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A Cross-Polarization as a Possible Cause for Color Shift in Illumination

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Abstract

Despite that a cross-polarization is a very efficient way to remove undesired reflections and specularities while imaging and digitizing certain type of materials. It does not come, however, with no risk when color fidelity and accuracy are of importance. This paper shows that a cross-polarization could alter and shift the Chroma component of a light source (D50) by different factors, undoubtedly, depending on the polarization filters' quality in-use. Statistics show a color difference, DE00, of at least 3.59 and at worst 7.34 when a cross-polarization is in-place compared to non-polarized settings. That corresponds to a shift in color correlated temperature ranging from 50K to 360K consequently.

Introduction

Controlling light polarization could be indispensable to certain applications either due to the material of the imaged object per se (e.g. glossy, shiny, metallic) [10, 9] or due to the restricted geometry an imaging system has to use and its technical design that could not afford 0°/45°or 45°/0°(e.g. check CultArm3D scanning system [9, 1, 2] where the camera and the light source share the same plane having 0°angle to each other). However, using polarizing light couldn't come with no risk, especially when it comes to how much color fidelity is affected during the imaging process and whether it is impacted negatively or not. This sort of questions are, unfortunately, usually overlooked and get too little attention, if any.

Controlling light polarization, simply put, is a technique that ensures that the light enjoys a specific and defined oscillation state (i.e. being polarized in a vertical or horizontal manner) while it is travelling –light, by nature, is considered to be randomly polarized. As well, it ensures that an imaging system, when a polarizer is fixed on top of its optical system, is filtering out unwanted reflections and specularities that would usually disturb the object's appearance, ensuring by that that the surface appearance is rather clearly visible than being hidden behind some strong highlights. Polarization could happen as a result of a multiple well-studied phenomena, most commonly due to reflection or scattering [5, 8][1].

Light, as it is established, can be treated and regarded as transverse electromagnetic waves, denoted as a vector $\overrightarrow{E_{xy}}$, that travels in the 3 dimensional space. In 3D, this $\overrightarrow{E_{xy}}$ would vibrate in the xy-plane ($\overrightarrow{E_x}, \overrightarrow{E_y}$) and travels across the z-axis. Given that $\overrightarrow{E_{xy}} = \overrightarrow{E_x} + \overrightarrow{E_y}$, simply put. It is said that the light *linearly polarized* when both components ($\overrightarrow{E_x}, \overrightarrow{E_y}$) are in-phase. Then it can happen that the oscillation occurs in one specific plane (e.g. along the x-axis if $\overrightarrow{E_y} = 0$, y-axis if $\overrightarrow{E_x} = 0$ or a plane in between like at 45°angle constituted of both vectors $\overrightarrow{E_x}$&$\overrightarrow{E_y}$). Another state of polarization is known as *circular polarization* in which $\overrightarrow{E_x}, \overrightarrow{E_y}$ have a similar magnitude and a relative phase difference of exactly a quarter wavelength $-\pi/2 + 2m\pi \ \forall \ m \in \mathbb{Z}$ [5].

When talking about artificially made polarization films/filters, it is important to keep in mind that, a little portion of the impinging light on the polarizer would be inevitably reflected off depending on the coating and the material (nearly between 2-10%) while the remaining would split in half as only half of the light would be polarized in a certain direction, which accounts for as much as 46% as an output on the other side of the polarizer in the best case scenario. Consequently, light intensity would drop at least by half (i.e. 1 f-stop in photography terms) [5].

Polarized light could be, as well, the result of reflection off certain materials (e.g. metal, glass, sheen surfaces...etc.) where the resultant reflected light is known to be partially polarized rather than completely polarized [5]. Removing this kind of unwanted reflections by only fixing one polarizer in front of the used imaging system (e.g. camera) would not suffice, in most cases, to fully remove them. Therefore, a cross-polarization could be more helpful when put in-use.

Cross-polarzation is a technique followed when two polarizers are mounted, one in front of a light source so that the light source is under control and delivers polarized light that oscillates in one specific state hence its reflection is more easily predictable, making removing this kind of reflections completely much easier. In addition to another polarizer (better knwon as an analyzer in this scenario) is mounted in front of the optical system of an imaging system (e.g. in front of the lens of a camera) that is perfectly crossed with the first polarizer (i.e. at 90°) so that no visible reflections would appear and the result is much clearer image full of details.

