Challenges of Lighting in Virtual Production Film Studios

An Analysis of the Lighting Quality of LED Walls

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Information Concerning Visuals

The images of my results in the Appendix in the digital version of this thesis are provided in Rec.709 color space. For an accurate visualisation it is recommended to view the images on a calibrated Rec.709 display in a dark or on a RGB display in a brighter environment.

Abstract

Filming in Virtual Production (VP) LED Volumes, as a totally new technique of filmmaking comes along with various undiscovered difficulties. As LED walls are required to realize In-Camera VFX (ICVFX), which takes a lot of preparation and testing to eliminate all the eventually occuring errors that may occur while filming in virtual production stages.
To capture the right image in concern of color reproduction it is important to recognize the architecture of the LEDs. LED walls used nowadays are built of pixels, with each pixel consisting of three diodes which are producing red, green and blue light. This is based on the fact, that these LED walls are manufactured to be great WCG (Wide Color Gamut) displays rather than being optimized cinematic light sources. This results in an extremely narrow banded color spectrum with larger gaps in between the different visually possible wavelengths and a highly poor color rendition of the scene when LED walls are used as a light source. Non-neutral refelcting objects potentially have a higher color shift, if their color is not represented sufficiently in the emitted light spectrum.
As it is always promised, that you can do image-based lighting with LED Volumes which nowadays still can't reproduce a wide spectrum of colors, it should be considered as a main issue to analyse. In this thesis was investigated from which amount of light coming from the walls, the colors of the scene are being affected. The following chapters will analyse how lighting a scene with currently available LED walls effects color quality in-camera and to what amount cinematographers should use additional full spectral light sources to minimize the occuring color shifts.
The examination leads to the fact, that as long as there are no LED walls with a more solid color spectrum for LED virtual production usecases, LED walls should not be used as a key-light in LED virtual production studios. To a certain extend the wall is a tolerable partial fill-light beside full spectrum lighting sources.

Kurzfassung

Das Filmen in Virtual Production (VP) LED Volumes als völlig neue Technik des Filmemachens birgt unterschiedliche, noch unerforschte Hürden. Da LED Walls genutzt werden um In-Camera VFX (ICVFX) zu realisieren, erfordert es einiges an Vorbereitung und Testing um alle möglichen Fehlerquellen zu eliminieren, die während des Filmens in Virtual Production Studios entstehen könnten.

LED Walls welche heutzutage in Virtual Production Umgebungen eingesetzt werden, bestehen aus Pixeln, welche aus Dioden zusammengesetzt sind, die rotes, grünes und blaues Licht erzeugen. Dies basiert darauf, dass LED Walls, welche in Virtual Production Umgebungen verwendet werden, ursprünglich produziert wurden, um gute Displays mit WCG (Wide Color Gamut) zu sein und nicht als gute Lichtquelle entwickelt wurden. Dies führt zu einem extrem schmalbandigen Farbspektrum mit einzelnen Peaks, was in einer schlechten Farbwiedergabe der Szene resultiert, wenn diese mit LED Walls beleuchtet wird. Dies hat zur Folge, dass viele nicht-neutrale Reflektanzen potentiell einen stärkeren Farbshift erleiden, wenn deren Farbe im emittieren Licht spektral nicht ausreichend vorkommt. Da es ein bekanntes Versprechen ist, dass man die Displays für Image-based Lighting verwenden kann, welche heutzutage einen großen Anteil sichtbarer Farben nicht reproduzieren kann, sollte die Frage, ob diese Art von Einsatzzweck auch tatsächlich empfehlenswert für die Praxis ist, genauer untersucht werden.

Das Ziel dieser Arbeit war zu untersuchen, bis zu welchem Anteil an Licht, welches von der Wall reflektiert wird, die Farben der Szene beeinträchtigt werden. Es wird genauer analysiert, ob es immer noch empfohlen werden sollte, eine Szene mit dem Licht der derzeit verfügbaren LED Panele auszuleuchten und welcher Anteil des Lichts von breiter spektralen Lichtquellen stammen sollte.

Im Rahmen der Arbeit konnte gezeigt werden, dass solange keine LED Wände mit umfassendem Farbspektrum für den Virtual Production Gebrauch existieren, LED Displays nicht als Führungslicht verwendet werden sollten. Bis zu einem bestimmten Maß kann die Wall als tolerable Aufhellung neben breiter spektralen Lichtquellen genutzt werden.

