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Improving Colour Constancy in a Sensory Substitution System

Real time Camera Calibration and Automation of Testing Procedures in NI LabVIEW

Bachelor's thesis in Electrical Engineering
Supervisor: Dominik Osiński
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Norwegian University of
Science and Technology

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Forbedring av fargekonstans i et sensorisk substitusjonssystem	
Sanntidskalibrering av kamera og automatisering av testsystem i NI LabVIEW	
Improving Colour Constancy in a Sensory Substitution System	
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Abstract

This report describes the development of a system to improve colour constancy in the Colorophone system. The Colorophone is a sensory substitution device developed at Department of Electronic Systems (IES) at the Norwegian University of Science and Technology (NTNU). The Colorophone uses a camera to detect information about colours in the surroundings, which in turn is transformed to an auditory signal. The goal is to help the blind and vision impaired in their everyday tasks.

One of the problem areas that occurred during the development of the Colorophone was handling of colour constancy. Colour constancy describes the phenomenon where colours are perceived similarly independent of external lighting conditions. The human visual system handles colour constancy remarkably well, but this is hard to replicate in technological systems.

The aim of this project is to determine whether a white reference patch can be used to improve the colour constancy in the existing Colorophone system. This has been examined by implementing a white reference patch on the existing camera module of the Colorophone, correcting the image based on the values measured on this patch and comparing the values before and after correction. The project has been limited to testing the solution in a closed environment for a limited range of different lighting conditions.

The project findings are that the current camera module in the Colorophone system will benefit from a reference patch. More work remains to conclude whether this will improve the usability of the Colorophone. In addition, our project shows how the built-in algorithms in different cameras handle colour constancy differently. Further research should consist of both testing and considering different cameras, as well as further developing the solution with the reference patch.

Sammendrag

Denne rapporten beskriver utviklingen av et system for forbedring av fargekonstans i Colorophone. Colorophone er et sensorisk substitusjonssystem utviklet ved institutt for elektroniske systemer (IES) ved Norges teknisk-naturvitenskapelige universitet (NTNU). Colorophone er et sett med smarte briller som bruker et kamera til å hente informasjon om fargene i omgivelsene, og gjør dette om til et lydsignal. Formålet med systemet er å hjelpe blinde og svaksynte i hverdagslige oppgaver.

Et av problemområdene som ble indentifisert under utviklingen av Colorophone, var håndteringen av fargekonstans. Fargekonstans beskriver fenomenet hvor farger oppfattes som like uavhengig av ytre lysforhold. Menneskets oppfatning av farger forblir bemerkelsesverdig konstant uavhengig av ytre lysforhold, men en slik kompenseringsmekanisme er vanskelig å gjenskape i maskinsystemer.

Målet med dette prosjektet er å undersøke om en referanselapp kan forbedre håndteringen av fargekonstans i Colorophone. Dette har blitt undersøkt ved å montere en hvit lapp på det eksisterende kameraet på Colorophone, for så å korrigere bildene fra kameraet basert på verdiene på denne lappen. Prosjektet har blitt avgrenset til å undersøke dette i et lukket, kontrollert miljø og for et gitt antall ulike lysforhold.

Resultatene fra prosjektet viser at den nåværende kameramodulen på Colorophone vil ha nytte av en referanselapp. Mer arbeid gjenstår for å kunne si om dette vil forbedre brukervennligheten til systemet. I tillegg til dette, viser prosjektet hvordan ulike kameraer har ulike innebygde algoritmer og håndterer fargekonstans svært ulikt. Videre arbeid burde innebære både testing og evaluering av ulike kameraer, i tillegg til videre utvikling av løsningen med referanselappen.

Acknowledgements

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Abbreviations

RGB Red, Green, Blue

Mfr. Manufacturer

FoV Field of View

CRI Colour Rendering Index

LED Light Emitting Diode

NI National Instruments

VI Virtual Instrument

Definitions

Black box   Used to describe the closed testing environment created to perform testing.

ColorChecker   An array with coloured patches that is used in photography to balance the colours of a picture [1].

RGB tuple   A list containing the R, G and B values from a RGB value.

Neutral colour A colour where the RGB values are even.

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Chapter 1

Introduction

Is it possible to hear colour? According to assistant professor Dominik Osiński at NTNU: YES! Using sensory substitution, a method where characteristics usually perceived by one sense are manipulated so that they can be perceived by another sense, he came up with an idea of a system that generates sounds from colour. This idea was realised in the Colorophone, a sensory substitution device which allows its users to perceive colour through sound. The goal is to make a system that can assist the blind and vision impaired in their everyday tasks, through equipping them with the ability to distinguish different colours by using their hearing. The system uses a camera sensor and speakers placed on a pair of glasses to convert colour to sound in real time for the user. Using sensory substitution may improve quality of life for the blind and vision impaired, and can contribute to goal 3 of the UN's 17 Sustainable Development goals. *Goal 3: Good health and well-being* is to ensure healthy lives and promote well-being for all at all ages [2].

Sensory substitution does not come without complications. The human visual system has evolved over thousands of years, resulting in a finely tuned and calibrated system. When using our eyes to sense our surroundings, we automatically interpret light to create a mental model of our surroundings. This interpretation happens both in the eye and the brain, and they work together to process information from the light. We do not have to spend time telling ourselves that different lighting conditions will give different inputs to our eye, and that we have to attune to this. This happens automatically in our visual system, and can be described using colour constancy. Colour constancy is a term which describes the ability to perceive colours as somewhat constant under varying lighting conditions. Colour constancy is one of the the reasons why humans perceive colours of everyday objects similarly despite seeing them in different light settings. Understanding and recreating this in a sensory substitution system is challenging.

During user tests with the Colorophone, a set of usability issues were identified based on users' comments on the system [3]. Usability in different lighting conditions varied, meaning the colour constancy was questionable [3]. Several solutions were proposed to improve the handling of colour constancy, with one of them being the implementation of a small white patch underneath the camera lens to provide the system with a reference point for calibration with regard to the lighting conditions. This solution was the basis for this project and thesis question.

This project seeks to answer whether the camera module of the Colorophone will benefit from implementing a white reference patch and associated software for colour correction.

The project has been limited to examining this through a practical and experimental approach, without going too deep in the theoretical field of colour constancy. This has been done by working systematically in a controlled environment, and the project seeks to answer whether this idea should be further developed and examined in real life situations in the future. The project goal is to answer the following thesis question:

> *Can the implementation of a white reference patch improve the handling of colour constancy in the Colorophone system?*

To explore the thesis question, we created a colour correction system, an automated test system and a black box for testing. The colour correction system uses normalisation based on measured values from the reference patch to correct the colours in the image in real time. This correction should compensate for different colour temperatures in the surrounding light, whilst maintaining information about the brightness. The test system is created to streamline the process of testing, and is used to evaluate the performance of the colour correction system inside the black box. This report will describe how each of these systems are designed and implemented, as well as the findings of the project. The streamlined test system and flexible setup in the black box turned out to be very useful for camera testing, and allowed us to test and compare different cameras. Although this was not originally a goal of the project, the findings are included in the results of this report.

Colour constancy proved to be a difficult parameter to measure. Because colour constancy is connected to our perception of colours, it is difficult to quantify. For a student project with a limited time frame, some limitations were necessary to be able to evaluate if our system improved colour constancy in the Colorophone or not. Together with the client of the project, we decided to look at the difference in measured colour for the reference patch before and after correction to evaluate system performance. This builds on the assumption that implementing a colour correction algorithm will improve the colour constancy of the system. Measuring the impact from this colour correction algorithm, would show if and how much the existing Colorophone system is in need of correction.

Chapter 2

Colorophone and Colour Constancy

This chapter describes the existing Colorophone system, what colour constancy is and relevant theory for this project. To understand the system performance, knowledge about colour representation and colour measurement is needed. Lastly, this chapter will present the equations used to implement the algorithms in the colour correction system.

2.1 The Colorophone System

The Colorophone is a sensory substitution system developed at the Department of Electronic Systems (IES) at NTNU. Its aim is to help blind and vision impaired in their everyday tasks, by providing them with a new way to interpret the world around them. The Colorophone does this by "turning" colour into sound. The system consists of a pair of glasses with built in speakers and a attached camera. By processing the images from the camera to obtain the RGB values of objects in the image, the system generates a sound corresponding to these values allowing the user to "hear colours". With training, users can learn to use the Colorophone by recognising these different sounds, and thereby be able to distinguish different colours from each other without seeing them. During development of the Colorophone, one of the problem areas that occurred was that the system performed with varying performance in different lighting conditions.
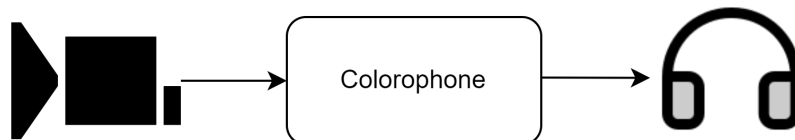
Figure 2.1: Symbolic presentation of the Colorophone, adapted from [3].

2.1.1 RGB Representation and Mapping in Colorophone

There are many ways to represent colours. The Colorophone uses the RGB colour model, where every colour consists of a red, green and blue parameter. These values are often

represented as a value between 0 and 255. The RGB colour model is an additive colour model, meaning that all other colours can be represented as different compositions of red, green and blue [4]. This is illustrated in Figure 2.2.
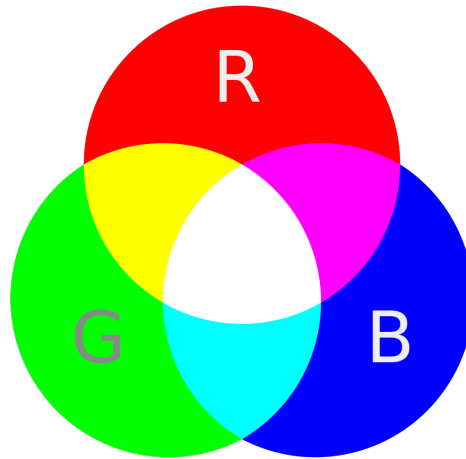
Figure 2.2: Illustration of RGB colour model represented as a Venn diagram [5]. The centre of the figure shows how all three colours combined evenly add up to white.

The Colorophone uses the RGB values of a colour to generate a musical chord. This chord consists of three tones, corresponding to the colours red, green and blue. The amplitude of each of the RGB parameters determine the volume of the corresponding tone.

2.2   Colour constancy

Colour constancy is a term which describes the phenomenon where colours are perceived as somewhat constant under varying lighting conditions [4]. Although the mechanisms behind our ability to correct the colours we perceive is not entirely known, we know that colour constancy is a complex phenomenon and is reliant on a number of factors. The handling of colour constancy in a technological system is therefore challenging. Our perception of colour can be different even though the physical parameters are the same, and colour constancy is therefore often the origin of visual illusions, such as the one seen in Figure 2.3.
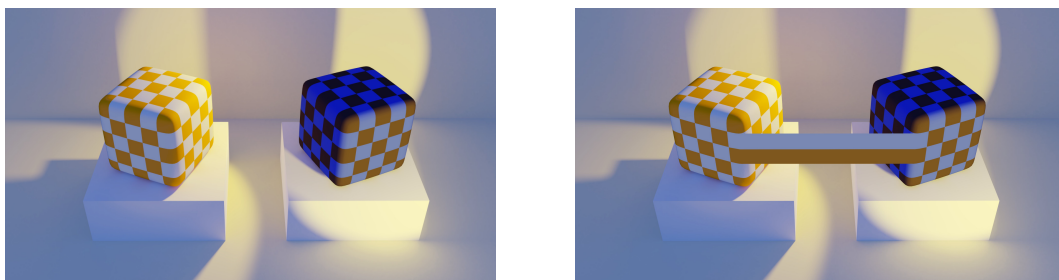
Figure 2.3: Illusion using colour constancy [6]. The front faces of both cubes are physically identical, but are still perceived as different when looking at the image.

2.3 Visible light

Visible light consists of electromagnetic radiation with wavelengths (λ) ranging from 380 nm to 700 nm as seen in Figure 2.4 [7]. Different light sources emit different compositions of these wavelengths, and will each have their own unique spectrum.
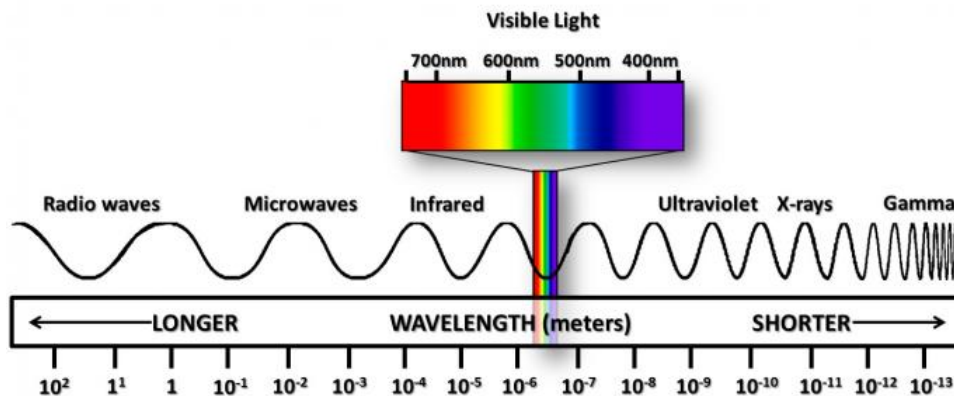
Figure 2.4: The electromagnetic spectrum with visible light [8].

When light hits an object, the light either gets absorbed or reflected. The reflected light can be processed by an eye or a camera to determine the colour of the object. This is illustrated in Figure 2.5.
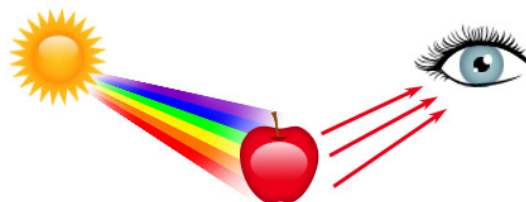
Figure 2.5: Illustration of how a light source emits light onto an object, and how the light then is reflected from the object to a viewer [9].

White light contains equal parts of the different colours, but different light sources will have different compositions. Sunlight has a more even spectral distribution than most commercial light bulbs. Specifically commercial LEDs have a tall, blue spike in their spectrum. This is illustrated in Figure 2.6. The spectrum of a light source will impact how objects illuminated by this light source are perceived by a viewer. A light source containing more blue wavelengths will cause objects to appear more blueish, and the same is true for other colours. This is an important factor to look at when measuring colour. Light sources with broad spectra and limited spikes for certain wavelengths will contribute to a more balanced reflection of the different light components.
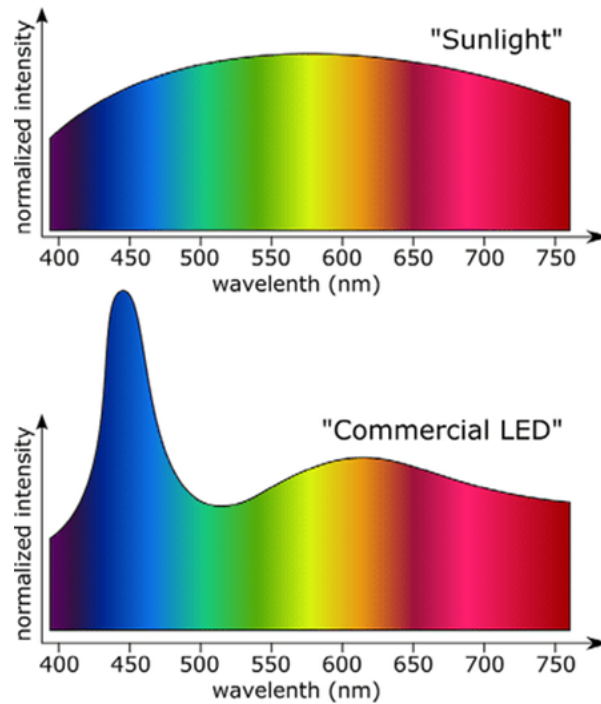
Figure 2.6: Illustration of the spectrum of sunlight and a commercial LED [10].

2.3.1   Characterisation of Light Sources

Brightness and Colour Temperature

It is possible to characterise a light source by its brightness and colour temperature.

Brightness, or luminous power, is a measure of the total emitted power of visible light from a light source [11]. It is often measured in lumen (lm).

Colour temperature describes how warm or cool a light source is, and is often described using Kelvin (K). This originates from the surface temperature from black body radiation [12], and is illustrated in Figure 2.7. Higher temperatures are more blueish or cool, and lower temperatures are more reddish or warm.
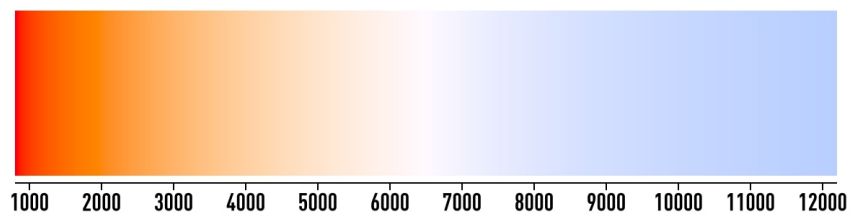
Figure 2.7: Colour temperature illustrated in relation to Kelvin (K) [13].

Colour Rendering Index

Colour Rendering Index, CRI, is defined as how well a light source replicates the colour of an object in reference to the colour in natural lighting or a standardised light source. CRI is specified on a quantitative scale from 0 to 100, where 100 equals natural light. The CRI

of a light sources is often stated by the manufacturer, and a light source CRI over 90 is considered to replicate colours well [14] .

