Comparing the colour representation of browsers through the coloured shadow phenomenon

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***Abstract**. In this paper we discuss virtually recreated simulations of the coloured shadow phenomena and try to verify whether different popular 3D renderers, like Maya, 3ds Max, Unity or Blender show the phenomena in a default setup, which is not mentioned in their documentations. We also discuss this property of web browsers, since the difference between displaying colours in different browsers would be a major problem for the digitalization of museum exhibits, that is a problem that our lab has been dealing with for more than a decade now. If there is any difference between the chromaticities of the same picture displayed in the most popular browsers, this task becomes impossible, or at least less consistent. In this paper we discuss the colour representation of some of the most popular browsers using the previously rendered pictures and photos of coloured shadows and see if there is any visible difference, that is said to be none in their documentations.*

Keywords. Virtual Reality, 3D renderer, web-browser, coloured shadow

1 Introduction

Coloured shadows are interesting phenomena, appearing when a solid object is illuminated by two differently coloured light sources from two different directions. In our previous research (Sik-Lanyi et al. 2019) we have shown experiments with a white and different coloured light sources and we saw the complementary colour of the coloured light source appearing in the shadow of the object that should be grey (Figure 1). As we shall see this is a consequence of the human eye's contrast vision. Photos of the experiment showed the phenomena beautifully and visibly, thanks to the camera's processing methods, similar to that of the human eye.

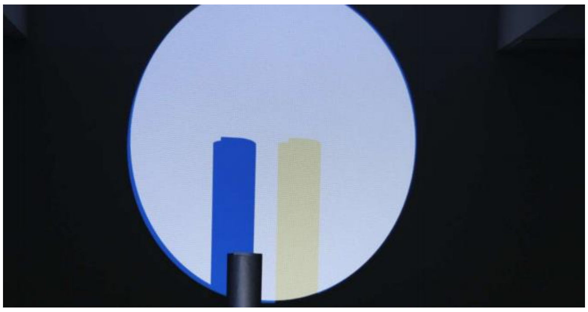

Figure 1: The coloured shadow phenomenon, a solid object illuminated by a blue and a white light in a dark room, yellow colour appearing in the area expected to be grey (right shadow).

After taking photos of the experiment, we decided to create models of the setup in different modelling engines. We recreated the experiment using the Blender, the Unity3D, the Autodesk Maya, the Autodesk 3ds Max and Autodesk Maya's built-in Arnold renderer. Measuring these pictures showed no chromatic aberration in the pictures, all the shadows remained grey. On the other hand, in the dissertation of one of our colleagues (Szucs 2019), differences were measured between colours of the same pictures displayed by different web browsers. In that paper Szucs used a photo displaying one of the frescoes in the Sistine Chapel and measuring the chromaticity of the same spots in different web browsers she found significant differences. This is a major problem, because for instance digital museums will never have a realistic and unified representation of their exhibits this way, which is a problem that our lab has been dealing with for a long time (Sik-Lanyi and Schanda 2011; Schanda and Sik-Lanyi 2007; Sik-Lanyi et al. 2008; Sik-Lanyi and Szucs 2017). We decided to recreate the experiment with other pictures and included software-based measurement methods to get less errors. Browsers in most of the cases are not colour managed, which means that they send sRGB values directly to the monitor, because images on the internet rarely use embedded ICC profiles and most users use sRGB compliant monitors. However, the described colour shift can happen when an ICC profile is applied in an image and the user doesn't use an sRGB compliant monitor and the web browser is set up not to directly display colours, but to convert the colour spaces. For further details on web browser colour management see Ballard (2020a; 2020b); Google (2020), Microsoft (2020) and Mozilla (2020). We decided to recreate the experiment with an sRGB compliant monitor and some pictures that use sRGB profiles, and also included software-based measurement methods to get less errors. This way we can see the average user experience which exists with a negligible number of exceptions. In this paper, we measure the chromaticity and luminance of the grey shadows in the previously created images in newer versions of the three browsers to see if the mentioned displaying problem exists today. We did two different experiments. In the first experiment, we measured the same „coloured shadows" in different browsers directly by a software. After that we asked volunteers to define the colours that they see in the different browsers similarly, on the same pictures.