Contents

List of Acronyms

ARRI Arnold & Richter Cine Technik

BNC Bayonet Neill Concelman

CIE Commission Internationale de l'Éclairage

CGI Computer Generated Images

CRI Color Rendering Index

HDMI High Definition Multimedia Interface

IMU Inertial Measurement Unit

ICVFX In-Camera VFX

LDC Light Distribution Curve

LED Light-Emitting Diode

MoCap Motion Capture

MPC Moving Picture Company

POC People of Color

RGB Red Green Blue

TIFF Tagged Image File Format

UCS Uniform Chromaticity Scale

VP Virtual Production

VR Virtual Reality

WYSIWYG What you see is what you get

WCG Wide Color Gamut

XR Extended Reality

List of Figures

List of Tables

1 LED Virtual Production Environments

1.1 Virtual Production Definition

There are various types of Virtual Production (VP) including completely Virtual Production, which involves no physical props or actors. There is green screen VP and performance capture VP, which uses real actors in Motion Capture (MoCap) Suits. This thesis is focussing on in-camera or so-called LED wall Virtual Production.
The term Virtual Production is quite diversified referring to a broad range of computer-based filmmaking methods. One notable definition of *Weta Digital* is: "Virtual Production is where the physical and digital worlds meet." [Kad, p. 3-4] *Moving Picture Company* (MPC) charged its definition with a more technical view: "Virtual Production combines virtual and augmented reality with Computer Generated Images (CGI) and game-engine technologies to enable production crews to see their scenes unfold as they are composed and captured on set."[Kad, p. 3-4].
The so called ICVFX (In-Camera Visual Effects) are one of the most sought-after techniques in VP. ICVFX can be divided into two types: live LED wall Virtual Production and live compositing VP. In live compositing VFX, real-life objects are filmed and composited together with virtual objects in real time. The elements are keyed with traditional green or blue screen compositing.

In the recent past, such ICVFX could be created with the help of rear or front-screen projections. LED wall cinematography is the new modern way of VP, a technique which combines real-time virtual objects with on-set real-life elements optically live in-camera with the help of LED screens, that are arranged in so-called LED Volumes [Kad21, p. 3-4].The essential concept is

creating a real-time rendered virtual scene, using a game engine, like *Unreal Engine* by *Epic Games*. It is about surrounding real life physical props or actors using a LED wall [Del20, p. 5-6] [Lux21] [Kad21, p. 52].
Unreal Engine by *Epic Games* is seen as the special tool in VP environments. LED wall VP combines a bunch of technologies from the gaming industry with those from film productions that were originally both independent disciplines. The synergy effect of using these two spheres in conjunction resulted in a revolutionary technique of film making [BC14, p. 1-8].
Unlike the traditional rear-projected movies, it's not just a simple case of displaying a 2D image of the 3D background on the screens behind the talents. When the cinema camera is moved, the virtual environment on the LED wall has to shift perspective, too. This is known as parallax and it creates the illusion that the scene is being filmed in a real-life location[Del20, p. 4] [Lux21].

The attention to detail is key to simulating a real-live location and leading the viewer into believing the environment is real. This is achieved using a method called live camera tracking. Live camera tracking involves tracking where the physical production camera is located and then translate it into *Unreal Engine*. Typically sensors or motion tracking cameras are used to track the system and reflect it into *Unreal* [Del20, p. 3-9] [Lux21].
A camera tracking system paired with rendering in real-time, allows a shift in perspective or so-called parallax in the LED wall projected environment matching the camera movement, and appearing in-camera identical to an authentic 3D (Three Dimensional) world [Kad21, p. 57].
Tracking systems can be split into several solutions. Basic sensor-based solutions like the *HTC Vive*, which is being tracked through lighthouses (laser scanning is used for locating puck) and an IMU (Inertial Measurement Unit), which was at first designed for Virtual Reality (VR) gaming gadgets, up to the more advanced tracking systems, which have been used for *The Mandalorian*. Tracking systems that work on an outside-in optical system use an array of fixed infrared cameras. The cameras are surrounding the Volume, usually on top of the LED wall or in the rigging system above, looking for markers, which have been placed all around the studio area. Examples for outside-in tracking systems are for example *Vicon*, *OptiTrack* or *BlackTrax* [Kad21, p. 57-58].

Another key component to successful LED wall cinematography is LED display technology. LED walls consist of interlocking LED bricks or modules combined into a large screen with additional video processing hardware and software [Kad21, p. 52-56]. LED walls will be observed in more detail in the following section 1.3 and in chapter 2.
Further components of the key hardware and workflow for in-camera visual effects such as the camera und a LED wall are visualized in Figure 1.1.