2.4 Colour Measurement and Calibration

To measure the colour of a non emitting object, you need a light source to illuminate the object and a light detector to perform the measurement [15]. A light detector can be a colour sensor or a camera, and is used to measure the light reflected from the object. When using the RGB colour model, the colour is defined based on measurements of reflected red, green and blue light as seen in Figure 2.8. The measured spectral reflectance of an object can be described as:

$$I_{obj}(\lambda) = S(\lambda) \cdot \rho_{obj}(\lambda) \tag{2.1}$$

where $S(\lambda)$ is the emission from the light source, $\rho_{obj}(\lambda)$ is the reflectance of the object and $I_{obj}(\lambda)$ is the measured spectrum [15].
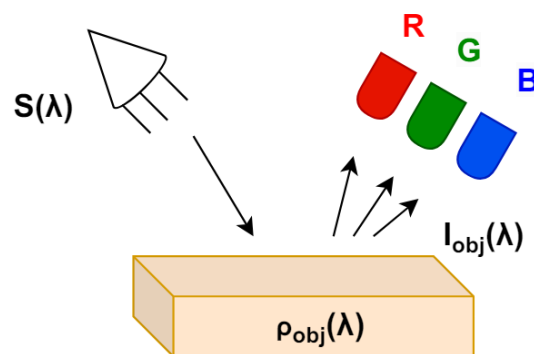
Figure 2.8: Illustration on how to measure colour. Adapted from [15].

2.4.1 Calibration using a Reference Object

When using Equation 2.1 to describe a colour, the measured spectrum $I_{obj}(\lambda)$ depends on the emission from the light source $S(\lambda)$. It is possible to calibrate a light detector for light sources with different spectra, and thereby obtaining more similar measurements of colours across different light sources. One of the methods for calibration is using a neutral point on a reference object with diffuse reflection and reflectance $\rho_{ref} = 1$ independent of λ [15]. No material is a perfect neutral diffuse reflector, but a white sheet is close [16]. The reflectance of the reference object can be described as:

$$I_{ref}(\lambda) = S(\lambda) \cdot \rho_{ref}(\lambda) = S(\lambda), \tag{2.2}$$

and the calibration of the measured object is then:

$$\rho_{obj}(\lambda) = \frac{I_{obj}(\lambda)}{I_{ref}(\lambda)}. \tag{2.3}$$

The RGB values for the measured object and reference object can be described as:

$$R_{obj} = \int I_{obj}(\lambda)r(\lambda)d\lambda \qquad R_{ref} = \int S(\lambda)r(\lambda)d\lambda$$

$$G_{obj} = \int I_{obj}(\lambda)g(\lambda)d\lambda \quad \text{and} \quad G_{ref} = \int S(\lambda)g(\lambda)d\lambda \tag{2.4}$$

$$B_{obj} = \int I_{obj}(\lambda)b(\lambda)d\lambda \qquad B_{ref} = \int S(\lambda)b(\lambda)d\lambda$$

where R_{obj}, G_{obj} and B_{obj} are the measured values of the measured object, R_{ref}, G_{ref} and B_{ref} are measured RGB values for the reference object and $r(\lambda)$, $g(\lambda)$ and $b(\lambda)$ are the spectrum of the respective RGB values for a λ [15].

Using these values, we can perform a normalisation to obtain the normalised RGB values based on the reference object:

$$R = \frac{R_{obj}}{R_{ref}}, \quad G = \frac{G_{obj}}{G_{ref}} \quad \text{and} \quad B = \frac{B_{obj}}{B_{ref}}. \tag{2.5}$$

Using Equation 2.5 gives RGB values between 0 and 1. To represent the RGB values between 0 and 255, we need to use a scaling factor and multiply the measured value between 0 and 1 with 255 [15]. The scaling factor can be any value.

2.4.2 White Balance

White balance is an image manipulation process where the temperature of the image is adjusted so that objects that are white in real life appear white in the image. The process causes the image to appear more realistic to the viewer, and the colours in the image are rendered closer to their colour in real life.

Most digital cameras have automatic white balance adjustment. The system has an algorithm that does this by evaluating the scene and determining the most white point in the frame [17]. The automatic white balance may improve colour constancy to a certain level, and some cameras are better than others.

Chapter 3

Method

This chapter will describe the methods used to answer the thesis question: *Can the implementation of a white reference patch improve the handling of colour constancy in the Colorophone system?* The project objective is to explore the thesis question through systemic testing in a controlled environment. For this objective, we require: A closed testing environment, a colour correction system to implement the algorithms based on the equations presented in chapter 2 and a test system to test the performance of the colour correction system. This chapter summarizes the design process and how testing was preformed. The design section is divided into three parts: testing environment, the software and the hardware. The test section describes how we tested the system to obtain results to answer the thesis question.

The approach to testing was through an engineering mindset, and we did not go too deep in the research field of colour constancy. The focus of the project was limited to creating a practical solution to the problem at hand, and using this to explore the thesis question. Although this project had a limited focus on the theory behind colour constancy, the software was developed so that algorithms and parameters are interchangeable. This was done in order to be able to use the same system with more advanced algorithms in the future.

To answer the thesis question, we proceeded on the basis that the implemented algorithm would improve the white balance in the images from the Colorophone. The research question will be discussed by comparing the measurements before and after the colour correction system, and thus examining the impact the colour correction system has on the Colorophone. If the corrected values show significant deviation from the original values, it is likely that the Colorophone will benefit from a reference patch and thus improve the handling of colour constancy.

To ensure quality control of the project, we conducted with several experts in the fields of spectral analysis, photonics, photography, signal processing and camera testing, both before and during developing the system and tests. Reports from these meetings and conversations are stated as sources in the bibliography, and referenced to throughout this chapter. We have also worked closely with the creator of the Colorophone and client of the project, Dominik Osiński, who has also been our supervisor.

During the process of system development and testing, we discovered that the automatic test system we implemented was very useful for evaluating the performance of different cameras. Testing and evaluating different cameras was something the client of the project saw as very useful, and this was therefore included in the project as a positive side effect.

3.1 Design

3.1.1 Testing environment

To reduce the amount of factors acting on the system from the surroundings, we created a closed testing environment, a black box, where the only light came from a light source inside the box. This section will describe the design of the black box and the choice of light source.

Black box

The specifications of the black box were chosen on the basis of meetings with several professionals in different relevant fields. Desired specifications when building it were:

- Flexibility in regards to placement of the light source, camera and object inside the box.
- Colour and reflectance of inside coating.
- Sustainability and price, and usage of materials already at hand.

The size specifications of the black box are shown in Figure 3.1. The box is made out of plastic cardboard, and is held together with duct tape, and magnets are used to create an open and close mechanism.

The specifications are chosen to create a large space, to ensure flexibility in placing the light source, camera and test object inside the box. During the development of the box, we experienced that building a smaller box limited the test setup, and would force us to make decisions about the test setup early in the process. A larger box allowed for testing different setups within the box without too many alterations on the box itself.

We considered both a square box and a cylindrical box. A square box would replicate a square room, but it would also be smaller and require more structural work with the available material. A cylindrical box would be easier to build, more stable with the plastic cardboard material available and require less cutting and assembling than a square box. It would also be easier to change the inside coating of a cylindrical box by using a single fabric curtain if desired.
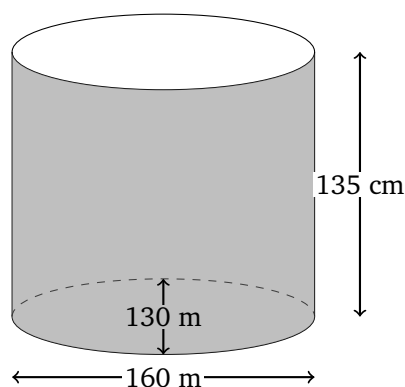

Figure 3.1: Black box specifications.

We chose to coat the inside of the black box with a neutral grey colour to prevent interference in colour from the surroundings, and also simulate a typical environment where the

Colorophone might be used such as a room with light coloured walls. The fabric used is not a standardised colour, but is similar to 18% grey which is a neutral, grey colour often used in camera testing and calibration [18]. The background should not absorb a lot of light, and for this a light grey colour is a good choice [19].

The light source is hung from the top cover using magnets. The magnets allow for the placement of the light source to be changed if desired.

One of the advantages of testing the system in a controlled environment such as a black box is the reduction of unknown parameters interfering with the test results. Because the inside of the black box was coated with a light grey cover, the light reflected from the surfaces was consistent throughout testing.

Light source

In the process of finding a suitable light source, some criteria for the specifications were made. These criteria were established after discussion with the client and studying different light sources. The criteria for the light source were:

- Possible to adjust the brightness and the colour temperature
- High CRI
- An even spectral power distribution, close to the spectrum of sunlight

This light source chosen was a LED light bulb from *LEDVANCE* (**SUN@HOME CLASSIC A 40 E27 TW**). The smart bulb can be controlled with a compatible app from the manufacturer, which allows easy adjustment of both brightness and colour temperature.

This light bulb was chosen for the project because the manufacturer states that the spectrum of *SUN@HOME* light bulbs is closer to the spectrum of sunlight than conventional LED light bulbs. This suggests that the light bulb will emit light with an even distribution of the different wavelengths, avoiding the typical blue spike often found in conventional LEDs. This was however found not to be the case when studying the datasheet for the light source [20]. This was late in the project so we chose to continue with this as our light source. Despite this the datasheet still suggests that the light source has a CRI of 95. That means that the light is close to representing natural light. The spectral power distribution from the datasheet can be seen in Figure 3.2.
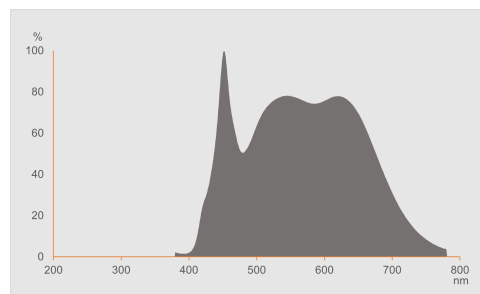

Figure 3.2: Spectral power distribution of the *LEDVANCE* (**SUN@HOME CLASSIC A 40 E27 TW**) [20].

The compatible app has six predefined settings for colour temperature, which were used when testing the system.

3.1.2 Hardware

The hardware for the system consists of the camera from the existing Colorophone system and the implemented reference patch attached to the camera. There is no embedded computer on the Colorophone, and the camera is therefore attached to a computer using a USB-C cable.

Camera

The camera module of the Colorophone consists of a customised camera produced by the Vsightcam company, utilising OV2735 image sensor from OmniVision and a 140° Field of view (FoV) [3]. Because the goal of the project is to improve the functionality of the existing Colorophone system, it was natural to test the system performance on this camera module. Further in this report this camera will be referred to as the Colorophone camera.

Because the system proved useful for testing and comparing different cameras, a second camera was tested after finalising the system. The client proposed testing a Microsoft LifeCam Studio camera, a web camera where the manufacterer states that is has TrueColor Technology and a 75° FoV [21]. The manufacturers description of the TrueColor Technology is that the camera "provides superior colour and brightness in even the worst lighting conditions" [22]. This claim was part of the reason why the client proposed this camera for testing. Further in this report this camera will be referred to as the Microsoft camera.

Reference patch

The reference patch is mounted horizontally underneath the camera lens, so that light hits it from above. This placement works well when we assume that most objects are illuminated by a light source from above. This makes the reference patch appear in the lower half of the image frame, as illustrated in Figure 3.3a. The implemented reference patches on the Colorophone and Microsoft camera can be seen in Figure 3.3b and Figure 3.3c.

Because the Colorophone camera has a wide FoV, the reference patch can be quite small and still provide the system with enough information to perform a colour correction. The dimensions of the white reference patch for the Colorophone camera are 5x5mm.

Because the Microsoft camera has a narrower FoV, it needs a larger reference patch for it to be visible in the camera frame. In addition to using a larger reference patch, the camera is disassembled to get the reference patch closer to the lens. The dimensions of white reference patch for the Microsoft camera are 23x20mm.

The requirement for a reference patch is that the patch reflects equal parts red, green and blue light. In other words, the RGB values need to be even. In this project, a small patch was cut out from a white card from *Caruba* to create the reference patch. The exact RGB values of the white card are not known to us, nor are they relevant to the algorithms, but the values are assumed to be equal and close to (255,255,255) based on the information from *Caruba*.

One of the weaknesses of using a white reference is that the patch can be saturated in bright lighting and/or if the contrast between the patch and the surroundings is high. If saturation occurs, the balance between red, green and blue is skewed, and the information from the white patch is practically useless [19]. When observing how the system with the white reference patch behaved outside the black box, we saw indications that the patch most

(a) Illustration of the intended placement of the white reference patch in the camera frame.

(b) The patch implemented on the Colorophone camera.

(c) The patch implemented on the Microsoft camera.
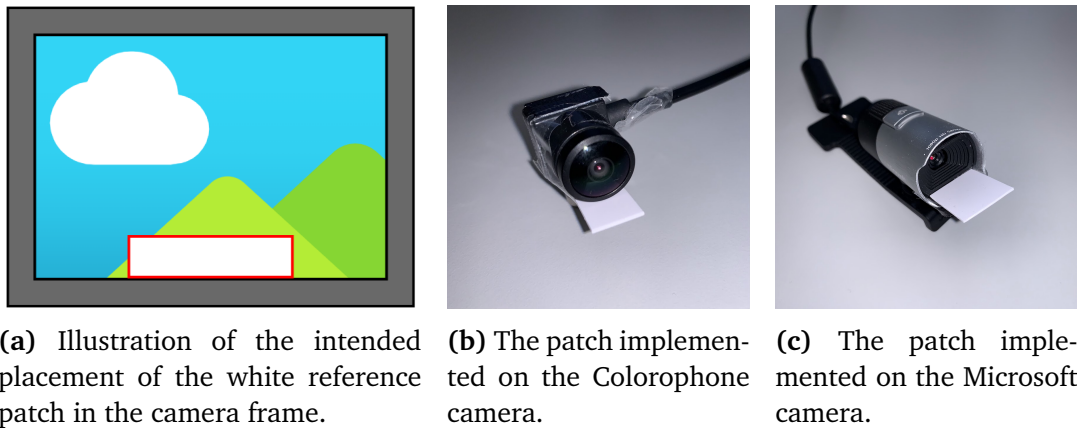
Figure 3.3: Illustration and images showing the white reference patch.

likely would saturate both indoors and outdoors in sunlight. Inside the black box, we did not observe saturation in any of the light settings. One of the possible solutions we discussed was using a neutral grey reference patch instead, but since this would require additional testing to find an ideal shade of grey, we decided to proceed with the white reference patch for the tests inside the black box.

3.1.3 Software

The software used for realising the system was implemented in NI LabVIEW, a graphical programming environment often used in instrumentation. The system has two main functionalities resulting in two subsystems: one for image correction and one for automatic testing. In addition to the LabVIEW program, a data processing script was made using Python to plot and visualise the results from the measurements. A simplified block diagram of the system is shown in Figure 3.4. The image correction system is the part of the project that directly tackles the research question, and implements an algorithm to improve the handling of colour constancy. The program for automatic testing is designed to easily evaluate the performance of the image correction system.
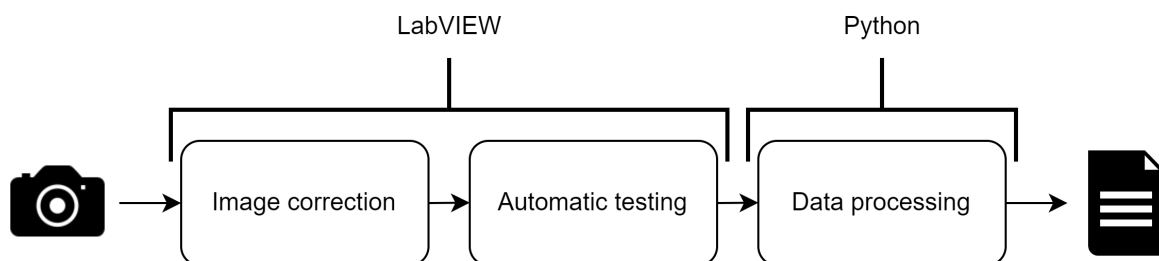
Figure 3.4: A simplified block diagram of the system.

At the start of the project we got access to the existing software for the Colorophone. The camera module from the LabVIEW program was used as the base in this project. Additional software to realise the image correction system and test system was implemented as a part

of this project. The complete program is submitted along with the submission of the project. This test system was, after the implementation, also found out to be useful to test and compare different cameras.

Image correction

The purpose of the image correction system is performing the mathematical calculations to correct colours in the raw image in real time based on data from the reference patch. The desired outcome of this correction is that the red, green and blue values become more even than before correction, but not necessarily the same across different brightness levels. This will ensure that the Colorophone gives the same ratio in the chord for the same objects in different lighting conditions, but with volume intensity based on the brightness level. An illustration of the desired functionality is shown in Figure 3.5.
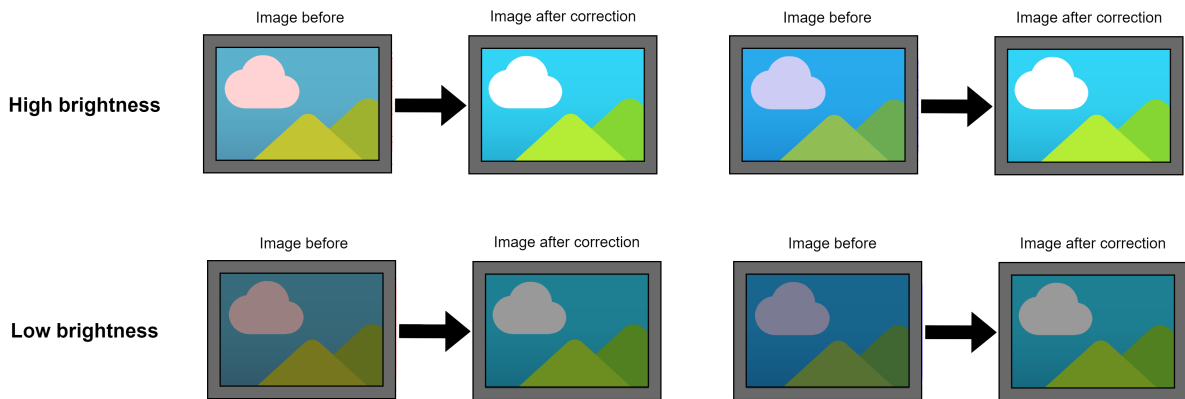
Figure 3.5: Visualisation of the desired functionality of the image correction system.