2 Why do we see coloured shadows?

This phenomenon has been known for centuries, but until the second half of the 19th century it was uncertain if the coloured shadow was really coloured (i.e. physically different from a neutral grey) or was it just an "optical illusion". This uncertainty is well demonstrated by the controversy between Osann (1836, 1837, 1860), who maintained that the colour of these shadows was real (physical) and Fechner (1838, 1860), who repeatedly confirmed the opposite. By the second half of the 19th century this question was settled, but then came the next question: was the cause physiological or psychological. This question raised a debate between two giants of 19th century German physiological optics: Hermann von Helmholtz and Ewald Hering (Delabarre, 1889).

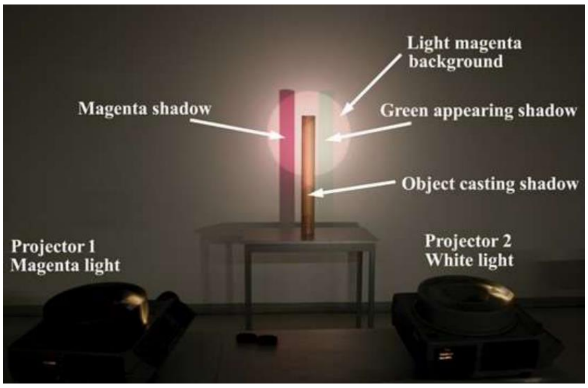

Figure 2: The coloured shadow experiment from Sik-Lanyi et al (2019)

We now know, as confirmed in the recent research by Kallmann et al. (2014) that "coloured shadows demonstrate primarily colour constancy, accompanied by colour contrast." If we look at the experimental setup (Figure 2.) we can easily see that there is no reason for the coloured shadow to be anything but grey. Here two slide projectors were used to shine a white and a magenta beam of light onto an object, casting thus two shadows. The shadow on the left of the object, blocking white light from Projector 2, is illuminated by the magenta light from Projector 1 and is therefore magenta. The shadow on the right of the object, blocking magenta light from Projector 1, is illuminated by white light, and it must be (and measurements prove that it is) neutral grey. The reason we see it appearing green (the complementary colour of magenta) is twofold. Our eyes (or, rather, our visual apparatus) is adapted to the magenta environment, and as a consequence of adaptation we see it as green. The effect of simultaneous contrast shifts the appearance of this shadow also in the same direction, reinforcing the effect of adaptation. This experiment can be repeated by any other coloured illumination resulting always in two coloured shadows: one would be the colour of the illumination (that from Projector 1), the other its complementary colour.

3 Materials and Methods

As demonstrated by Sik-Lanyi et al. (2019) the coloured shadow phenomenon is reproduced in photographs taken by digital cameras (even, to a certain extent by conventional film cameras), so would it be present when the experiment is rendered virtually? This chapter describes the virtual recreation of the phenomenon, the software and hardware equipment that we used during the measurements, and the different measurement methods.

3.1 Recreating the phenomenon virtually

We created similar setups in Blender, Unity3D, Autodesk's Maya and 3ds Max. We rendered the images with the four default renderers and added Maya hardware renderer and the built-in Arnold renderer. Taking into account the length of human tests. If all the rendered images taken by Unity3d, Maya, 3ds Max, and Blender, had been used the test could be more hours long. Therefore, only images taken with the Unity and Maya software renderers were left. Each engine comes with 6 images, and we have added 6 photos from the original experiment, each illuminated by red, blue, green, cyan, magenta, and yellow, and white light. In total, we tested the differences between browsers with 18 images. The experiment was performed with Mozilla Firefox, Google Chrome, and Microsoft Edge browsers. In both image sets (taken by Unity and Maya software renderers) we exported a white (#FFFFFF) light with one of six coloured lights, including red (#FF0000), green (#00FF00), blue (#0000FF), yellow (#FFFF00), magenta (#FF00FF) and cyan (#00FFFF) colours, counting 6 images per renderer.