Looking at the same image before and after the use of polarization, it is clear that colors change in different amounts and show more saturated hues than how they appear to the naked eye (e.g. the sky becomes suddenly bluer, grass and tree leaves show clearer and deeper green) due to cutting out polarized reflections and haze. As well, the contrast and the amount of surface details start to stick out to be more readily noticeable. The change in the level of saturation depends highly on the polarization state of the light and the angle at which one is looking. For instance, light is scattered by the tiny molecules in the atmosphere (i.e. Rayleigh

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[1] For more detailed clarification and understanding of the physics behind polarization please consult the mentioned references.

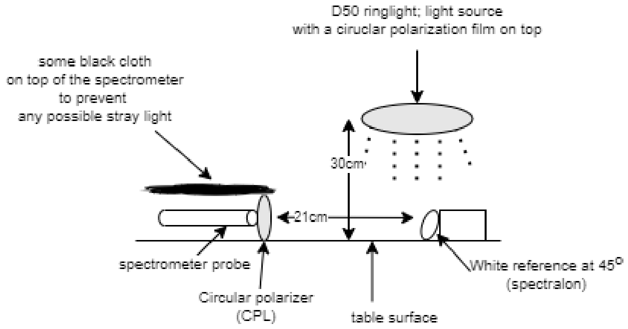

Figure 1: A Sketch of the Experiment Setup

and Mie scattering) and as a result it would be considered to be partially polarized, hence it suffers from some polarity that make the actual color to look a bit washed-out and dull (less intense and less saturated). However, if those partially polarized rays were to be filtered out, to a good degree, with the use of a polarizer, then the actual color looks more saturated or simply shows a deeper tone.

However, what about color fidelity and accuracy? It turned out that, polarization is not only helping in removing unwanted reflections but also causing some unwanted Chroma shift, and some shift in lightness as well. Yet moreover, it could cause some loss in color information especially for black shades [3]. In this paper, we discuss further how cross-polarization could yet cause a shift in the correlated color temperature (CCT) of a light source by analyzing its spectral power distribution (SPD), which could have consequences on the surface color appearance of the imaged object at the end. This change in the behavior of the SPD of the light source is highly dependent on the quality of the polarizers in-use and very likely on their coating layers, as well as on their transmission rate and range obviously.

Objectives

The incentive behind this study was the shortage in the reading materials that discuss polarization and its effects on color in real-life applications away from the basic principles behind polarization and how it works from the physics point of view. Some of the questions that have risen and were the reason behind this work are:

- Is my light source after applying a cross-polarization still performing as expected in terms of its CCT, white-point and SPD?
- How much is the imaged surface color being affected by a cross-polarization, does it still depict its actual appearance?
- How much can I trust the imaged surface color in terms of color accuracy and fidelity when this is of a high concern (e.g. digitization and archiving museum artifacts)?

To answer these kind of questions, we have prepared the following experiment setup and analyzed the collected data so that we could quantify the effect and the impact of the use of a cross-polarization in a controlled environment.

Methodology

1.Setup

We have prepared the following hardware in order to test the effect of different circular polarizers (CPL) on a specific light source, namely D50:

- Light source - A D50 illuminant (Our ring-light full of LED's).
- Four different high-quality circular polarizers (CPL), for the visible domain, that are usually to be mounted on a camera lens:
  - B+W XS-Pro HTC Polfilter KSM MRC nano
  - HOYA REVO SMC CIR-PL
  - Zeiss T* Pol-Filter
  - Marumi Fit+Slim PL
- 1x circular polarization film that is fixed in front of the light source - brandless with transmission rate $42\pm2\%$ and operating range 380-780nm.
- Avantes spectrometer for spectral measurement in the visible domain.
- A metallic reflective sphere to check the polarization alignment.
- White reference - Spectralon.

A sketch showing the used components and the experiment setup can be viewed in Fig.1. The experiment was conducted in a completely dark room. The light source was mounted and fixed parallel to a table at distance of nearly 30cm and 0°angle. A white reference was fixed at an angle of nearly 45°directly below the light source, on the opposite side of the white reference there was the probe of the spectrometer fixed at a distance of nearly 21cm away from the white reference. A piece of very dark cloth (black) was laid on top of the mount that held the probe as an extra measure just to eliminate any chance of a direct incoming stray light toward the probe. Directly in front of the probe, the tested polarizers were fixed in place after getting sure that they were well aligned with / rotated to match the polarization state of the polarized light by using the metallic sphere placed next to the white reference and checking when the reflections are diminishing completely from the probe angle.