A block diagram of the implemented image correction system is shown in Figure 3.6. In the fourth box we use the methods presented in subsection 2.4.1 to calculate correction coefficients. Using Equation 2.5, the system uses the measured RGB values from the white reference to normalise the RGB values of the image pixel by pixel. As mentioned in subsection 2.4.1, using Equation 2.5 gives the relation between the measured RGB values in the image and the measured RGB values of the reference patch $(RGB)_{ref}$. This means we have to determine a scaling factor. The correction coefficients implement both the normalisation based on $(RGB)_{ref}$ and the multiplication with the scaling factor.
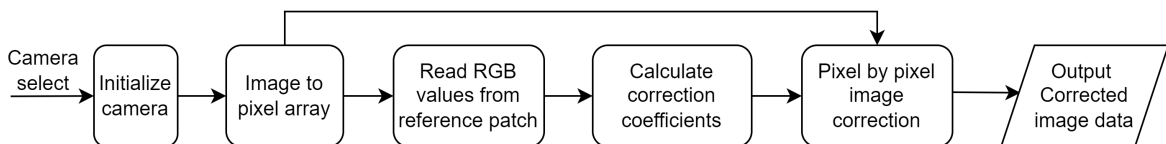
Figure 3.6: block diagram of the image correction system.

To achieve the desired functionality presented in Figure 3.5, the criteria for the scaling factor were that it contributed to an even ratio between the red, green and blue parameters

and still retained information about the brightness level. During development of the system, using a scaling factor of 255 was found to not give the desired results. When dealing with light settings with low brightness and/or colour temperatures with one very prominent colour, a scaling factor of 255 would result in drastic changes in the image correction step. This constant scaling factor may cause users of the Colorophone to receive less information about the surroundings than intended with the system. For example, it would remove information from the output of the Colorophone about the brightness of the surroundings.

Together with the client, three different scaling factors were proposed, based the values in $(RGB)_{ref}$: the maximum value, the minimum value and the mean between the maximum and minimum value. Three calibration algorithms were implemented in LabVIEW based on these three scaling factors, with the ability to select the desired algorithm in the front panel: *max*, *min* and *midrange*. An example of the three different algorithms is shown in Table 3.1. Note that the values in the RGB tuple for $(RGB)_{ref}$ are chosen to easily show how the different algorithms work, and do not represent values from testing.

Calibration method	$(RGB)_{ref}$	Scaling factor	Correction coefficients
Max	(100,170,200)	200	$\frac{200}{100}$, $\frac{200}{170}$ and $\frac{200}{200}$
Min	(100,170,200)	100	$\frac{100}{100}$, $\frac{100}{170}$ and $\frac{100}{200}$
Midrange	(100,170,200)	150	$\frac{150}{100}$, $\frac{150}{170}$ and $\frac{150}{200}$

Table 3.1: Overview of the implemented calibration algorithms.

The results in this report are presented using the midrange method. This method was chosen because we presume that this cause the smallest amplitude change for the RGB values in order to achieve the desired results. Results using max can be found in Appendix B.

Automatic testing

The purpose of the automatic testing program is to automatically run repeated tests and collect measured data about the performance of the colour correction system. The program is designed to iterate trough different light settings and log the measurement parameters and images in data files. A block diagram of the test system is shown in Figure 3.7.
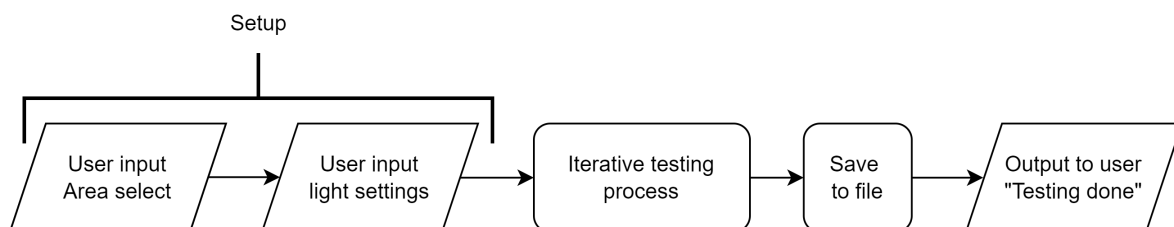

Figure 3.7: Block diagram of the test system.

In the setup, the user can input desired parameters for *area select* and *light settings*. Area select allows the user to select an area in the image frame. This was implemented to be

able to measure different colours and compare the results before and after correction. The program supports measuring multiple areas simultaneously, and the number of areas can be specified in the settings tab in the front panel. The light settings specify the number of different colour temperature settings and brightness levels.

The iterative testing process can be described in four steps. This is illustrated in a block diagram in Figure 3.8. The image system logs data about the measured RGB values after the light settings have stabilised, meaning that the system is testes in steady state.
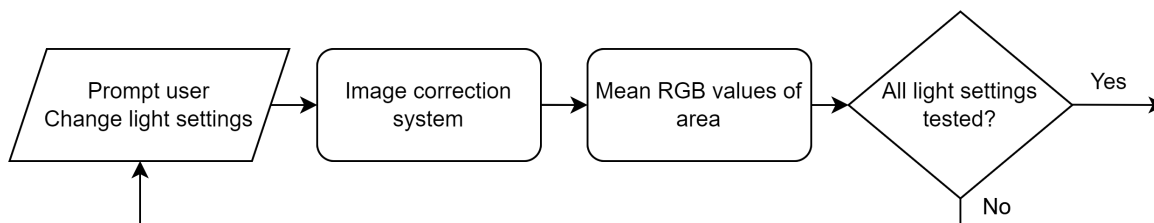

Figure 3.8: Block diagram of the iterative process in the test system.

The first box, *Prompt user - Change light settings* can function both automatically and manually. The manual implementation is the one referenced to in the block diagram, and uses pop ups to prompt the user to change the light settings in the Ledvance app. The automatic implementation uses a smart assistant connected to Google Home to control the light bulb, and gives instructions to the smart assistant using an existing VI for text to speech in LabVIEW [23]. During trial tests when implementing the automatic control of light settings, the implementation worked as desired and allowed for fully automatic change of both brightness and colour temperature. However, we discovered that the colour temperature settings for the light bulb in Google Home had a much narrower range than when using the Ledvance app. This meant that all the colour temperature settings were relatively similar, and would not provide us with the desired variation in colour temperature. We were not able to work around this in the settings for Google Home, and the manual implementation was used for the remainder of the project.

The rest of the steps in the iterative testing process do not require any manual input and happen automatically when the user has indicated that the light settings have been changed. This means that implementing an automatic adjustment of light settings would result in a totally automatic test system.

Data processing

The LabVIEW program outputs data as a .csv file with the parameters object number, brightness, colour temperature and white reference colour before and after colour correction. A python script generates a PDF report with tables and charts from the data file. ΔR, ΔG and ΔB are calculated as:

$$\Delta R = R_{after} - R_{before}, \quad \Delta G = G_{after} - G_{before} \quad \text{and} \quad \Delta B = B_{after} - B_{before}$$

and plotted as bar plots. An overview of the contents in the data report are shown below:

Tabular outputs:

- Raw RGB data for the white reference patch
- Corrected RGB data for the white reference patch
- ΔR, ΔG and ΔB

Graphical outputs:

- Bar plots for ΔR, ΔG and ΔB with colour temperature along horizontal axis
- Bar plots for ΔR, ΔG and ΔB with brightness along horizontal axis

Image outputs:

- Image before and after correction for every light setting

Front panel user inputs and user interface

The front panel of the LabVIEW program is shown in Figure 3.9. The front panel shows the live image from the selected camera before and after correction, and has buttons for starting and stopping the testing program. A light indicator shows if the reference patch is saturated, where saturated is defined as any of the RGB parameters being measured to 255. During testing inside the black box this was not a problem, but we found a light indicator to be useful for future testing in real life scenarios and as a easy way to identify if saturation occurred. In the test settings, shown in Figure 3.10, it is possible to control:

- Placement of the white patch measuring area in the camera frame
- Calibration method
- Number of areas to collect data from (for measuring different coloured objects)
- Automatic or manual selection of test areas
- Automatic or manual adjustment of light settings
- Headers for output .csv file

In the camera settings, shown in Figure 3.10, it is possible to control:

- Select video mode from the displayed available video modes
- Image type

When the "Start" button is pressed, the program will go through several pop ups where the user can determine the following specifications for the test:

- Selection of area(s) to measure colour
- Light parameters (brightness and colour temperature settings)
- Object number/test descriptor

After specifying the parameters in the setup, the measurements start. The program iterates through the specified light settings, prompting the user through pop ups to change the light settings in the app for the light bulb, and then logging data for each light setting. A pop up will appear informing the user whenever the measurements are ready, and the data is saved.
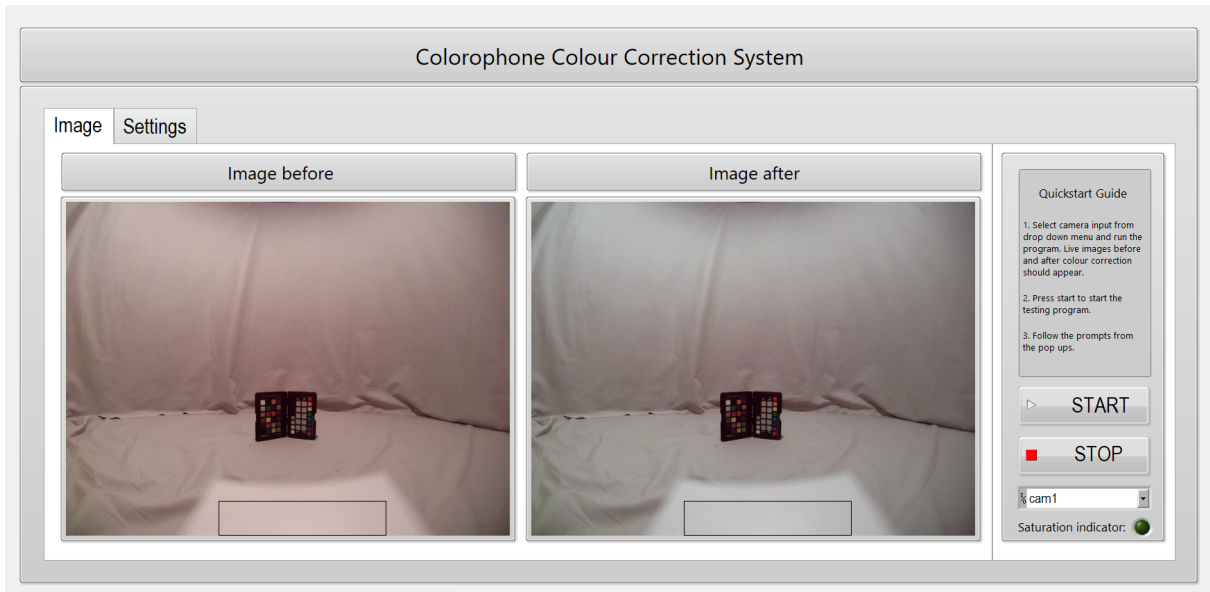
Figure 3.9: Front panel with images before and after in LabVIEW.
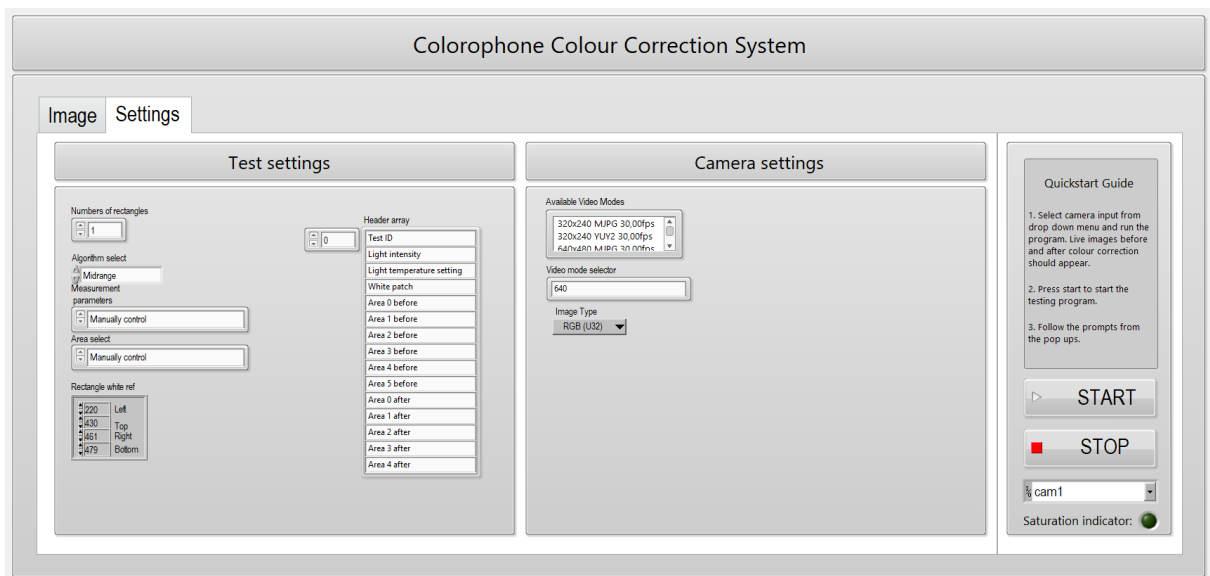
Figure 3.10: Front panel settings in LabVIEW.

3.2 Testing

Studio scene

To test the performance of the correction system, we created a studio scene with different objects with varying colour, texture, reflectance and size. The purpose of this setup was to visually examine the before and after images from the camera, and how the correction algorithm changed the colours of a wide selection of different objects. The setup consisted of different everyday objects, the *xRite ColorChecker Passport 2* and a white card from *Caruba* in the same material as the white reference patch.

Test setup

Inside the black box, the Colorophone camera is placed on a cardboard box ∼30 cm from the studio scene, to get every object got in the frame. The cardboard box is ∼16 cm up from the floor of the box, and the camera is placed here to avoid half of the camera image to be of the floor.

The Microsoft camera used is placed further back because of the lower FoV. It is placed ∼70 cm from the objects to get them in the frame.
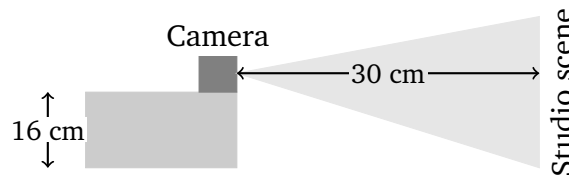
Figure 3.11: Test setup for the Colorophone camera inside the black box.

Testing procedure

A step by step description of the testing procedure is described below.

1. Turn on and connect the light bulb to a smart phone or similar.
2. Open the LabVIEW program. Make sure the camera is placed correctly and that the frame displays the desired area.
3. Press 'Start' to start testing. Follow the prompts from the pop ups in the LabVIEW program.
4. Run test data through python script to generate a report of the results.
5. Repeat process or terminate testing program.

During testing, the colour temperature was adjusted used based on the preinstalled settings from the manufacturer of the light bulb. There were in total six different settings, ranging from warm to cool. Before testing, the different setting were enumerated as presented in Table 3.2. The manufacturer provided an approximate temperature range for the different light settings [24]. The different brightness levels tested for were 1%, 10%, 20%, 40%, 60% 80% and 100% in the app.

Light setting no.	Mfr. description	Temperature [K] from mfr.
1	Candlelight	2,200 K and Under
2	Incandescent	2,200 K and Under
3	Warm white	2,700 K to 3,500 K
4	Ivory	3,500 K to 4,500 K
5	Daylight	5,000 K to 6,000 K
6	Cool white	6,000 K to 7,000 K

Table 3.2: Colour temperature settings.

Chapter 4

Results

This chapter presents the results from testing the implemented system. The findings of our project include:

- How well the Colorophone camera handles colour constancy and how this can be improved by implementing a reference patch.
- Insight in how different cameras show different performance regarding colour constancy and colour reproduction.

The results showing the impact from the image correction step in the implemented system are presented as before and after images for a selection of the tested light settings. All the images from testing can be found in Appendix A. Image and colour reproduction in both computer screens and physical print outs has to be taken into consideration when interpreting these images. Data collected during these tests is presented as bar plots showing ΔR, ΔG and ΔB for the white reference patch. The Δ values are plotted both with regard to brightness along the horizontal axis and with regard to colour temperature along the horizontal axis. The colour temperature scale in the plots is based on the colour temperature settings presented in Table 3.2, where setting 1 is the warmest, and setting 6 is the coolest.

As mentioned in chapter 3, two cameras were tested: the Colorophone camera and a Microsoft camera. The same test with the same light settings was performed on both cameras. This chapter will present the results from both cameras separately, and their key differences will be discussed in chapter 5.

4.1   Colorophone Camera

The Δ values for the white reference patch are shown in Figure 4.1 and Figure 4.2. The before and after images for the Colorophone camera can be seen in Figure 4.3.

Impact from the Colour Correction System

Testing indicates that the Colorophone camera benefits from the white reference patch and colour correction in both warm and cool light settings. Figure 4.1 shows that the two warmest colour temperature settings, setting 1 and 2, have the highest absolute Δ values and benefit most from the colour correction. However, there are very few total settings where the Δ values are so low that they can be negligible, and most of the settings seem

to benefit from the colour correction to a greater or lesser extent. This improvement is also notable when looking at the before and after images from testing the Colorophone camera.