3.2 Measurement plan

Step 1: Measurement of the shadow colours of images rendered in Unity3d, Maya, 3ds Max, and Blender with an I1 spectrocolorimeter. Step 2: Measurement method 1. Software measurement of photos taken from the original experiment and images taken with the selected Unity and Maya software renderers. (The description of the software for this purpose Chapter 3.3.) Step 3: Measurement method 2. Performing human measurements. (The description of the software for this purpose Chapter 3.4.

3.3. Software development for machine measurements

A "colour measurement" software, a script, was created to determine the colours of the rendered and photographed images. With this script, pixel colour values can be read from screenshots. The script was written in python, using the latest version of opencv and numpy libraries. As shown in Figure 3, the script iterates through the images, displaying them one after the other. The software allows selecting rectangles on each displayed image (Figure 3). The average values of the pixels inside the rectangles are calculated and saved after hitting the enter.

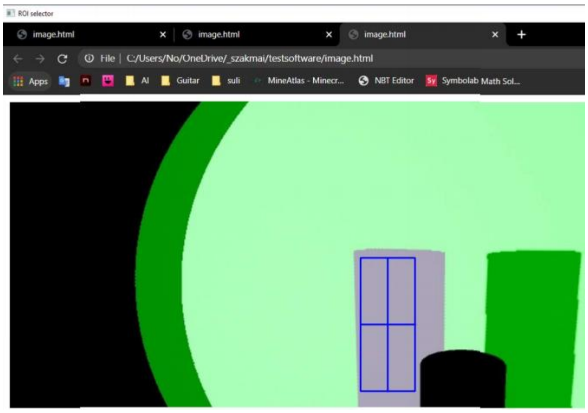

Figure 3: Selecting a pixel matrix in a screenshot of the green Unity3D picture displayed in Google Chrome

3.4. Software development for human measurements

This software allows viewing images and selecting the colours seen on the coloured shadows on them in a simple graphical interface. The software, like the previous one, was also made in Python. The graphical interface was created using the TKinter library, and the built-in colour selector for windows was added, and the python .csv manager was used to save the results. The software consists of four windows, a main window containing a "next" button to spawn a colorpicker and open the next image in the current browser, and a terminal window for debugging. The experiment starts with running the script, then the observer can iterate through the images in each browser, setting the percieved colour of the "coloured shadow". The software for human measurement is shown in Figure 4.

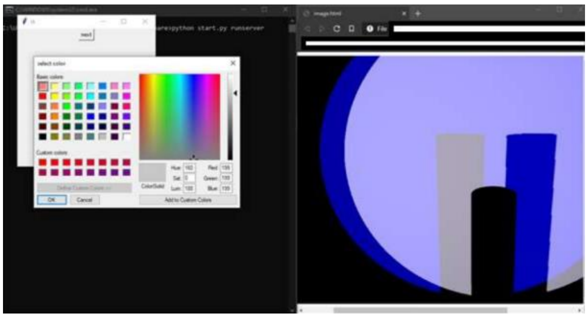

Figure 4: Colour picker and the running software (left) and the currently opened picture (right), blue image of Unity3D opened in Google Chrome.

3.5. Measuring the colours

After all the images were exported, we started to measure their colours with three different methods. In these measurements we measured only the grey spots, or „coloured shadows" of the pictures to see if there is any difference between the images illuminated by differently coloured lights. Firstly, we used an I1Pro spectrophotometer on a calibrated monitor. During this, all the shadows were zoomed to fill the measured area and the device was locked on the same spot of the monitor to avoid quality issues of the display coming from different pixel errors or chromaticity differences, since no monitor is perfectly homogenous. Next, we used a tool to select rectangles on the pictures and calculate the average sRGB value of the „coloured shadows" within. The tool is described in the „software method" chapter. The sRGB values were then converted to CIE L*a*b* (CIE, 2018) values. Next, we measured the pixel values with Adobe Photoshop by selecting 10-10 random points of the shadows and taking their average L*a*b* values. Finally, the human measurement was the last measuring method.