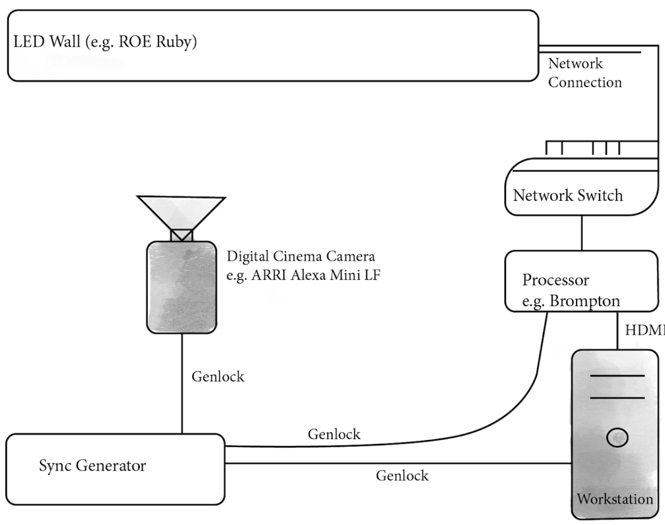

Figure 1.1: Key Hardware of a LED Virtual Production Setup

Game Engines like *Unreal Engine* play a crucial role in in-camera visual effects by generating final-quality environments, characters, objects, lighting, and more in real time. *Unreal Engine* also incorporates live camera tracking to accurately reproduce the physical camera's corresponding perspective on the display as the camera moves. The ability to calculate perspective in real time makes live LED wall cinematography with a freely moving camera possible [Kad21, p. 52-56] [Gre21, p. 200-201]. A high-end digital cinema camera with high-quality optics is a crucial part of ICVFX. As moiré patterns can occur when having the LED wall in focus, a more shallow depth of field could help to combat the issue. Large-format camera sensors and a lenses which guarantee a widely open iris lead to a narrow depth of field and might be a good solution to use in LED Virtual Production Volumes [Kad21, p. 52-56].

All components of the VP workflow need to run on the same clock. To capture the image on the wall, a digital cinema camera, as well as the wall itself, need to be synchronized to the image, mainly a 3D environment. A careful synchronization between the camera's shutter and the refresh rate of the LED wall is key to avoid scan lines and banding in the resulting image. To ensure this, all components are connected via BNC (Bayonet Neill Concelman) cable to a Sync Generator which produces the so-called *Genlock Signal*.
The processor receives a video signal from a workstation via HDMI, which is transmitted to the wall via ethernet connection.

Another main issue is to make sure that the linear scene color, luminance values and contrast in the virtual scene are being properly represented on the LED display. The displayed content should appear as it would in real-life, without any look applied, since that will be added on the composited final in-camera image. This requires an optimal camera calibration process. OpenColorIO configurations are supported by *Unreal Engine* and enable users to apply the necessary transforms for color management during asset approval and final shooting [Kad21, p. 52-56].
The display for the real-time image, an LED output, the camera tracking, real-time color correction and compositing, and other connected operations work together as a nerve center of a VP and has the nickname *Brain Bar*.

1.2 LED Virtual Production Development and Prospects

“With more than two hundred production stages already in operation, Virtual Production is on the rise around the globe and continues to transform the art and craft of filmmaking for everyone involved in the production pipeline.“ Marché du Film, Festival de Cannes [Mar22].
The global pandemic 2020 might have had a great impact on the tremendously fast development of LED Virtual Production studios, as it caused generally an

increase of XR (Extended Reality) production solutions [KK22, p. 1-2].
As the "content desert" in filmproduction was caused by COVID-19, governments around the globe were looking forward to set new safety measures to be able to reopen. As Virtual Production assures a controlled environment rather than traveling and on-location shooting, it reopened opportunites [Del20, p. 3-9].

Friese and Odar, creators of the worldwide successful series *Dark*, came up with the idea to shoot the upcoming series *1899* in a LED Volume, due to the corona pandemic. It seemed to be the optimal solution in order to on the one hand keep the crew and cast safe, and on the other hand realize their idea. Considering the scale of the production, they built their own LED VP Studio in Potsdam-Babelsberg, Germany [McG22].
Baran bo Odar explains that at Netflix they were told about the new technology. Being tired to film in the traditional way after 3 Seasons of Dark they decided to produce 1899 in another way. Friese and Odar describe the process as being dominated by frustration at the beginning, because being pioneers in a new technique of filmmaking has hidden obstacles to overcome. It is literally a new way of filmmaking [Net22].