2.Measurements

The data were captured as follows:

1. The light source was switched on in order to set the proper integration time of the spectrometer automatically that is more adequate to the CPL in-place that is being tested.
2. Then, the light was switched off in order to capture a dark reference / dark spectrum for the chosen integration time which to be subtracted from the measurements in the next step.
3. The light was switched on again to take the measurement and capture the light source SPD that fell directly on the white reference and has been reflected towards the probe going through the CPL on the way. The dark reference was set to be subtracted automatically from the measurements.

The above steps were repeated for each of the four CPL's we have, in addition to one more measurement where all the polarization elements were removed so that we have a reference measurement of the light SPD itself with no interfering elements in-between.

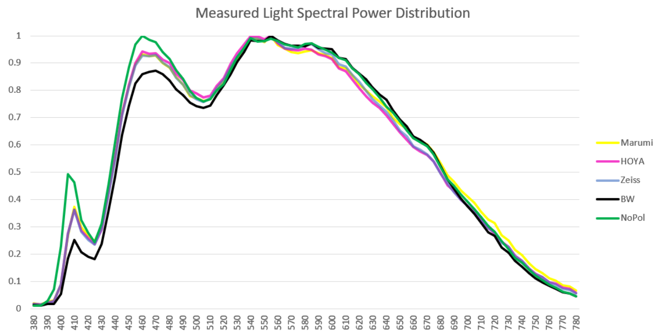

Figure 2: Spectral Power Distribution (SPD) of each of the recorded measurement in the range 380-780nm.

Results

After collecting all the necessary data, the measurements were saved in 5nm step in the range 380-780nm and normalized. The SPD of each measurement, Fig.2, then was converted into CIEXYZ[2] so it is possible to derive xy-Chromaticity coordinates as well moving to CIELAB and CIELCh(ab) color spaces[3]. We have also approximated and calculated the color correlated temperature (CCT) of each of the measurements based on McCamy's polynomial equation [7] Eq.1. The McCamy's approach was chosen as it shows very minimal to negligible error in the range in which it is intended to be used here. Moreover, a ground-truth of a D50 measurement was downloaded from the website of the University of Waterloo[4] to compare against and verify our results furthermore.

$$CCT(x,y) = -449n^3 + 3525n^2 - 6823.3n + 5520.33 \quad \text{(Eq.1)}$$

where x and y are the calculated chromaticity coordinates and

$$n = \frac{x - 0.3320}{y - 0.1858}$$

Table 1 shows the different measurements expressed in xy-chromaticity coordinates and in CIELAB, CIELCh(ab) color spaces, in addition to the approximated CCT values. "NoPol" stands for "No Polarization" when all the polarization elements were removed while taking the corresponding measurement. First, a simple Euclidean distance[5] is calculated between each xy-chromaticity coordinates and the reference D50. Then, the color difference DE2000 (also known as DE00) is calculated based on CIELAB coordinates once against the reference D50 and once against the used light source D50 with no polarization (NoPol). Chroma and hue-angle were derived from CIELAB and indicated in the table, as well, to help comprehend better the shift happening in the Chroma component. Finally, an approximation of the CCT was calculated based on McCamy's formula. Two symbols show up in the table, '*' to indicate the closest CPL filter to the used light source (NoPol), and '†' to indicate the farthest.

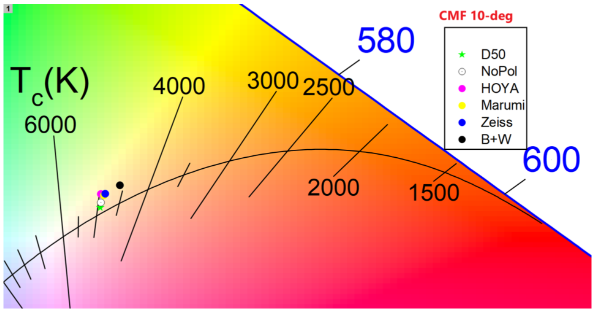

Figure 3: xy-Chromaticity coordinates of the taken measurements for the 10-degree standard observer (CMF). The black-body curve (Planckian locus) is also illustrated for clarity.