3.6. Measured differences using spectrophotometer

As you could have guessed, the values of the first two measurements had almost no differences, only a little that easily can be rounding error. These digital measurements showed that all the „coloured shadows" in all renderers are identically grey, so the phenomenon does not appear there. Although, there was some chromatic aberration, like all the Maya software and hardware images were somewhat purplish and Unity images happened to be a bit green. If someone is thinking about to repeat this experiment, we highly recommend reading the documentations of the rendering engines first to compare the results. The spectrophotometer measurements have shown the same results, there were no noticeable differences in colour between the different images of the same renderer. Measured values are in the figures below (Figure 5, 6, 7, 8, 9 and 10).

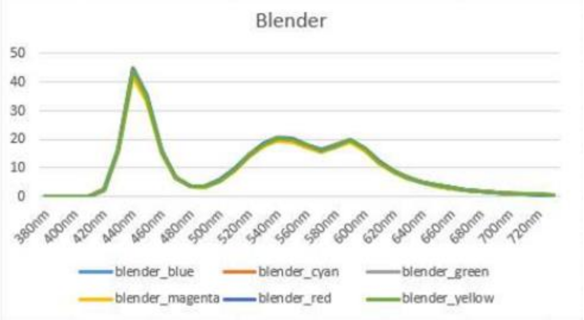

Figure 5: Spectrophotometer results 1: Colour spectra of the "coloured shadows" in Blender

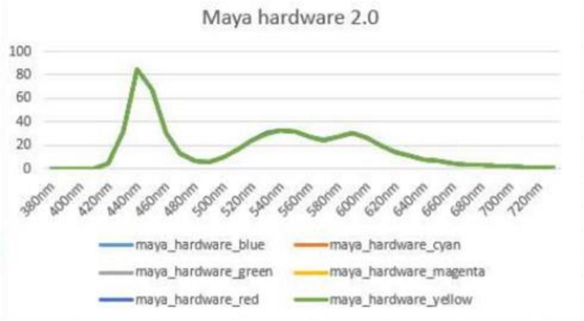

Figure 6: Spectrophotometer results 1: Colour spectra of the "coloured shadows" in Maya hardware renderer 2.0

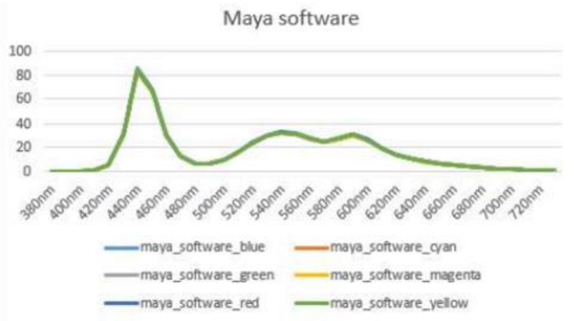

Figure 7: Spectrophotometer results 1: Colour spectra of the "coloured shadows" in Maya software renderer

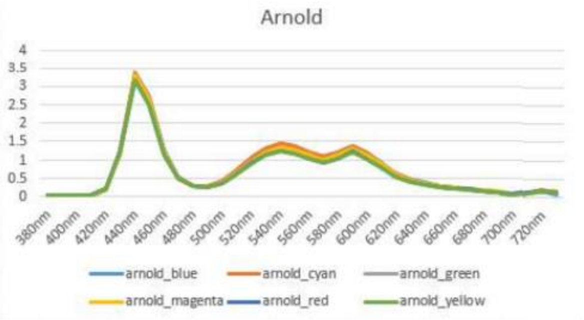

Figure 8: Spectrophotometer results 1: Colour spectra of the "coloured shadows" in Arnold