Tendencies for the different Colour Temperatures

When viewing the plots for different colour temperatures separately, we are able to get useful information about how the colour correction system works differently on the warmer, cooler and more neutral settings. Figure 4.1 shows plots for each of the six different colour temperature settings with brightness level along the horizontal axis. We observe that there are similar behaviours between the two outermost colour temperature settings, between the two next to outermost settings and between the two centremost settings. The most prominent colour in the light can be identified by the lowest negative Δ value. Key observations are:

- **Temperature setting 1 and 6:** These are the warmest and coolest settings. We observe that the Δ values are somewhat even along the horizontal axis, indicating an even impact from the colour correction for all brightness levels. Because these are the outermost settings, it is as expected that red is most prominent in setting 1 and blue is most prominent in setting 6.
- **Temperature setting 2 and 5:** These are the second warmest and second coolest settings, and it is still as expected that red is most prominent in setting 2 and blue is most prominent in setting 5. The Δ values each have the same sign along the horizontal axis, but show a decreasing and increasing trend in amplitude as the brightness increases. The decreasing trend for setting 2 indicates that red becomes less prominent as the brightness increases. The increasing trend for setting 5 indicates that blue becomes more prominent as the brightness increases. This may be a result of the automatic adjustment within the camera itself as the brightness changes, the qualities of the light source, or a combination of both. One theory is that the light source emits more blue light as the brightness increases.
- **Temperature setting 3 and 4:** These are the most neutral colour temperature settings. We observe an interesting change in which colour is the most prominent value as the brightness increases. At low brightness levels red is the most prominent value for both colour temperatures, but as the brightness increases blue becomes the most prominent value. As for setting 2 and 5, this may be a result of the automatic adjustment within the camera itself, the qualities of the light source, or a combination of both.

Tendencies for the different Brightness levels

Figure 4.2 shows plots for each of the seven different brightness levels with colour temperature setting along the horizontal axis. With this way of representing the results, the observations that indicate more blue light for higher brightness levels becomes more noticeable. Plotting the results with colour temperature along the horizontal axis, shows us where along the horizontal axis the most prominent colour in the light changes from red to blue. A trend is that the change moves towards the left as the brightness increases. For example, we see that with a brightness of 1% the change happens between colour temperature settings 5 and 6, and with a brightness of 100% the change happens between settings 2 and 3.

Comparing the Different Visual Representations

When comparing Figure 4.1 and Figure 4.2, a tendency is that the Δ values are more alike when looking at the colour temperature setting separately. This is as expected because the change in brightness should be more linear than change in colour.

Before and After Images

The before and after images for the Colorophone camera can be seen in Figure 4.3. We see that that the images are significantly more alike across the different lighting conditions after correction than before, indicating an improvement from using our system. This is especially visible for the grey background and the white reference patch itself. A tendency is that the warmer before images appear a bit cooler after correction, and vice verca. This can indicate that our colour correction algorithm shifts the colour temperature a little too much, and that there is room for improvement in the implemented algorithm.
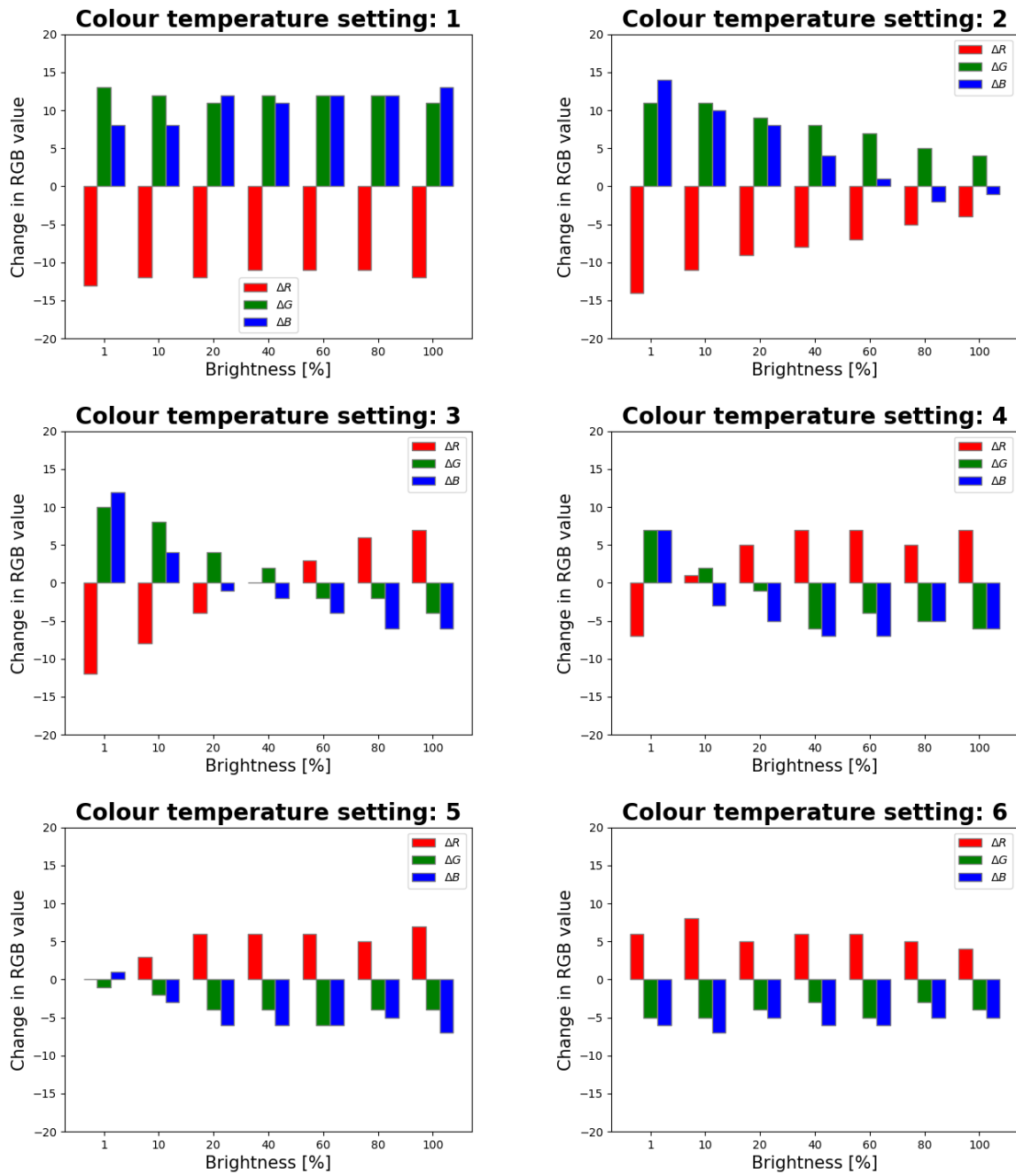
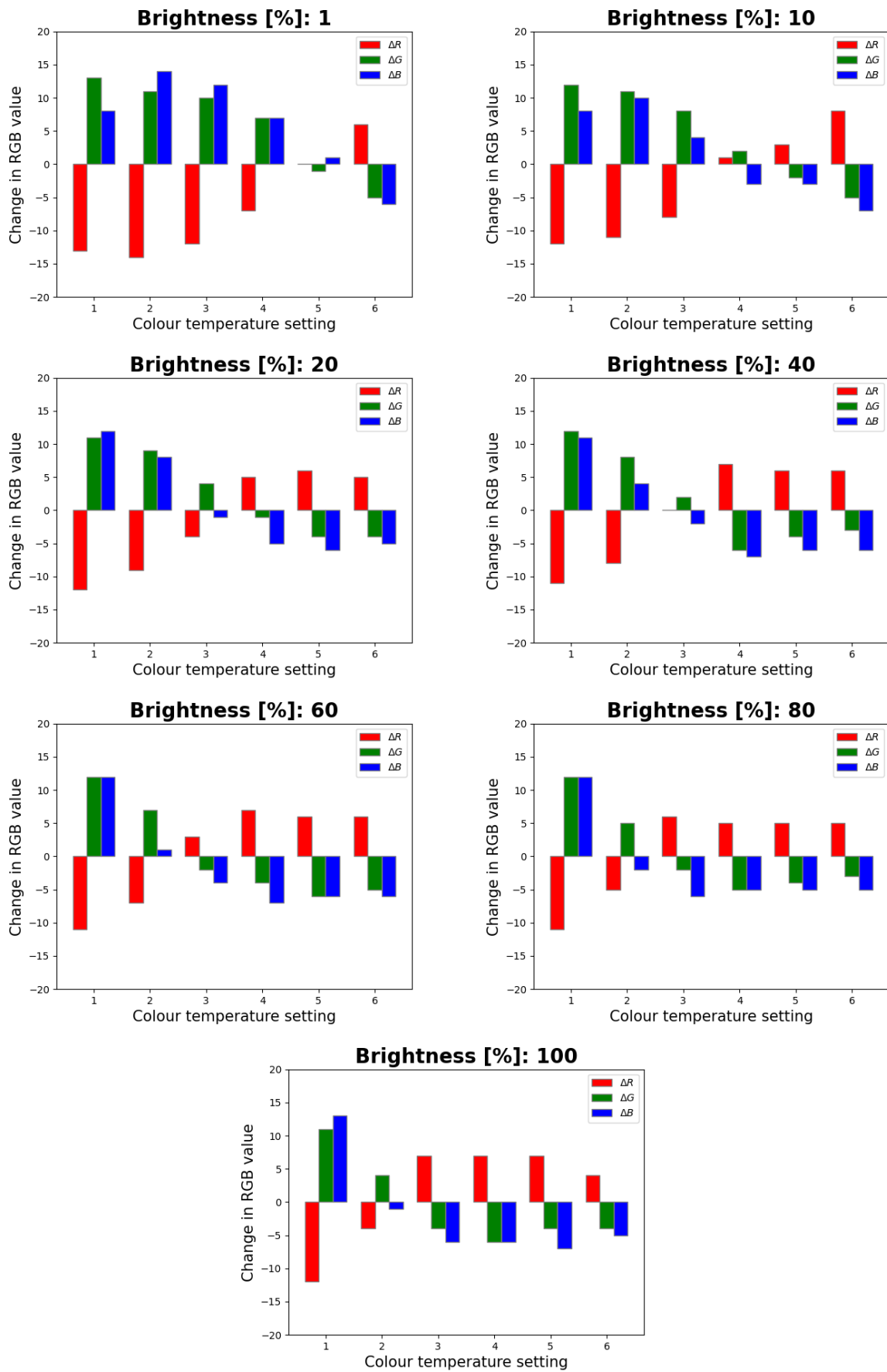**Figure 4.1:** Bar plots with brightness along the horizontal axis.

Figure 4.2: Bar plots with colour temperature along the horizontal axis.

(a) Image before correction. Colour temperature setting 1 and brightness 10%.

(b) Image after correction. Colour temperature setting 1 and brightness 10%.

(c) Image before correction. Colour temperature setting 1 and brightness 100%.

(d) Image after correction. Colour temperature setting 1 and brightness 100%.

(e) Image before correction. Colour temperature setting 6 and brightness 10%.

(f) Image after correction. Colour temperature setting 6 and brightness 10%.

(g) Image before correction. Colour temperature setting 6 and brightness 100%.

(h) Image after correction. Colour temperature setting 6 and brightness 100%.

Figure 4.3: Images from Colorophone camera before and after correction for the extremities in colour temperature and brightness.

4.2   Microsoft Camera

The before and after images for the Microsoft camera can be seen in Figure 4.6. The Δ values for the white reference patch are shown in Figure 4.4 and Figure 4.5.

Impact from the Colour Correction System

Testing indicates that the Microsoft camera benefits from the white reference patch and colour correction only in the warmer light settings. Figure 4.4 shows that the two warmest colour temperature settings, setting 1 and 2, have the highest absolute Δ values and benefit from the colour correction. The cooler the colour temperature gets, the less the system corrects the image. The two coolest colour temperature setting have Δ values $= 0$. This is also visible when looking at the before and after images from testing the Microsoft camera, where we see that only the warm images have a change before and after correction. This indicates that the built in automatic adjustment of white balance in the camera performs very well when blue is the most prominent colour in the light. Because the camera is a web camera developed for use in office areas, where neutral coloured light from LEDs often is used, it is natural that the camera performs best in these light settings.

Tendencies for the Different Colour Temperatures

Figure 4.4 shows each of the six different colour temperature settings with brightness level along the horizontal axis. As for the Colorophone camera, we are able to get useful information about how the colour correction system works differently on the warmer, cooler and more neutral settings with the Microsoft camera. The camera shows different behaviours between the to warmest colour temperature settings, and similar behaviours between the two coolest colour temperature settings and between the two centremost settings. The key observations are:

- **Temperature setting 1:** This is the warmest setting. We observe that the Δ values are somewhat even along the horizontal axis, indicating an even impact from the colour correction for all brightness levels. Because this is the warmest setting, it is as expected that red is most prominent colour.
- **Temperature setting 2:** This is the second warmest setting. We see a decreasing trend in amplitude for ΔR and ΔB as the brightness increases. This indicates that blue becomes more prominent when the brightness level increases. ΔG does not appear to have a pattern. Why this happens is unknown.
- **Temperature setting 3 and 4:** These are the two neutral light settings. We see that there are some changes for the lower brightness levels. From around a brightness of 20% and up, the Δ values equal 0. This shows that for the higher brightness levels, the camera needs no correction.
- **Temperature setting 5 and 6:** These are the coolest light temperature settings, and they have no changes from our colour correction system. This indicates that the camera's auto white balance works very well for these settings.

Tendencies for the different Brightness levels

Figure 4.5 shows plots of the seven different brightness levels with colour temperature setting along the horizontal axis. These plots show that the lower brightness levels are more in need of correction than the higher brightness levels.

Before and After Images

The before and after images for the Microsoft camera can be seen in Figure 4.6. As for the Colorophone camera, we see that that the images are significantly more alike across the different lighting conditions after correction than before, indicating an improvement from using our system. The images visibly show how the warmer before images in light setting 1 are corrected, and how no correction is done for light setting 6. This corresponds with what we saw in the the bar plots in Figure 4.4.