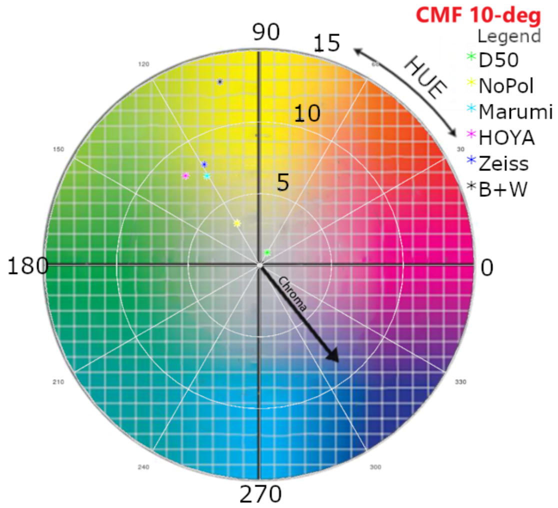

Figure 4: The CIELCh Chroma-hue circle. The CIELCh(ab) coordinates are plotted for each measurement considering that data were derived based on the 10-degree standard observer (CMF)

Figure 3 shows xy-Chromaticity coordinates plotted on the spectral locus, and Figure 4 shows the Chroma-hue coordinates of CIELCh(ab). In both cases the underlying data were calculated based on the 10-degree standard observer of the Color Matching Function (CMF).

Table 2 accompanied with Fig.5 show, furthermore, $u'v'$ coordinates on CIE 1976 u'v' diagram as it is considered to be more perceptually uniform.

Discussion

Looking at the statistics in Table 1 shows clearly that doing a cross-polarization has a non-negligible effect on CIELAB coordinates, namely the Chroma components a*b*. It would double, at least, the value of a*b* compared to no polarization at all - not necessarily that both coordinates to be changed by the same factor and regardless of the coordinates sign. If no polarization were to be used then our ring-light D50 shows a slight Chroma, by the nature of the used LED's, with -1.59 and 2.92 for both a*b* respectively, this Chroma tint in our ring-light compared to the reference D50 from the University of Waterloo, that is originally from Hunt's Measuring Colour's book [6], results in $DE00 = 3.53$. Whereas, the worst case scenario would be when B+W CPL filter is in-use that shows a huge shift in b* coordinate specifically that jumps up to 12.79, while a* stays as low as -2.78 and that is consequently translated into a shift in CCT from 4937K for no-polarization to 4576 for B+W CPL filter - it is a drop of about 360K. B+W CPL filter shows a color difference of

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[2] 10° standard observer was used for the conversion.

[3] For all the necessary formulae please consult [4].

[4] http://www.npsg.uwaterloo.ca/data/illuminant.php

[5] Euclidean distance (x,y) = $\sqrt{(x-\bar{x})^2+(y-\bar{y})^2}$

xy-Chromaticity / Euclidean Distance to D50				CIELAB			DE00 Color Difference		LCh(ab)		Approx.
	x	y	Euc. Dist.	L*	a*	b*	to NoPol	to D50	C	h	CCT
D50	0.3477	0.3595	0.0	100.0	0.5125	0.8885	3.5274	0.0	1.0257	60.021	4931.06
NoPol	0.3480	0.3644	0.0048	100.0	-1.5851	2.9243	0.0	3.5274	3.3263	118.46	4937.57
HOYA	0.3481	0.3725	0.0129	100.0	-5.1788	6.2375	4.861	8.4314	8.1072	129.7	4958.37
Marumi*	0.3501	0.3713	0.0120	100.0	-3.6889	6.2236	3.5883	7.0922	7.2347	120.66	4887.53
Zeiss	0.3511	0.3727	0.0136	100.0	-3.87	7.0266	4.1419	7.6021	8.0218	118.84	4860.28
B+W†	0.3612	0.3809	0.0253	100.0	-2.7795	12.786	7.3421	9.9339	13.085	102.26	4576.15

Table 1: Statistics of different CPL polarization filters calculated from spectral measurements and converted into xy-Chromaticity coordinates as well as into CIELAB and CIELCh(ab) color spaces based on the 10-degree standard observer data. Correlated color temperature (CCT) also approximated using McCamy's formula. '*' indicates the closest CPL filter to NoPol, while '†' indicates the farthest.

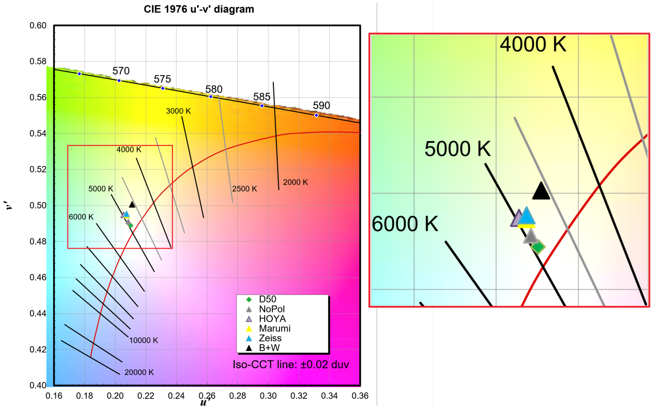

Figure 5: The u'v' coordinates on CIE 1976 u'v' diagram that is more perceptually uniform than xy-Chromaticity diagram.