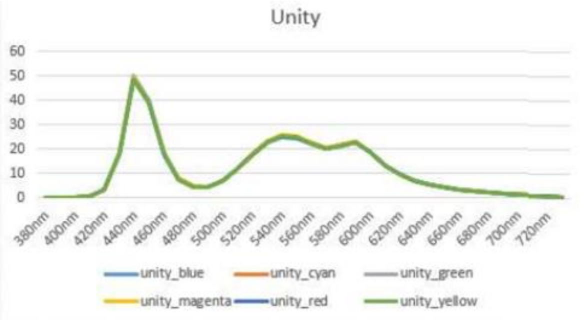

Figure 9: Spectrophotometer results 1: Colour spectra of the "coloured shadows" in Unity

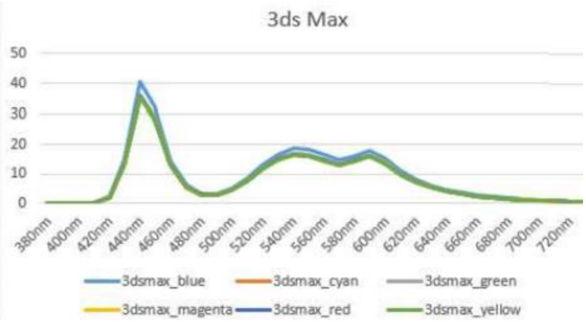

Figure 10: Spectrophotometer results 1: Colour spectra of the "coloured shadows" in 3ds Max

3.7. Versions and dataset for browser testing

During the experiments we used the Windows 10 pro operating system and web-browsers with the following properties: Google Chrome 86.0.4240.183 (Official Build) (64-bit) (cohort: Stable), Mozilla Firefox 82.0.2 (64-bit), Microsoft Edge 86.0.622.61 (Official build) (64-bit). In these browsers we displayed an image set containing the 6-6 images rendered in Unity3D and Autodesk Maya, and we also used the six real life photos, counting 18 images at all. All pictures and devices in this experiment used the sRGB format.

3.8. Software method

The first method is based on reading information directly from screenshots. First things first, we made sure that no filter or shader is applied on the display and created screenshots of the images displayed in the three browsers. After that we used the Python script described in Chapter 3.3 to iterate through the created images and select an area on the images. In each of these iterations we selected a rectangle (Figure 3) inside the shadows that we wanted to measure, and the script calculated the average colours of the selected pixel matrices.

3.9. Human method

The second method included human vision. We created a software to open the same 18 images one after the other, directly in the web-browsers, and it also opened the colour picker of the operation system (Figure 4). The participants had to specify from the colour picker (on the left of Figure 4) the colour which they judged to be the same as the colour of the coloured shadow (on the right of Figure 4) and the software saved the information. The human testing was done in a dark room on the same monitor. The testing included a short test with pseudo chromatic circles to make sure that all participants have normal colour vision. Due to the fact that the tests were performed during the COVID-19 epidemic, we could find only 9 volunteers, so the results may not be highly reliable. Further research is needed to get more appropriate data.

4 Results

Measurements were performed 3 times on a set of 54 images in total, and the results were averaged. In this section we present the measured values and differences.

4.1. Results of the first method (measuring by software)

To compare the results, we separated the L* values of the images, making pairs of the browsers. The figure in the appendix below shows the results (Appendix 1). As we can see, all values are below 1 and numbers rarely go above 0.5.

This means that the luminance difference between the browser pairs is not visible (CIE 2018; Witzel et al. 1973).

Next, we can see the Euclidean differences of a*b* values (Appendix 2). The calculations show almost the same results, all values (except two) are below 0.5, so no visible differences were found.

However, there are two values above 3, they are both connected to the cyan coloured photo shown in Firefox. It is most likely that they came from measurement errors due to inconsistent rectangle drawing, because the photos have a visible gradient in the coloured shadows, especially in that specific image (Figure 13).