We observe that the white reference patch in the images blends with the the colour of the background. Possible reasons for this is that the camera focus is on the objects further away, causing the white reference patch be out of focus and appear blurry. The material of the white reference patch is not perfectly diffuse, and it is possible that it reflects some the grey colour from the inside coating of the box.
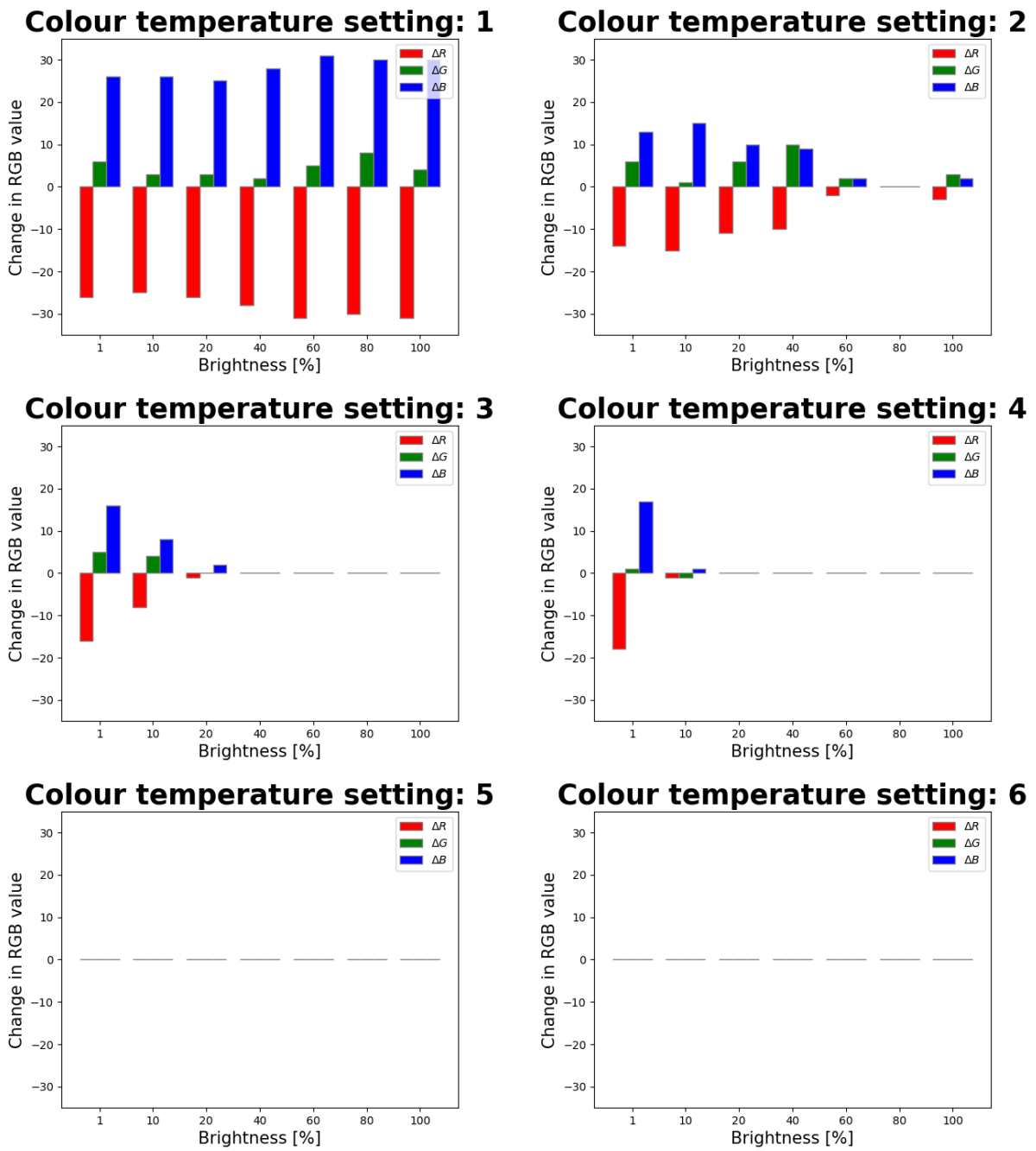
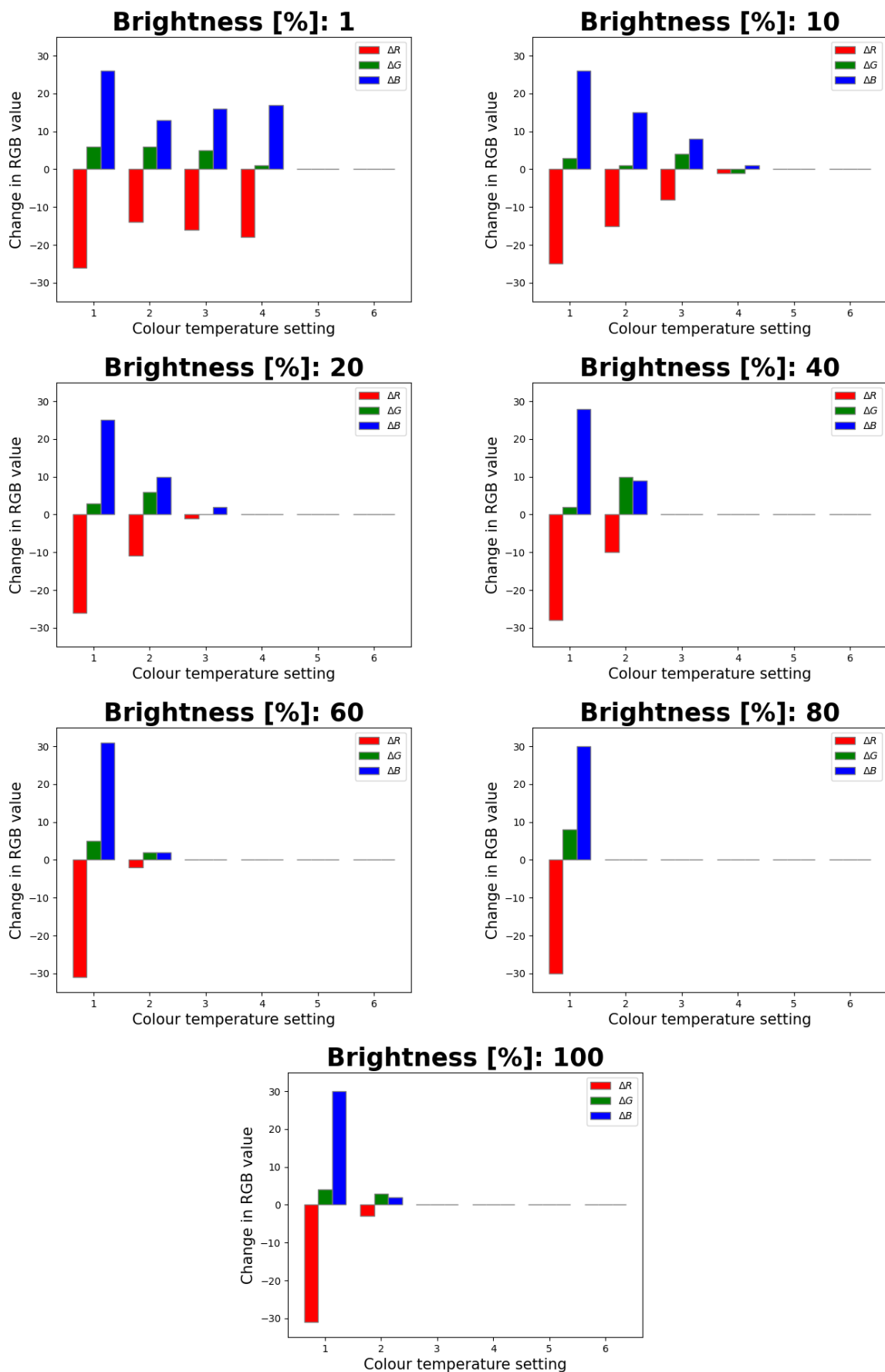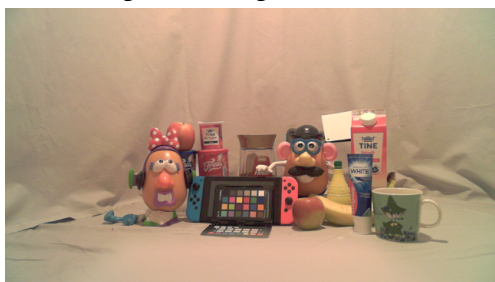**Figure 4.4:** Bar plots Microsoft LifeCam with brightness along the horizontal axis.

Figure 4.5: Bar plots Microsoft LifeCam with colour temperature along the horizontal axis.

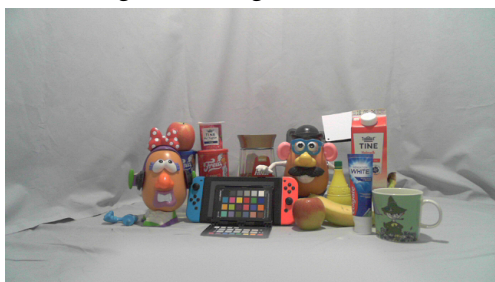**(a)** Image before correction. Colour temperature setting 1 and brightness 10%.

(b) Image after correction. Colour temperature setting 1 and brightness 10%.

(c) Image before correction. Colour temperature setting 1 and brightness 100%.

(d) Image after correction. Colour temperature setting 1 and brightness 100%.

(e) Image before correction. Colour temperature setting 6 and brightness 10%.

(f) Image after correction. Colour temperature setting 6 and brightness 10%.
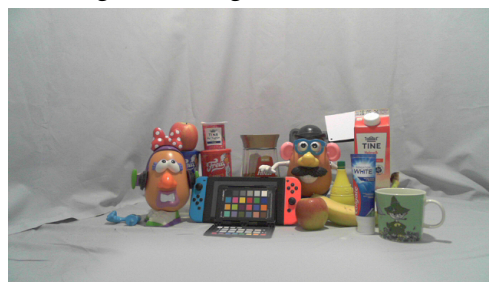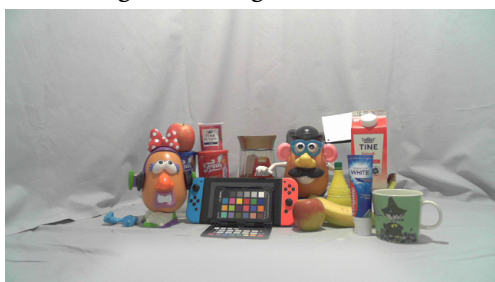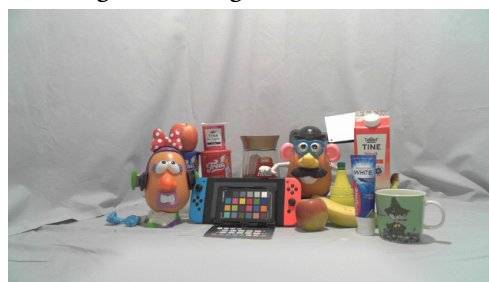
(g) Image before correction. Colour temperature setting 6 and brightness 100%.

(h) Image after correction. Colour temperature setting 6 and brightness 100%.

Figure 4.6: Images from the Microsoft camera before and after correction for the extremities in colour temperature and brightness.

Chapter 5

Discussion

In this chapter we will explain and evaluate the results from our project, to answer the research question: *Can the implementation of a white reference patch improve the handling of colour constancy in the Colorophone system?*

The results presented in chapter 4 indicate that the existing Colorophone system performs better regarding colour constancy after the implementation of a white reference patch. As mentioned in chapter 1, the performance does not have to be perfect, as long at is is better than without the reference. Although the system performs the desired way, there are several problem areas that need to be addressed and discussed, and more experimental research remains to say whether this solution should be implemented in the existing Colorophone system.

The findings of our project indicate that different cameras perform differently regarding colour measurement and colour reproduction, and considering different camera modules may contribute to better handling of colour constancy as well.

5.1   Camera Comparison

The results show that the two cameras tested in this project handle colour constancy differently. The Colorophone camera benefits from colour correction in every light setting, whilst the Microsoft camera only benefits from correction in the warmer colour temperature settings. For the cooler colour temperatures, the Microsoft camera handled colour constancy very well without any correction from our system. This can indicate that implementing a different camera in the Colorophone system could contribute to improving colour constancy. We have only tested two cameras in this project, but this can be further explored through testing more cameras and comparing their handling of colour constancy, size and price.

The two different cameras have different sized reference patches due to their different FoVs, which causes the patch to appear differently in the camera frame. The reference patch implemented on the Colorophone is small enough to be further developed for a practical solution in real life, but the size of the reference patch for the Microsoft camera is considered to be too big for this. In addition, the patches blend differently with the surroundings. It is unclear whether this difference impacts how the colour correction system works on the cameras.

1

5.2   Problem areas

The main problem areas we found when implementing our solution was saturation of the reference patch, as well as the unknown parameter of the camera's own adjustments. This section describes how we handled these problem areas in our project, and in section 5.5 we go more in depth in how they should be addressed in further work.

Saturation of the reference patch

Saturation of the reference patch is a possible problem area that can occur if implementing a *white* reference patch. If saturation occurs, a colour correction system would not benefit the Colorophone. One of the possible solutions we looked into to avoid saturation, was using a neutral, light grey reference patch instead of a white reference patch. Because saturation did not occur when testing inside the black box, testing could be carried out with a white reference patch for this project. Because of this, and due to lack of time we prioritised to not investigate different grey materials because testing with a white reference patch would provide data on whether the idea of a reference patch should be further looked in to or not. Future work should therefore include testing different grey patches, and this is further discussed in section 5.5. To test this, the saturation indicator in the implemented software is a useful feature to identify if and when saturation occurs.

Automatic camera adjustment

The automatic camera adjustment remains an unknown parameter in the colour correction process. This means that implementing algorithms that work well across a wide range of light settings, and for different cameras, can be complicated. However, implementing a colour correction algorithm that uses values from a reference patch will always come as an addition to the automatic camera adjustments. This indicates that our solution can work well without too much insight in the camera's own adjustments.

5.3   Project Implementation and Method

Throughout the whole process, we have iterated on the system and solution of problem at hand. This has been done by expanding our theoretical knowledge on the subject, experiences and observations and through conducting with knowledgeable and more experienced people in the field. This strengthens the method used to obtain the results.

Implementing the Algorithm

The algorithm implemented in the colour correction system is based on normalisation and scaling in relation to a reference point. One limitation of our implemented algorithm is that it simplifies colour reproduction in images, and this simplification may not necessarily work in all situations. However, in a student project with a defined time frame, this simplification is a natural limitation. Additionally, obtaining the desired results with a simple algorithm can be a good first step in finding out if the solution works well or not.

Colour constancy is a complicated and on going research field, and we have limited both time spent on research and how in depth out algorithm needed to be. The implemented algorithm was developed based on colour measurement theory and conducting with the client and experts in the field of colour measurement. The software has been developed with this in mind, so that different algorithms can be easily tested.

Test environment

The realised test environment, consisting of the black box, the inside coating and the light source, had several limitations. Neither the inside coating nor the light source were standardised, meaning that knowing if some of our findings were caused by our colour correction system, the spectrum of the light source or the camera itself was difficult. Additionally, the pre defined colour temperature settings in the light bulb determined the range we were able to test the system for. Using standardised equipment could better this to some extent, but would require more money and/or facilities. A workaround to using standardised equipment could be performing a spectral analysis on the light source inside the black box, and providing the project with useful information. This was considered, but due to limited knowledge about performing the spectral analysis, we were not able to prioritise it.

A natural limitation due to the scope of the project, is that we by testing in a controlled environment ended up not collecting data about how well the system performs in real life situations. This is further addressed in section 5.5 as a key point in further work.

Test design

In our project, we included data for the measured colour of the reference patch before and after correction, which meant we did not collect data about different coloured objects. Although different colours are represented in the before and after images for comparison, we do not show any numerical data how the colour correction system impacts them. The images show that some of the colours look a little muted after correction, especially when corrected from the warmest settings. This is something that could be further looked into, and the ColourChecker could possibly be used to collect data about this. The implemented software has functionality for logging data from multiple colours in the image frame simultaneously, and how this can be used is discussed further in section 5.5.

The tests were designed so that the program measures data when the system is in steady state. This means that our findings do not show how our system tackles dynamic changes in light settings, and if this is improved or not.

Programming in LabVIEW

LabVIEW was chosen as the programming environment for the project based on a recommendation from the client. Because the software for the Colorophone is developed in Lab-VIEW, using LabVIEW would make it easier to merge the programs in the future. Throughout the implementation process, the focus was mainly on what the program was designed to do and the functional requirements, and not necessarily system development itself. Our skills in LabVIEW have improved significantly throughout this project, but we have still kept many of the VIs developed early in the process that fulfil their functional requirements, even though

they could be improved from a systems design perspective. This decision allowed us to spend more time on other parts of the project than system maintenance.

During the development of the software, we used GitHub to collaborate. Because LabVIEW is a graphical programming language, collaborating on the same project is more demanding than when using a text-based programming language because conflicts between files are not solvable. Because of this, we focused on communicating and planning which parts of the program we were working on and how we merged our program, as well as using VIs to compartmentalise different functions of the program. The implemented program is documented well with comments and explanations in the main program and the VIs.

Our Results with regard to improved usability of the Colorophone

This project does not provide any specific results in regard to how well our colour correction system improves the usefulness of the Colorophone. However, with the results obtained in this project, we expect that further experimental research with user testing can be developed based on the findings of our project, and this is described in section 5.5. Because the mapping from colour to sound is based on the ratio between red, green and blue parameters in the light, it is likely that when this ratio is more alike across different light settings (i.e. colour constancy is better after correction than before), the sound mapping will show this as well. But even though the measured colour constancy is better after than before, we cannot know whether this improvement is substantial enough to provide a perceptible difference to the users.

5.4   Submitted Product

The client of this project wanted a mechanism that could improve the colour constancy in the Colorophone system. The idea of implementing a reference patch to do this came from the client, who wanted the project to examine if this idea should be further developed or not. At the end of this project the following have been submitted to the client:

- LabVIEW program for image correction and automatic testing
- Python script for result visualisation
- Test environment for camera testing (black box)
- Report of project findings

This delivery corresponds with the requirements from the client.

The software for the image correction system can be implemented in the existing software for the Colorophone, because of how the LabVIEW program is built up using VIs. It is also possible to use parts of the program in other projects. The automatic measurement program and the python script can be used as a basis for testing cameras and different implementations of reference patches.

The test environment, the black box, is useful for the client as a closed environment for testing different cameras, the Colorophone system and additional features.

5.5   Further Work

The findings of this project provide a basis for further work in developing a mechanism to improve colour constancy in the Colorophone. Further work on the solution itself includes evaluating different materials and colours for the reference patch, as well as the algorithm for colour correction. Further testing should include testing in real life situations, evaluating the system during dynamic changes and lastly user testing to evaluate usefulness of the system.

Reference patch material

Based on the observations made during testing, it is likely that a white reference patch will saturate in sunlight or another bright light source, or when the contrast to the surroundings becomes high. Based on this, we can assume that a light grey coloured reference patch would be more ideal. Further testing should include evaluating different shades of grey in different materials to find the most suitable reference patch. Important factors when deciding this should be how diffuse the material is and signal to noise ratio for the information provided by the reference patch, meaning the patch can not be too dark.

Algorithm development

This project shows promising results from using normalisation based on values from a reference patch to perform colour correction, and it is possible to further develop the implemented algorithm. Important criteria for the algorithm, in addition to improving colour constancy, is that the system avoids causing colour to saturate after correction. Our findings indicate that the implemented algorithm may cause some of the warmer images to be corrected so they appear a bit cool, and vice verca. This should be further investigated and taken into consideration when further developing the algorithm.

Camera testing

The implemented test environment and testing program turned out to be very useful for testing and comparing different cameras. Our project showed how two different cameras handle colour constancy very differently, and this indicates that implementing another camera module in the Colorophone system might solve some of the difficulties regarding colour constancy without an additional reference patch.

Whether changing the camera module of the Colorophone or implementing a white reference patch is the better solution, is not possible to conclude from this project. Further work on this area should include using the black box and test system to test and compare more cameras. Testing inside a closed environment might also give more insight in how the different cameras' built in adjustments perform.

Colour measurement and collection of data

Further work should include testing how different colours are impacted by the correction system. One way to do this is using the ColorChecker, which is widely used as a standard in the field of colour measurement. This could give information about how well the colour

correction system works to maintain colour constancy, beyond showing just the impact from the colour correction step.

Real life situations and dynamic changes

Testing in a closed environment does not give data about how the system will work in real life conditions where the Colorophone might be used. This limits our findings, but gives useful insight in how we might expect the system to behave. Further testing should therefore include testing in real life conditions with different light sources, such as outside, in an office, in a supermarket and/or in a home.

When performing the tests, we observed that it could be interesting to examine the dynamic changes when the light settings changed. Because the Colorophone is intended as a real time sensory substitution, collecting data about the systems performance during light changes might provide useful insight.

User testing

The results from this project show that the implementation of a reference patch can improve the colour constancy in the Colorophone system. This does not necessarily mean that the usability will improve. Future user testing could include testing the usability of our implemented system in comparison to the existing Colorophone system.

Chapter 6

Conclusion

Throughout this project we have gone from the idea that a reference patch can contribute to improving colour constancy in the Colorophone, to a functional system that implements this idea. We have built a closed testing environment, implemented a colour correction program to correct images based on a reference patch, and implemented a test program to evaluate the performance of the colour correction program. The results from testing have been presented to show the visual difference in images before and after correction, as well as plots showing the impact from our system.

We found that the camera module of the Colorophone benefited from the reference patch and colour correction, and that colour constancy was improved. This interpretation is based on the assumption that the implemented colour correction algorithm improves colour constancy, and examining the impact this algorithm had on the existing Colorophone system. Our findings indicate that this solution can contribute to improving colour constancy in the Colorophone if further developed. More testing remains to determine if the solution can contribute to increased usability of the Colorophone.