$DE00 = 9.93$ compared to the reference D50 and $DE00 = 7.34$ compared to our ring-light which is supposed to be very striking shift in terms of color difference. On the other hand, Marumi CPL filter performs the best among all the others with as little change as 50K in CCT and about $DE00 = 3.59$ compared to our ring-light. nonetheless, even such a low DE00 still should be perceptible to the naked eye in DE00 metric.

If we have a look at the Chroma component, we notice how the Chroma is jumping from 3.33 no-polarization to 7.23 for Marumi, to around 8.0 for both HOYA and Zeiss and to 13.08 for B+W, Which is more observable by looking at Figure 4. The Chroma shift is rather occurring in the yellow-greenish region, which is very likely something to do with the coating layers and the manufacturing technology of the tested CPL filters, as well with the specification of the tested light source in the first place.

The hue-circle in Figure 4 shows how using a CPL filter is dragging the Chroma component of the used light-source towards the circle's circumference (i.e. towards more saturated colors), mostly along the same radial line on which the original light source lies. However, one of the CPL filters, namely B+W, shows a stronger deviation towards the deep yellow region with Chroma value larger than 10.0, while the Chroma values of the other CPL filters lies around 7.0-8.0 which is already double, at least, the initial value of the tested light source $CIELCh(C) = 3.33$.

Table 2: The u'v' coordinates based on CIE 1976 u'v' coordinates system.

Source	u'	v'
D50	0.2101	0.4889
NoPol	0.2085	0.4912
HOYA	0.2056	0.4949
Marumi	0.2073	0.4946
Zeiss	0.2074	0.4954
B+W	0.2110	0.5006

It is worth noting that, despite all this Chroma shift and the reported color difference –that is supposed to be strikingly noticeable. If one looks actually at the light source directly or at its direct reflection off a white-reference (e.g. Spectralon) a Chroma shift would not be very clearly perceptible, if at all, due to the fact that this Chroma shift is actually hiding behind the light maximum lightness component CIELAB(L*) and its effect would be only observable when the light starts to interact with different surfaces and colors as reported in A. Haila's study[3]. It seems as if the calculated DE00 of the different measurements of the light source's CIELAB coordinates has a shortcoming in stating how such color difference is to be observable when assessing the Chroma component of a light source.

Conclusion

It is evident that, a cross-polarization could cause undesirable shift in Chroma component of the used light source (D50 in this report). The shift is not completely predictable (in our case the Chroma shift was in most cases along the same radial line of the tested light source on the CIELCh hue-circle) and strongly affected by the material and the quality of the used polarization elements, hence different polarizers would cause different shifts in different color regions on the hue-circle. Calculating the color difference of the reflected light off a perfect white (e.g. spectralon) between if the light to be in the state of polarization or not shows a $DE00 = 3.59$ in the best case, and $DE00 = 7.34$ in the worst case scenario for the polarization set we tested. This shift in Chroma is translated into a change in color correlated temperature (CCT), as well, of around 50K in best case and of around 360K in worst case. However, given all that shift in Chroma and the DE00 values the effect would still elude the naked eye if one looks directly at the polarized light source or at its reflection off a perfect white. It seems as if this Chroma component is rather hiding behind the lightness component CIELCh(L*) of the light source making it hard to be easily observed unless the polarized light source starts to interact with certain surfaces and colors, only then one would start to feel and perceive clearly the actual effect of the polarization phenomenon on colors (e.g. Chroma and lightness shifts).

Having a label stating "high quality" on the selected polarization filters, that are to put in use, does not necessarily guarantee that your light source and imaged colors will not undergo some alteration and undesired changes, that would put the imaged color, at the end, in question especially if the task is as sensitive as digitizing some museum's artifacts, for example. It is important to be careful when selecting the set of polarization filters and understand how that would impact the used light source in the first place, and the imaged colors consequently. Despite the fact that polarization filters should be avoided at all costs when possible and when color accuracy is sought, to certain technology and certain applications that may be very indispensable. In that case, we advise to run a systematic analysis, if possible, on the properties of the chosen polarization filters and to have a good understanding of how much compromise and risk one is taking by putting these polarization elements in use.

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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.

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