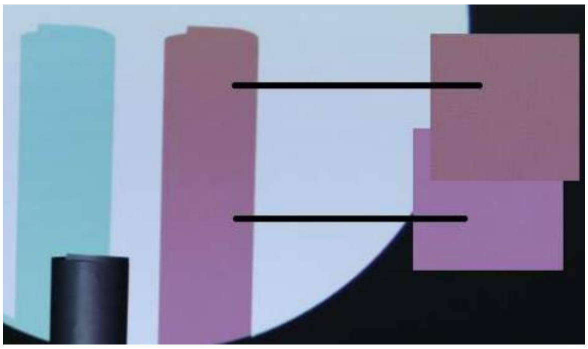

Figure 13: The cause of salient deviation between Firefox and the other browsers

4.2. Results of the second method (human measurement)

The results of the tests were evaluated in Excel, similarly to the first measurement method. The results were firstly averaged and then their CIE L* a* b* coordinates were calculated. The values are shown in Appendices 3 (Google Chrome), 4 (Microsoft Edge) and 5 (Mozilla Firefox).

5 Conclusion

So, we measured six differently rendered image sets and concluded that the renderers we used are not applying any filter that shows us the coloured shadow phenomena by default. . Therefore, it is not possible to simulate a real-world experiment by using them. Although they show shadows in grey, they do not simulate how the camera displays the coloured shadows and how people perceive them in the real world. All in all, we concluded, that if there was any visible difference in colours between different browsers, it is not relevant anymore or it is due to embedded ICC profile management and/or the usage of a wide colour gamut monitor, which is not too common yet. Usage of wide gamut monitors have a big chance of getting more popularity in the future though, so this is not a topic to be ignored. Finally, sRGB compatible images and monitors as far as we know will not show noticeable differences between images displayed in different web browsers.

Acknowledgments

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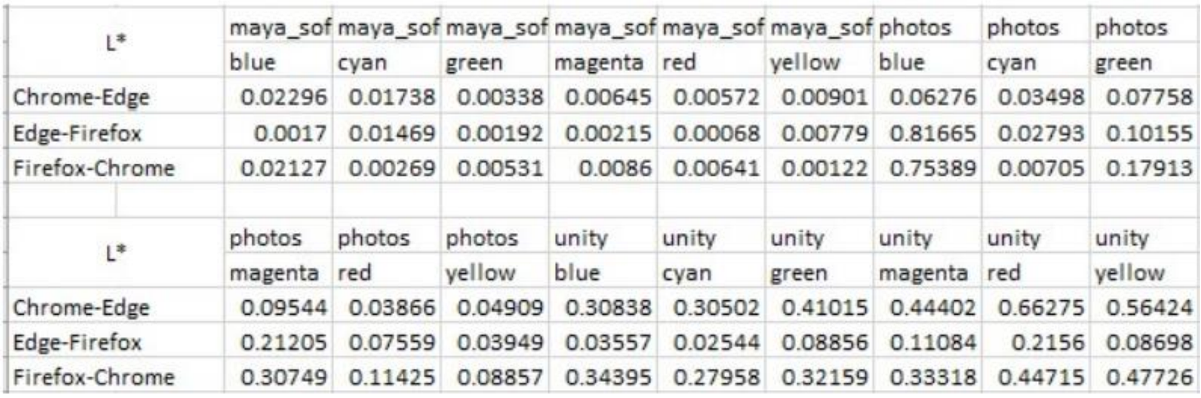
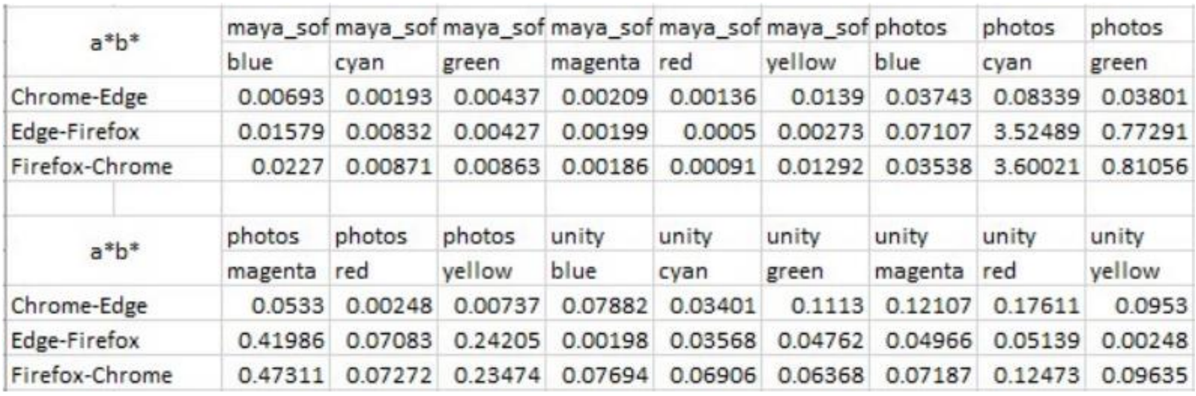
Appendix 1