In addition to evaluating colour constancy in the Colorophone, our project streamlined the process of camera testing. Because of this, we were able to compare the behaviour of the camera in the Colorophone to a second camera. This comparison showed that the two cameras had very different abilities regarding colour reproduction, and indicates that considering another camera module for the Colorophone could be beneficial regarding colour constancy. The streamlined process of camera testing is useful to continue to improve both colour constancy in the Colorophone, as well as other camera features that can benefit from systemic testing in a closed environment.

This project has resulted in a first study of colour constancy in the Colorophone. The implemented solution shows promising results, and gives valuable insight for future development. Further work should look into the colour and material of a reference patch, the algorithm for colour correction and different ways to test and evaluate the performance of the system.

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Appendix A

Images from testing

Images before and after correction with Colorophone camera, midrange calibration:

Figure A.1: Colour temperature setting 1: Before and after correction for different brightness settings.
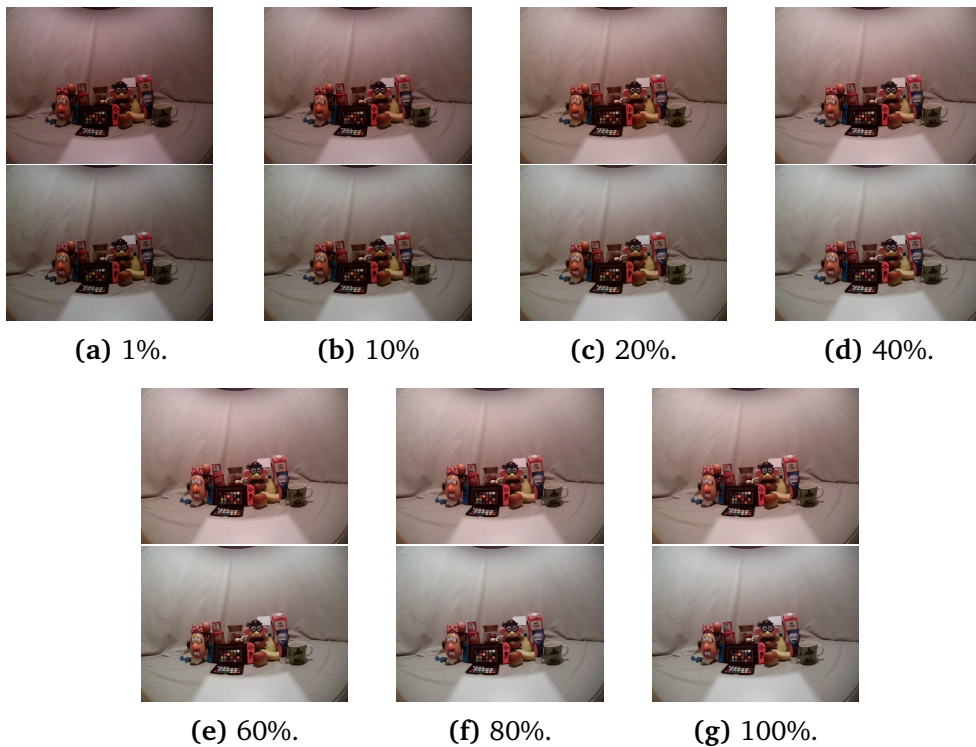

(a) 1%.   (b) 10%   (c) 20%.   (d) 40%.
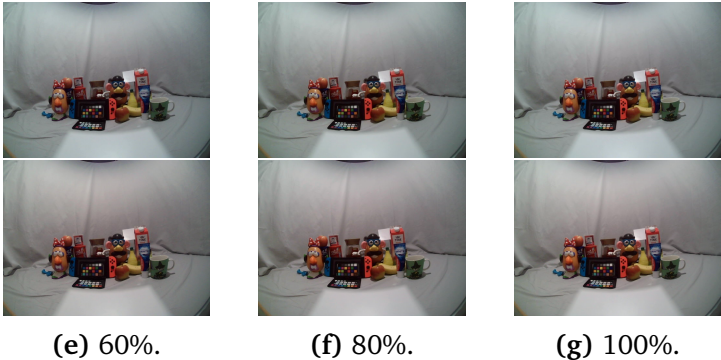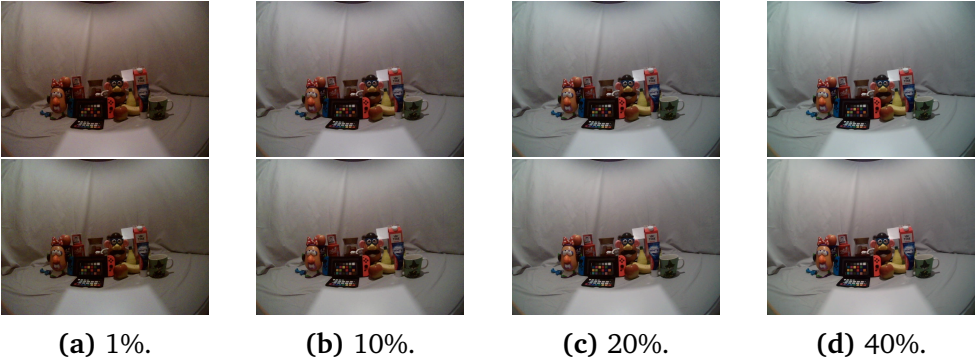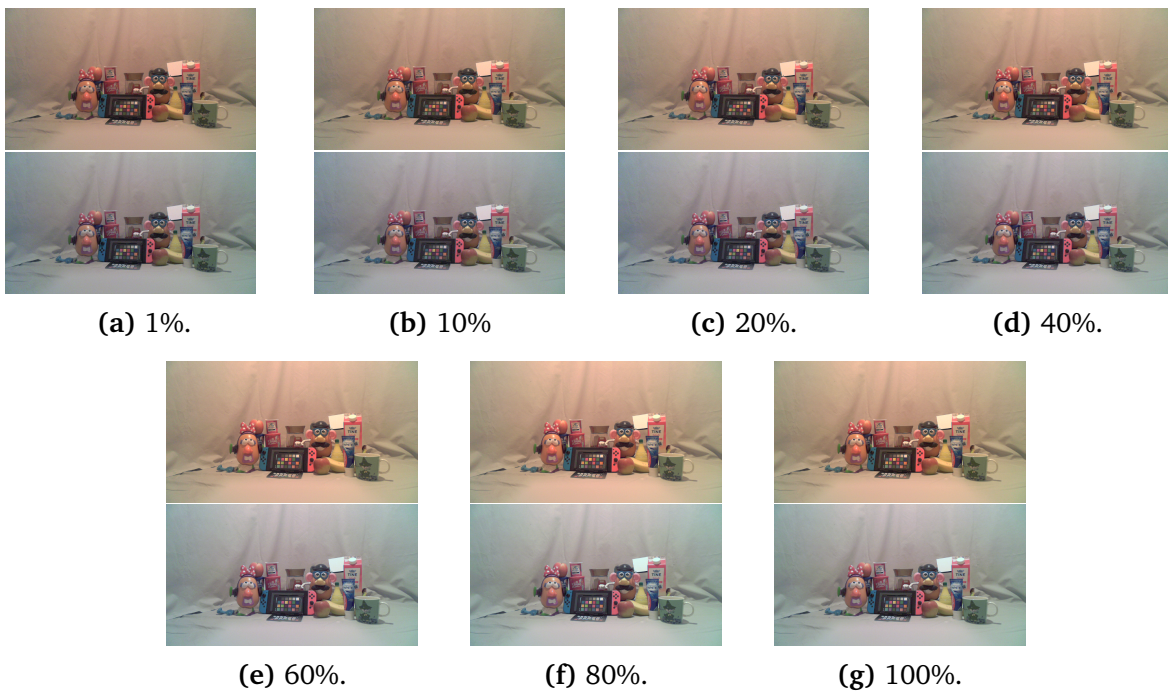

(e) 60%.   (f) 80%.   (g) 100%.

Figure A.2: Colour temperature setting 2: Before and after correction for different brightness settings.

(a) 1%.   **(b)** 10%.   **(c)** 20%.   **(d)** 40%.

(e) 60%.   **(f)** 80%.   **(g)** 100%.
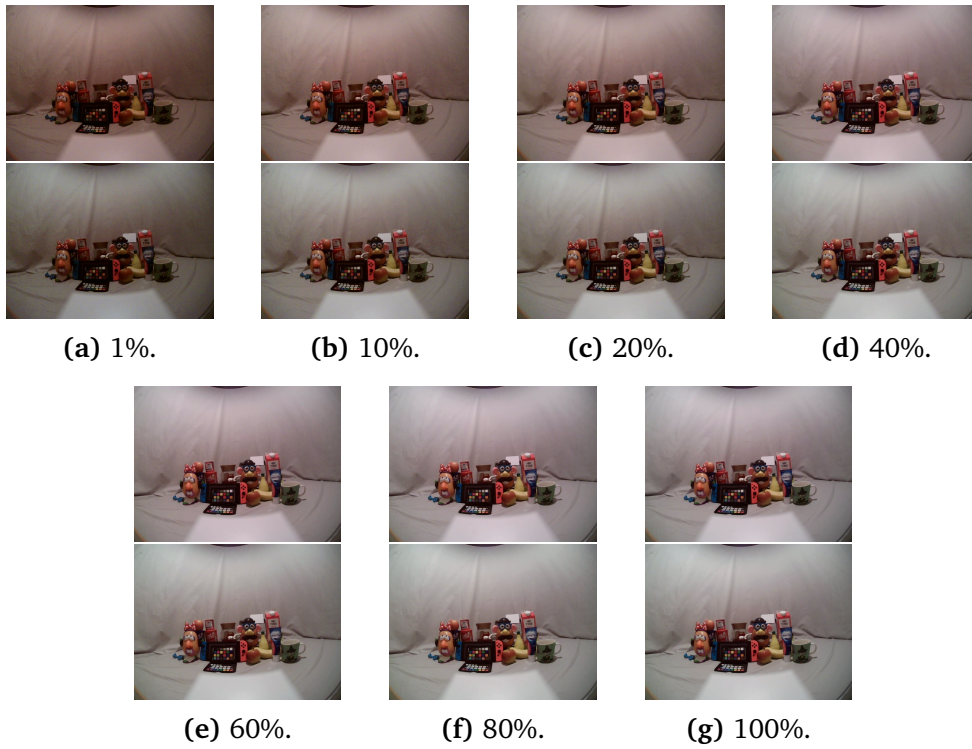
Figure A.3: Colour temperature setting 3: Before and after correction for different brightness settings.

(a) 1%.   **(b)** 10%.   **(c)** 20%.   **(d)** 40%.

(e) 60%.   **(f)** 80%.   **(g)** 100%.
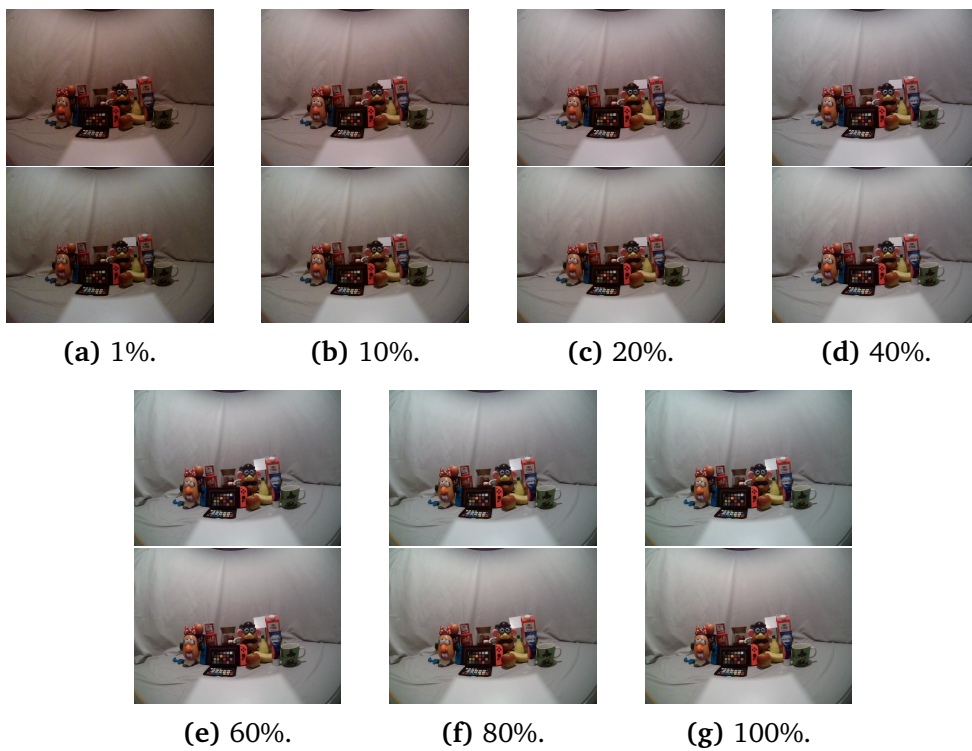
Figure A.4: Colour temperature setting 4: Before and after correction for different brightness settings.

(a) 1%.   **(b)** 10%.   **(c)** 20%.   **(d)** 40%.

(e) 60%.   **(f)** 80%.   **(g)** 100%.

Figure A.5: Colour temperature setting 5: Before and after correction for different brightness settings.

(a) 1%.   **(b)** 10%.   **(c)** 20%.   **(d)** 40%.

(e) 60%.   **(f)** 80%.   **(g)** 100%.
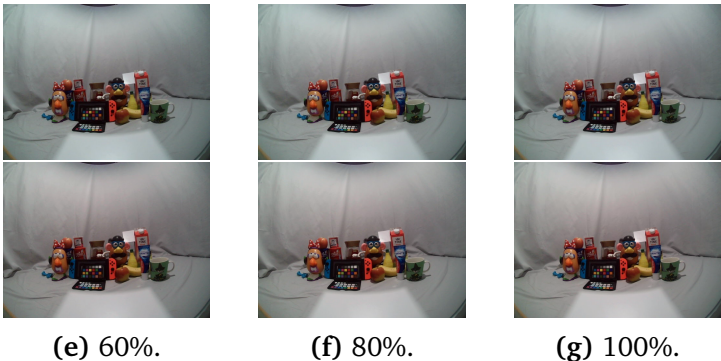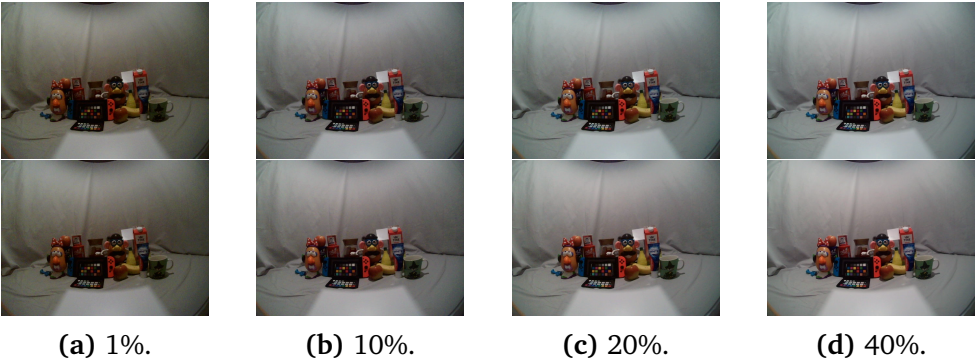
Figure A.6: Colour temperature setting 6: Before and after correction for different brightness settings.

(a) 1%.　　**(b)** 10%.　　**(c)** 20%.　　**(d)** 40%.

(e) 60%.　　**(f)** 80%.　　**(g)** 100%.
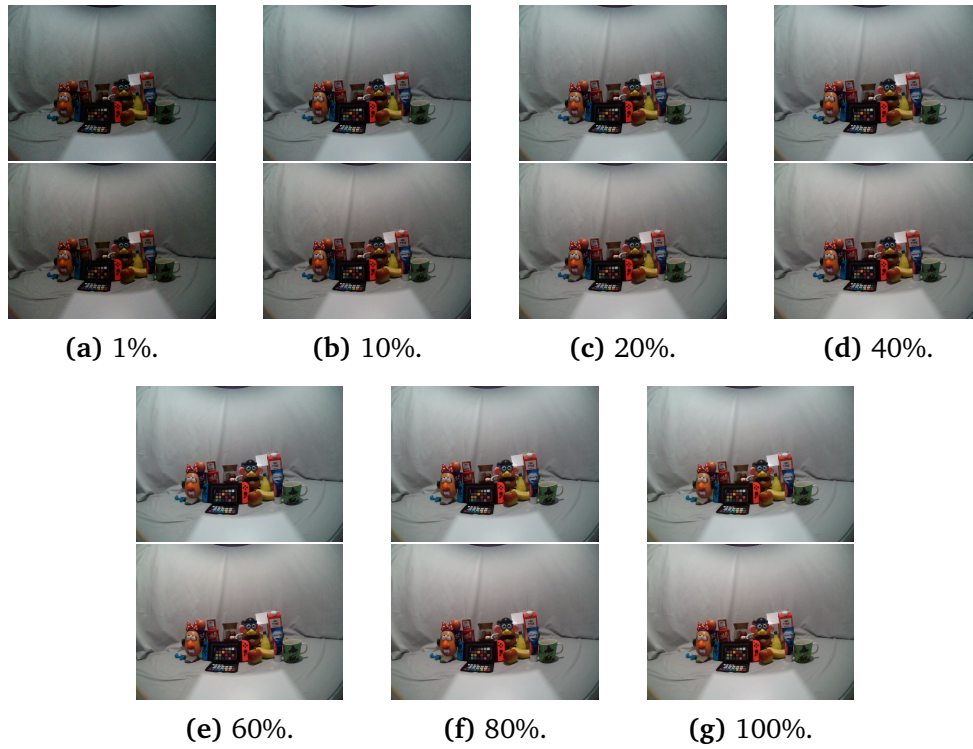
Images before and after correction with Microsoft camera, midrange calibration:

Figure A.7: Colour temperature setting 1: Before and after correction for different brightness settings.

