COSI) that is coordinated among 4 European universities in France, Spain, Finland and Norway. The author is currently a Marie Skłodowska-Curie PhD fellow (MSCA-ITN) conducting his research and making use of his expertise in color management at Fraunhofer IGD institute in the competence center cultural heritage digitization department, in Germany.*