L*	maya_sof	maya_sof	maya_sof	maya_sof	maya_sof	maya_sof	photos	photos	photos
	blue	cyan	green	magenta	red	yellow	blue	cyan	green
Chrome-Edge	0.02296	0.01738	0.00338	0.00645	0.00572	0.00901	0.06276	0.03498	0.07758
Edge-Firefox	0.0017	0.01469	0.00192	0.00215	0.00068	0.00779	0.81665	0.02793	0.10155
Firefox-Chrome	0.02127	0.00269	0.00531	0.0086	0.00641	0.00122	0.75389	0.00705	0.17913
L*	photos	photos	photos	unity	unity	unity	unity	unity	unity
	magenta	red	yellow	blue	cyan	green	magenta	red	yellow
Chrome-Edge	0.09544	0.03866	0.04909	0.30838	0.30502	0.41015	0.44402	0.66275	0.56424
Edge-Firefox	0.21205	0.07559	0.03949	0.03557	0.02544	0.08856	0.11084	0.2156	0.08698
Firefox-Chrome	0.30749	0.11425	0.08857	0.34395	0.27958	0.32159	0.33318	0.44715	0.47726

Appendix 1: L* absolute differences of web browser pairs

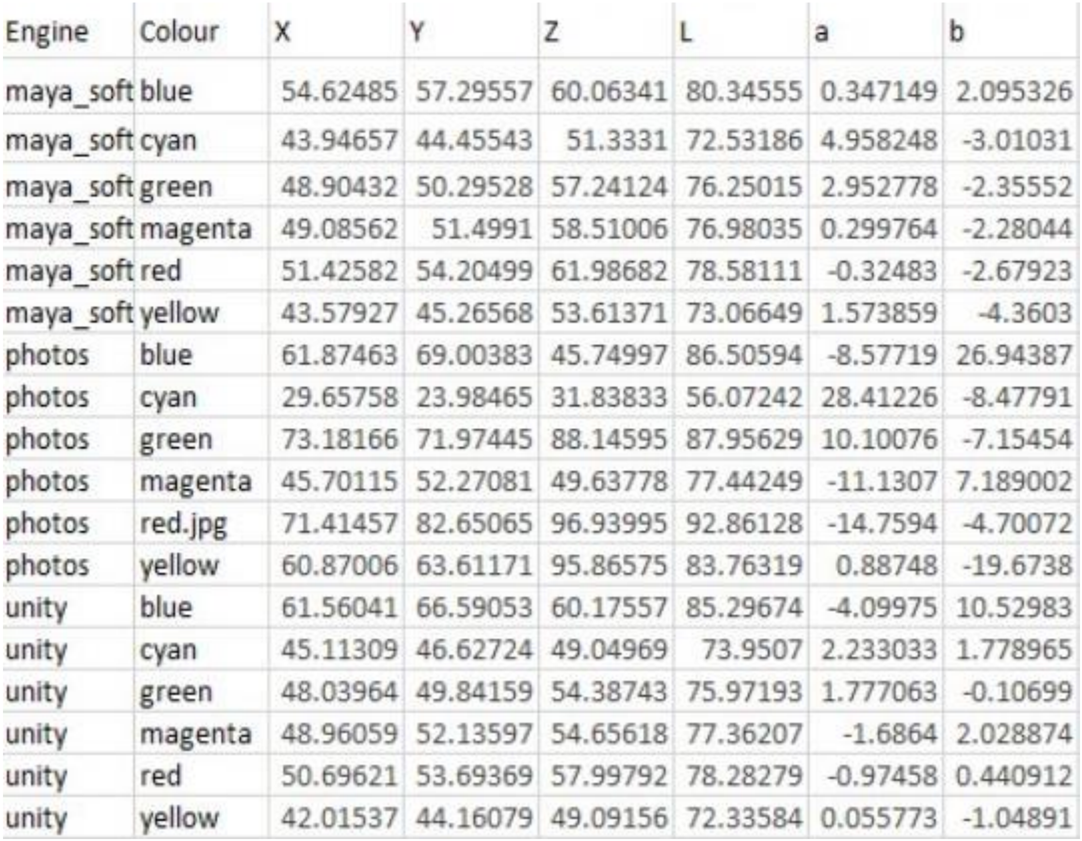
Appendix 2



a*b*	maya_sof	maya_sof	maya_sof	maya_sof	maya_sof	maya_sof	photos	photos	photos
	blue	cyan	green	magenta	red	yellow	blue	cyan	green
Chrome-Edge	0.00693	0.00193	0.00437	0.00209	0.00136	0.0139	0.03743	0.08339	0.03801
Edge-Firefox	0.01579	0.00832	0.00427	0.00199	0.0005	0.00273	0.07107	3.52489	0.77291
Firefox-Chrome	0.0227	0.00871	0.00863	0.00186	0.00091	0.01292	0.03538	3.60021	0.81056
a*b*	photos	photos	photos	unity	unity	unity	unity	unity	unity
	magenta	red	yellow	blue	cyan	green	magenta	red	yellow
Chrome-Edge	0.0533	0.00248	0.00737	0.07882	0.03401	0.1113	0.12107	0.17611	0.0953
Edge-Firefox	0.41986	0.07083	0.24205	0.00198	0.03568	0.04762	0.04966	0.05139	0.00248