(a) 1%.　　**(b)** 10%　　**(c)** 20%.　　**(d)** 40%.

(e) 60%.　　**(f)** 80%.　　**(g)** 100%.

Figure A.8: Colour temperature setting 2: Before and after correction for different brightness settings.

(a) 1%.

(b) 10%.

(c) 20%.

(d) 40%.

(e) 60%.

(f) 80%.

(g) 100%.
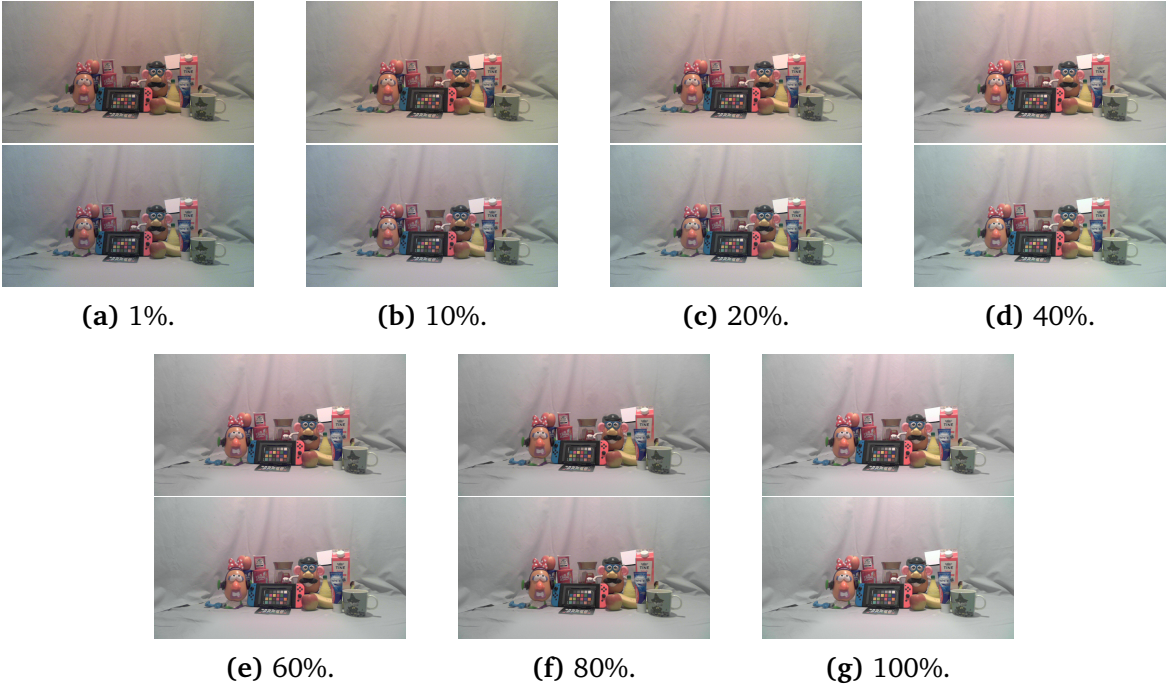
Figure A.9: Colour temperature setting 3: Before and after correction for different brightness settings.

(a) 1%.

(b) 10%.

(c) 20%.

(d) 40%.

(e) 60%.

(f) 80%.

(g) 100%.

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Figure A.10: Colour temperature setting 4: Before and after correction for different brightness settings.

(a) 1%. (b) 10%. (c) 20%. (d) 40%.

(e) 60%. (f) 80%. (g) 100%.

Figure A.11: Colour temperature setting 5: Before and after correction for different brightness settings.

(a) 1%. (b) 10%. (c) 20%. (d) 40%.

(e) 60%. (f) 80%. (g) 100%.
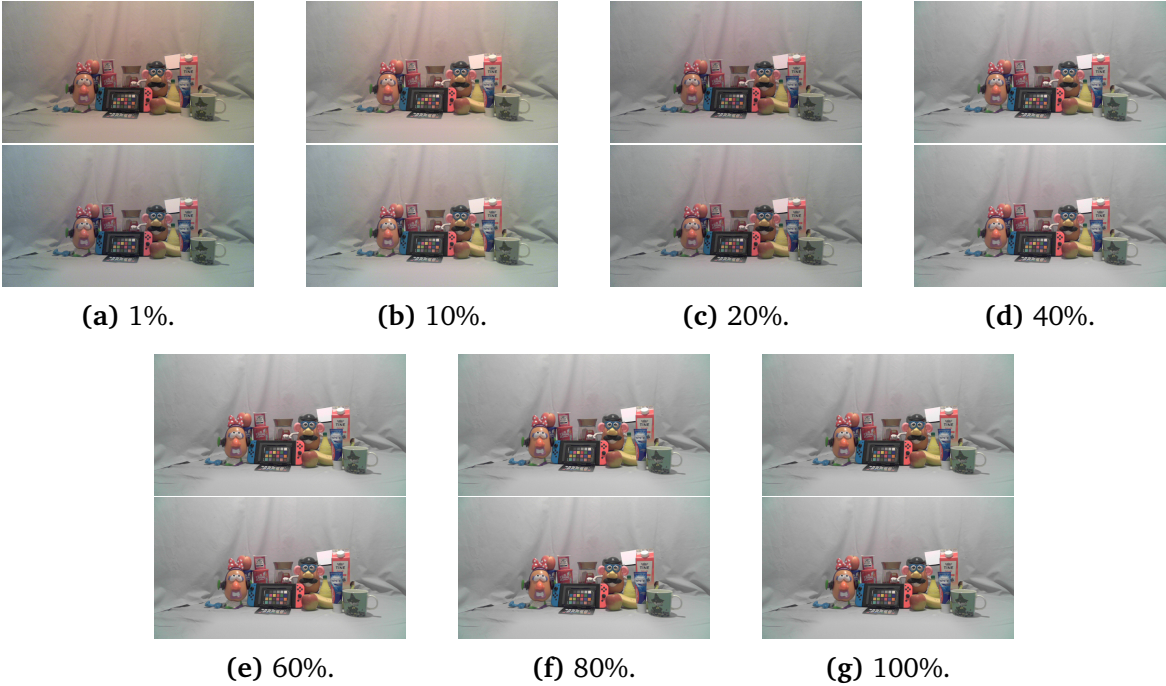
Figure A.12: Colour temperature setting 6: Before and after correction for different brightness settings.

(a) 1%.

(b) 10%.

(c) 20%.

(d) 40%.

(e) 60%.

(f) 80%.

(g) 100%.
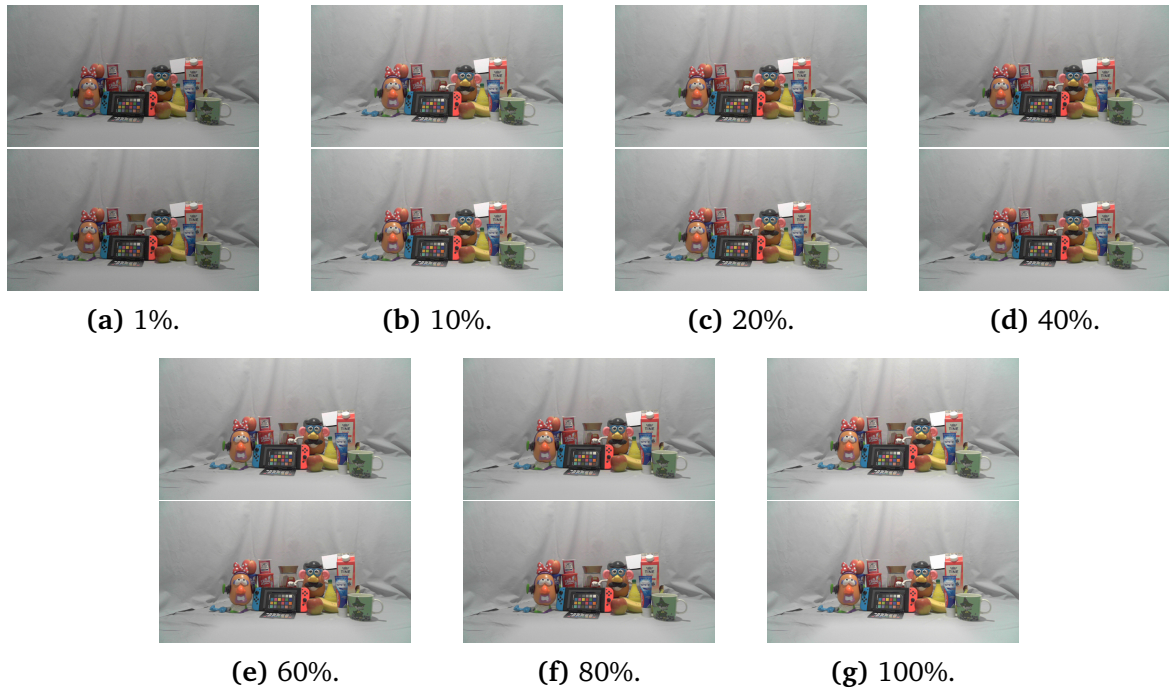
Appendix B

Barplots

This appendix contains the output reports from testing, with barplots of the ΔR, ΔG and ΔB values from the white reference patch. Reports included in this appendix:

- Colorophone camera, calibration method midrange
- Colorophone camera, calibration method max
- Microsoft camera, calibration method midrange

Note that the annotation along the vertical axis varies for the different tests, due to varying maximum and minimum values for the different tests.