Firefox-Chrome	0.47311	0.07272	0.23474	0.07694	0.06906	0.06368	0.07187	0.12473	0.09635

Appendix 2: a*b* Euclidean distances of web browser pairs

Appendix 3



Engine	Colour	X	Y	Z	L	a	b
maya_soft	blue	54.62485	57.29557	60.06341	80.34555	0.347149	2.095326
maya_soft	cyan	43.94657	44.45543	51.3331	72.53186	4.958248	-3.01031
maya_soft	green	48.90432	50.29528	57.24124	76.25015	2.952778	-2.35552
maya_soft	magenta	49.08562	51.4991	58.51006	76.98035	0.299764	-2.28044
maya_soft	red	51.42582	54.20499	61.98682	78.58111	-0.32483	-2.67923
maya_soft	yellow	43.57927	45.26568	53.61371	73.06649	1.573859	-4.3603
photos	blue	61.87463	69.00383	45.74997	86.50594	-8.57719	26.94387
photos	cyan	29.65758	23.98465	31.83833	56.07242	28.41226	-8.47791
photos	green	73.18166	71.97445	88.14595	87.95629	10.10076	-7.15454
photos	magenta	45.70115	52.27081	49.63778	77.44249	-11.1307	7.189002
photos	red.jpg	71.41457	82.65065	96.93995	92.86128	-14.7594	-4.70072
photos	yellow	60.87006	63.61171	95.86575	83.76319	0.88748	-19.6738
unity	blue	61.56041	66.59053	60.17557	85.29674	-4.09975	10.52983
unity	cyan	45.11309	46.62724	49.04969	73.9507	2.233033	1.778965
unity	green	48.03964	49.84159	54.38743	75.97193	1.777063	-0.10699
unity	magenta	48.96059	52.13597	54.65618	77.36207	-1.6864	2.028874
unity	red	50.69621	53.69369	57.99792	78.28279	-0.97458	0.440912
unity	yellow	42.01537	44.16079	49.09156	72.33584	0.055773	-1.04891

Appendix 3: Google Chrome results with calculated CIE L*a*b* values (from right to left: b*: rightmost column, a*: second column from right, L*: third column from right), second method