Delta values for white reference patch with Colorophone camera

Calibration method: Midrange

Delta values for white reference patch with Colorophone camera

Calibration method: Midrange
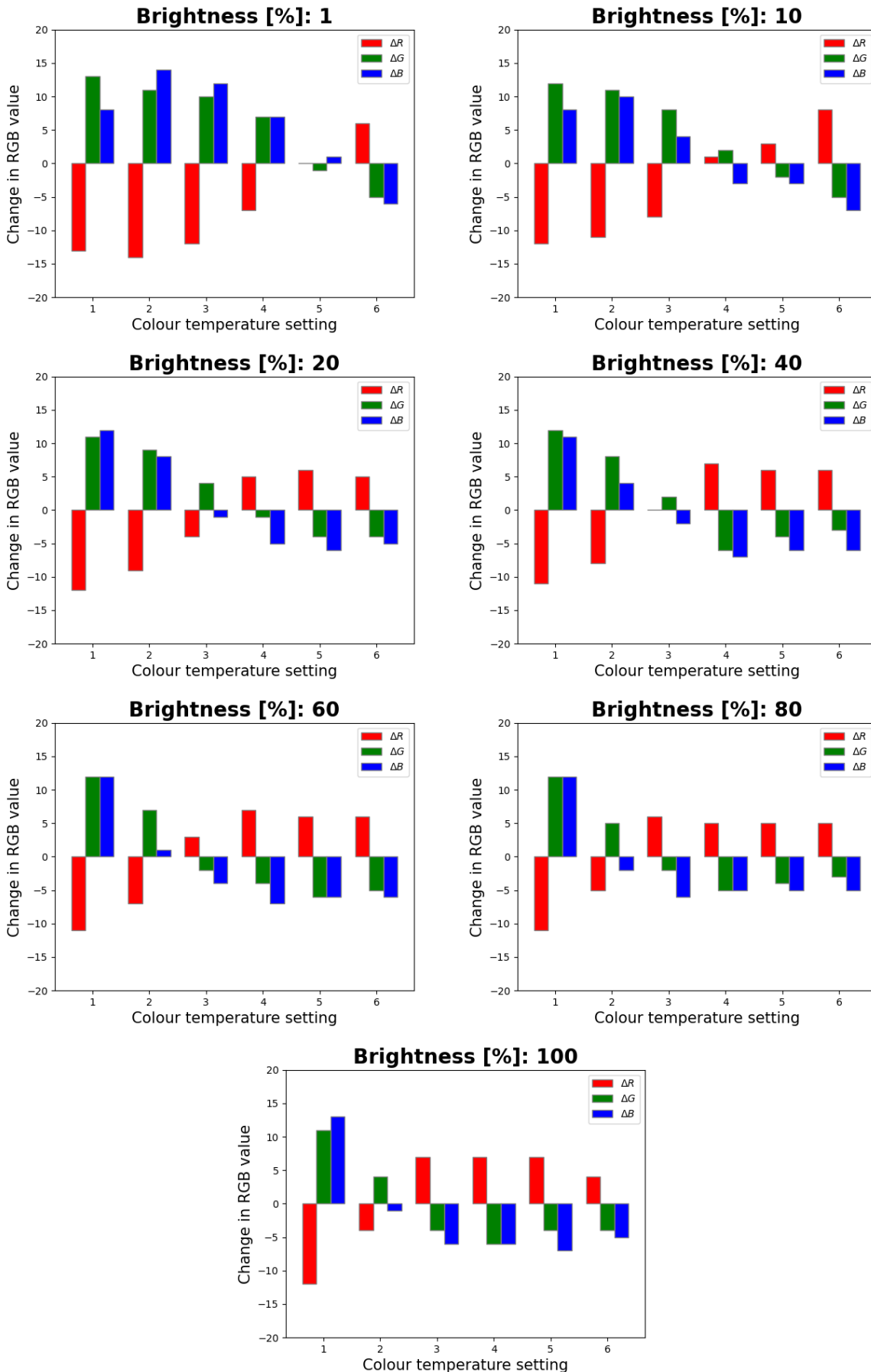
Delta values for white reference patch with Colorophone camera
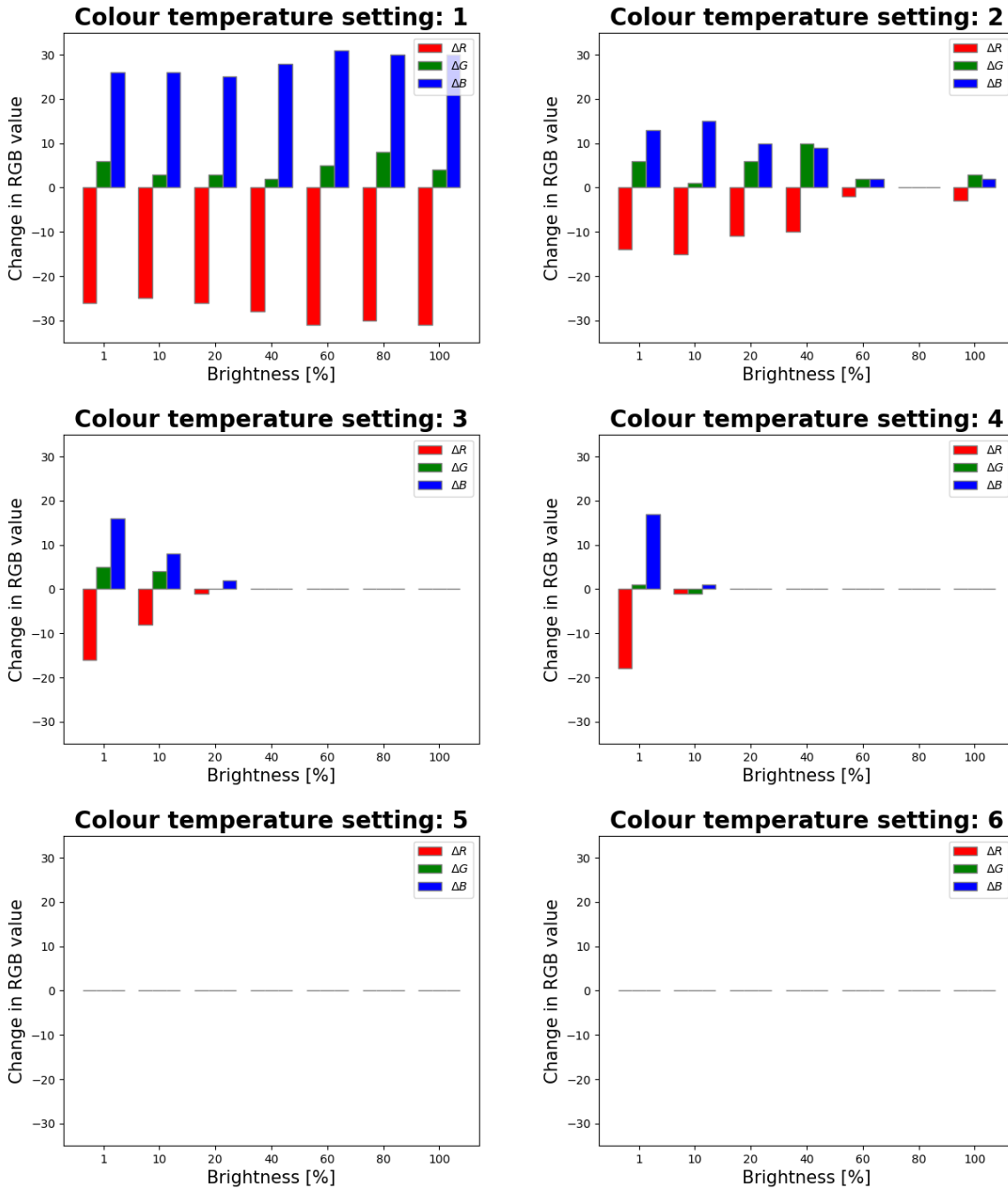
Calibration method: Max
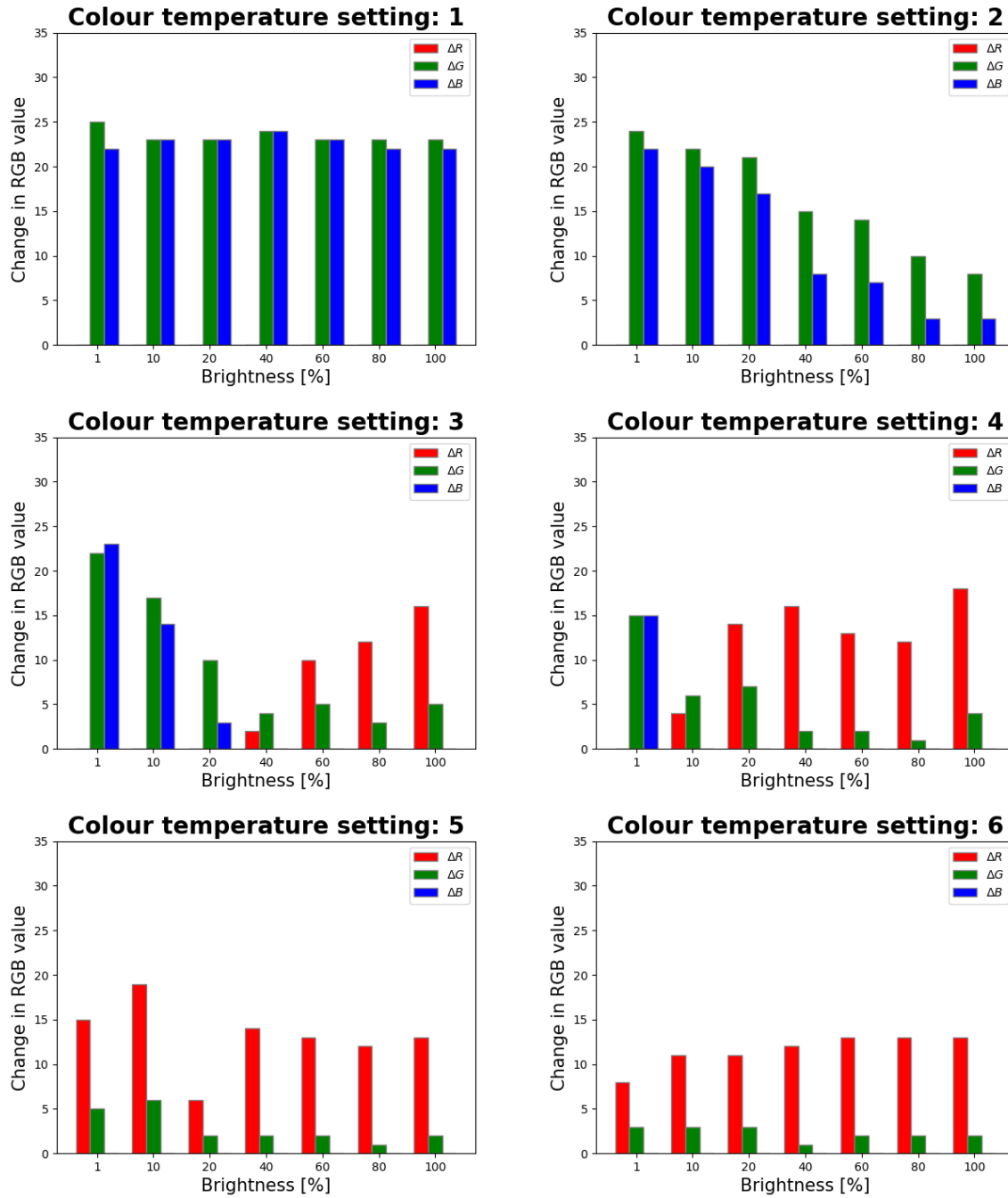
Delta values for white reference patch with Colorophone camera
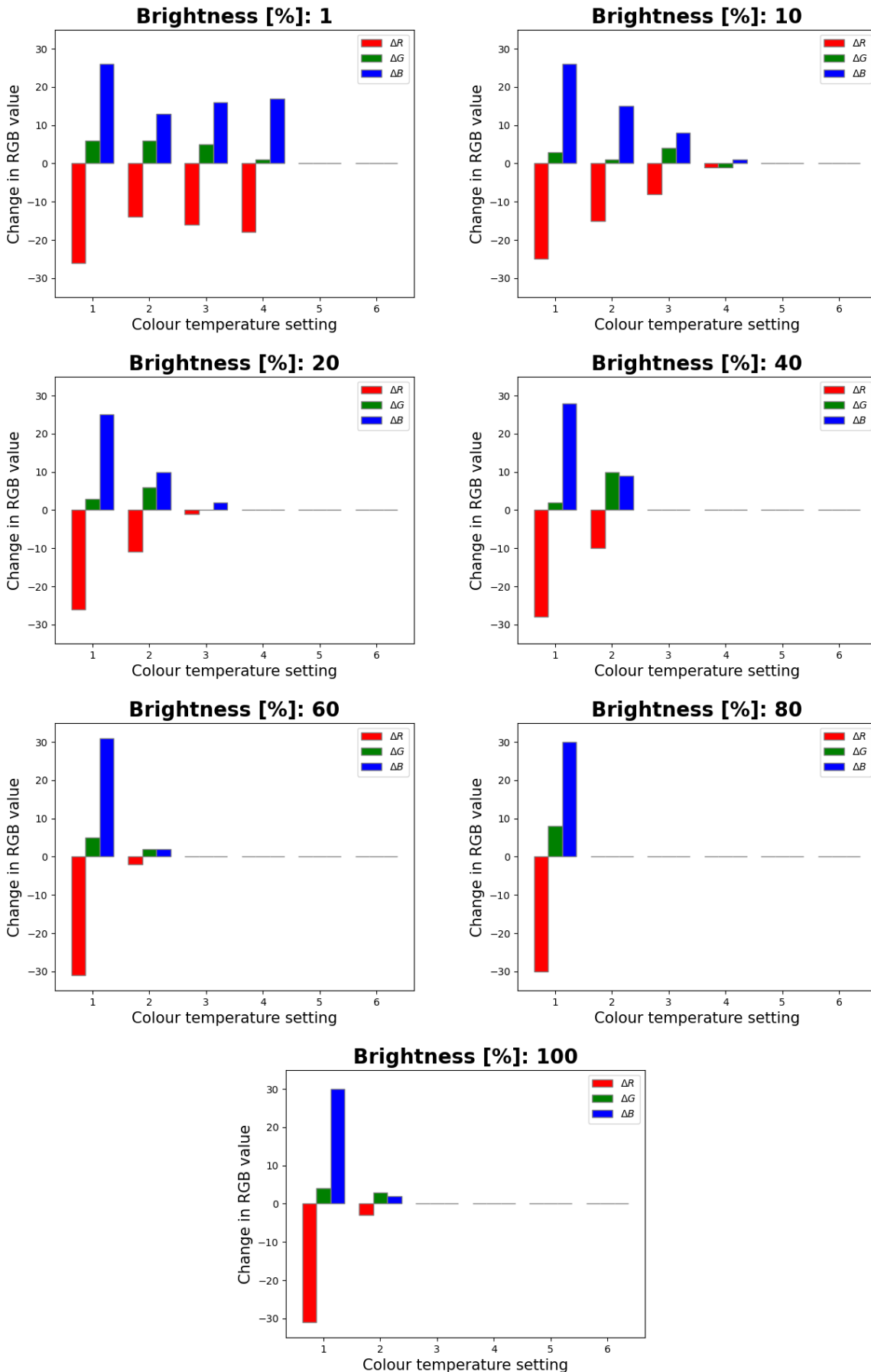
Calibration method: Max
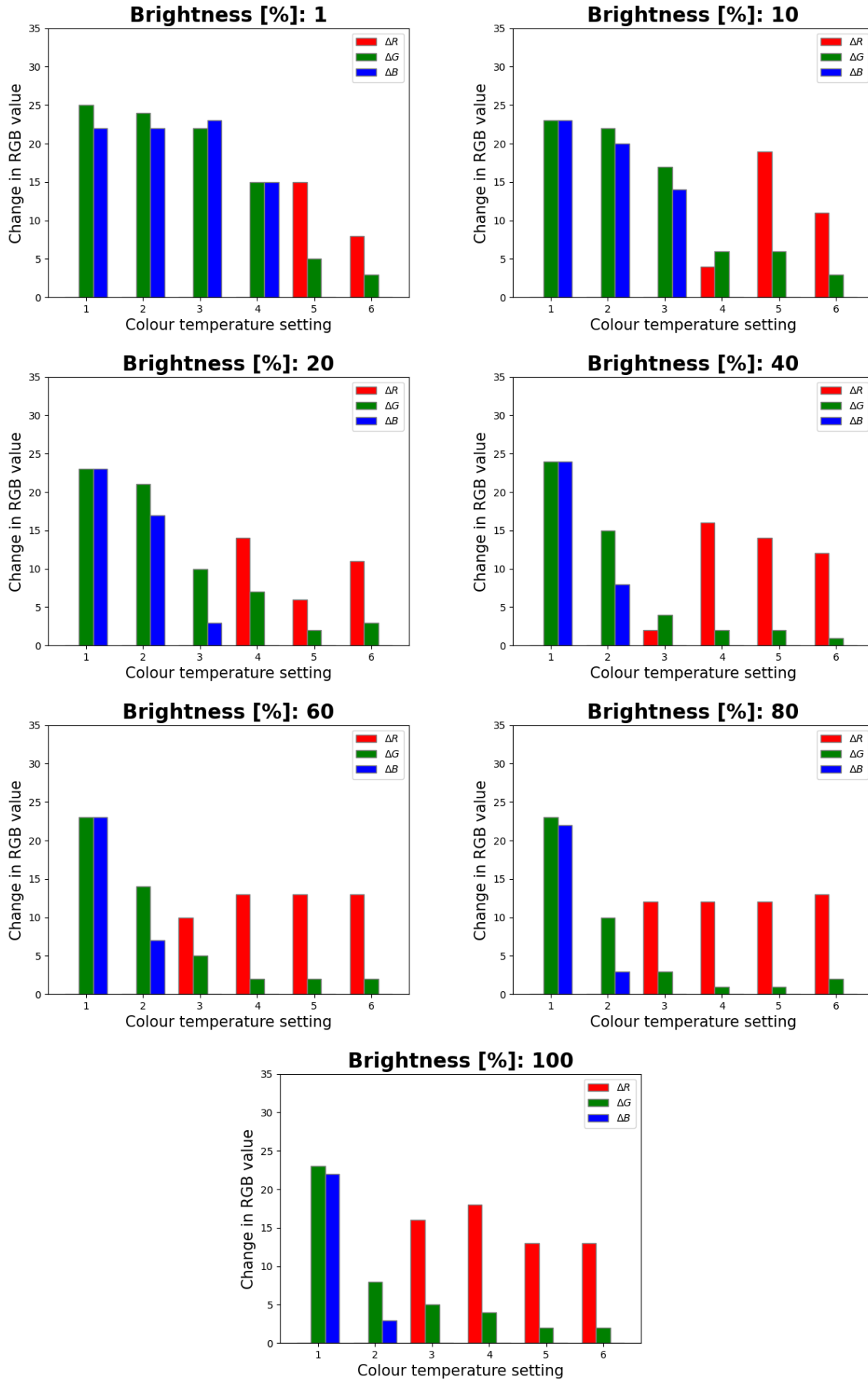
Delta values for white reference patch with Microsoft camera

Calibration method: Midrange

Delta values for white reference patch with Microsoft camera

Calibration method: Midrange

Appendix C

Photos from process

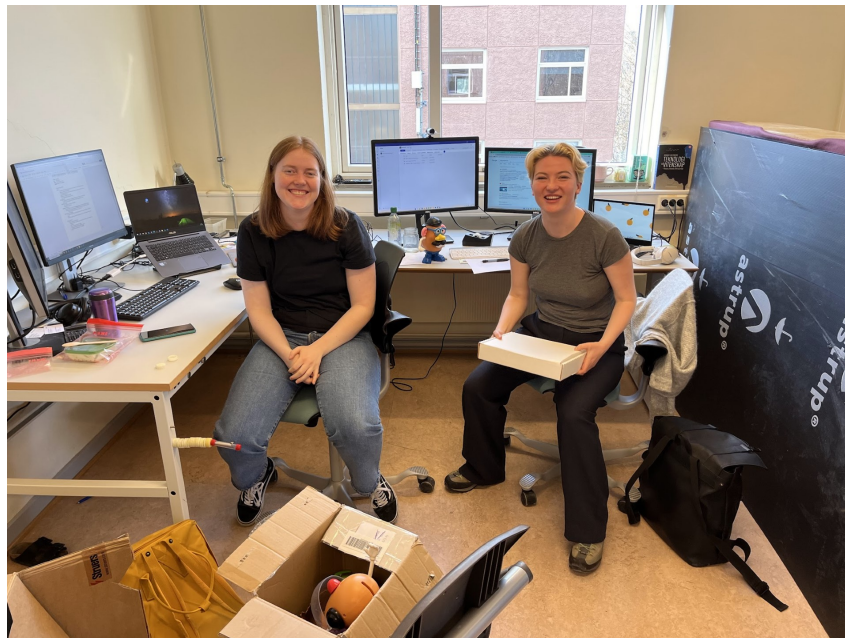This appendix includes photos from the process of building the black box.

Figure C.1: Ingrid and Hanne at their office setup with *a lot* of equipment.

Figure C.2: Ingrid and Dominik trying out a round shape for the black box.

Figure C.3: Cutting out the roof/floor of the black box.

Figure C.4: Ingrid testing the camera inside the black box while building.

Figure C.5: View of the inside of the black box while building.

Appendix D

Poster

Improving Colour Constancy in a Sensory Substitution System

Real time camera calibration and automation of testing procedures in NI LabVIEW

Background

The Colorophone is a sensory substitution device developed at Department of Electronic Systems (IES) at the Norwegian University of Science and Technology (NTNU). The Colorophone uses a camera to detect information about colours in the surroundings, which in turn is transformed to an auditory signal. The goal is to help the blind and vision impaired in their everyday tasks.

The problem

One of the problem areas that occurred during the development of the Colorophone was handling of colour constancy. Colour constancy describes the phenomenon where colours are perceived similarly independent of external lighting conditions. The human visual system handles colour constancy remarkably well, but this is hard to replicate in technological systems.

The solution

Can the implementation of a white reference patch improve the handling of colour constancy in the Colorophone system? Providing the system with information from a neutral point, a white reference patch, may give enough information to adjust for different lighting conditions. This possible solution has been implemented and tested in a closed environment for a limited range of different lighting conditions.
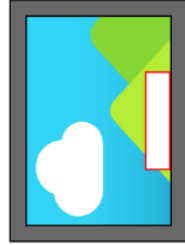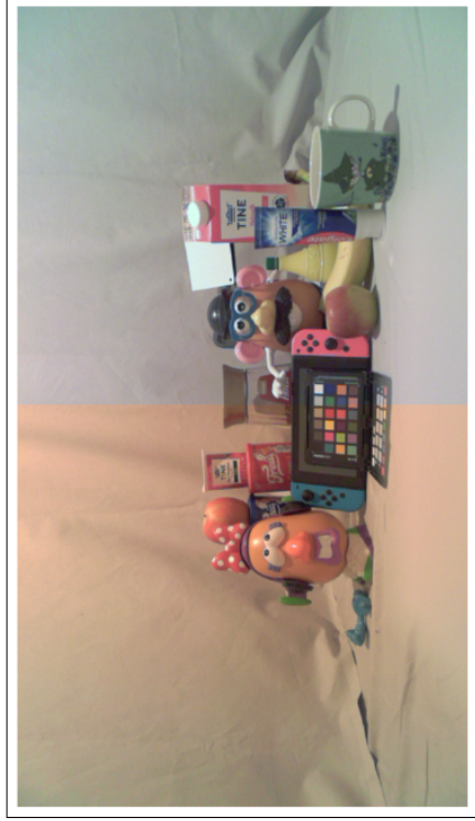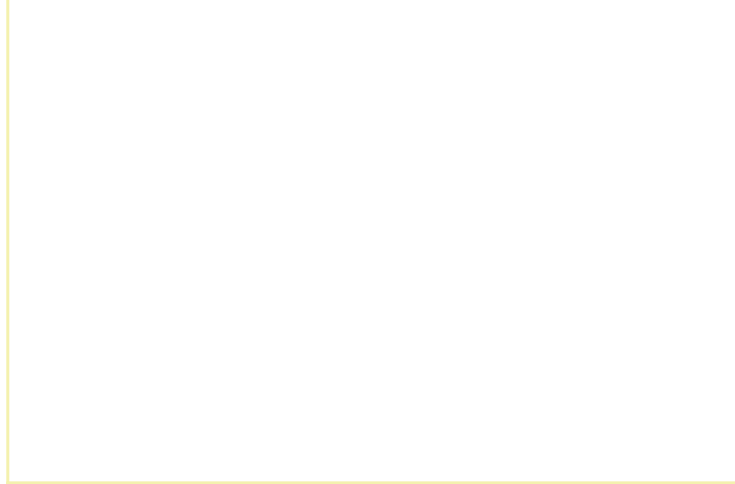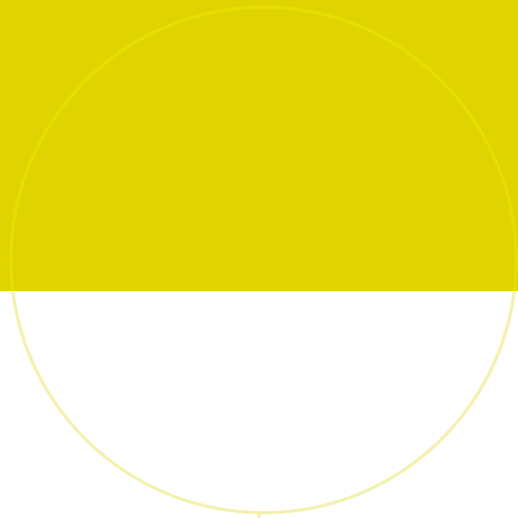
The implementation

A white reference patch has been implemented on the camera module of the Colorophone system with assosiated software for image correction.

Results and conclusion

We found that the camera module of the Colorophone benefited from the reference patch and colour correction, and that colour constancy was improved. This interpretation is based on the assumption that the implemented colour correction algorithm improves colour constancy, and examining the impact this algorithm had on the existing Colorophone system.

Our findings indicate that this solution can contribute to improving colour constancy in the Colorophone if further developed. More testing remains to determine if the solution can contribute to increased usability of the Colorophone. The implemented solution shows promising results, and gives valuable insight for future development.

NTNU