Virtual Production is seen as an emerging technique which will replace the usage of blue screen and green screen in filmmaking. There are several advantages of using a live image and capturing it directly. In contrast to common filmmaking approaches, VP includes a process which is more collaborative, non-linear, and iterative. Iteration is already part of the very early production schedule. LED wall Virtual Production has a WYSIWYG (What You See Is What You Get) effect. When shooting the composited image directly, the cinematographer has more power over the image, which is much nearer to the final pixels, than when shooting with green screen. A cinematographer can frame und composite the image in the studio in front of the wall nearly as good as outside on the field. The crew needs to do to a lot more of preparation work than before, whereas the work load in the postproduction shrinks [KK22].
All the on-set departments, like lighting or art department have much more influence on the final imagery, but also the following departments in post

production, like color correction and editing, have a better base to work on as being able to work with the already composited image. With this process being more agile, connected and collaborative, the decisions maintain with their department heads and happen in real-time, when the team is still present in the production process [Kad, p. 7-8] [PS1, p. 52-55] [Viv03] [Kad21, p. 52-56]. In former postproduction technologies a director had less control over the several steps in production, as the live action performance and the characters to be animated were part of separate processes [BC14, p. 1-8].
As VP came up when the global pandemic and the restrictions started in 2020, it is a technique which is highly conform with pandemic situations. It is not only easier to control the processes and the people on set, as it all takes place in a studio instead of on-location. The several processes can also be separated from each other. For example the whole brain bar can be either set on site or half up to entirely remotely. It is highly beneficial for social distancing requirements [Kad21, p. 61].
Another advantage is the planning. Location scouting could be done via virtual glasses, as filmmakers want to be able to do location scouting or direct an acting performances of characters regardless of whether they are real or virtual [Jun] [BC14, p. 1-8].
Dan Hamill, director at rental company *80six*, mentions: *"An LED Volume gives film-makers complete control over the environment they're shooting in. In a single day, you can shoot in a variety of locations, instantly switching between environments on the LED screen."* [Bur]
The whole scene could be prepared including the lighting setups, already days before. It would be easy to shoot in several daytimes like sunset, blue or golden hour for days, which makes production much more flexible. Shots could be reshot easily in the event of an incident. There is much more preparation and preproduction and much less postproduction, than in a comparable technique of filmmaking before. Traveling to only one location results in a greener production and just a fraction of costs than filming in the field [Jun].
One of the most underestimated benefits of in-camera VP is that you are able to finish a day of shooting and have directly a nearly finalized shot, that has also a great impact on how precise the editing could be done [McG22].
Finally there is plenty of creative freedom in this new way of filmmaking and yet undiscovered potentials [Jun].

The negative effects of LED wall Virtual Production mainly concentrate on the still remaining technical difficulties. There is the classical moiré effect, which is caused especially in smaller Volumes due to the physical pixel density of the LED wall. Moiré can occur if there is an insufficient resolution of the source image relatively to the sensor resolution of the camera. The result is a visible interference pattern. Moiré can be avoided when keeping the focus off the screen [Jun][Kad21, p. 61].
There are still difficulties regarding the *Genlock Signal* and keeping everything in synchronization. Additionally color distortion related to the POV (Point of View) occurs, when new geometries of LED Volumes are set up [Jun].
With regard to the light there are several advantages and disadvantages. As lighting with the LED wall is a big topic in LED VP Volumes, this thesis keeps a closer eye on this issue in the following chapters.

1.3 LED Walls as a Lighting Tool

"Production teams have the incredible benefit of using interactive lighting from the LED Volume, which enhances the realism of the scene. By casting realistic lighting onto the set, they can now capture high-fidelity visuals with the surrounding shadows and reflections, which isn't possible by other means, such as green screen." [Bur]
When considering that LED VP stages will replace the method of green-screen compositing, the first thing occurring regarding the light is that there won't be green spill anymore. Instead of that, the scene will be lit with a real time image of the LED wall, so-called image-based lightning.
There will be realistic reflections and refractions, especially in mirroring or shiny materials, like cars or sunglasses [Jun].
There is even a technique, called *Ghost Frame* from *Brompton*, which allows to shoot green screen and a VP background at the same time, using every second frame, the camera won't see for keying in post-production.
This results in the natural glase an illumination not only being an artistic clue, which enhances realism in the captured images, but also color mixing from traditional green screen being avoided [PS1, p. 52-55] [Jun].

An actress of the movie series 1899 mentions, that it is a totally different experience than performing on green screen: „It just illuminates literally everything. You could see the whole landscape in front of you and the lighting and everything, so you are really looking at the scene." [Net22]
Emmanuel Lubezki, DOP of the movie *Gravity* needed a method to integrate live action and computer generated images as well as an adequate virtual lighting to credibly show zero gravity. He found the answer in a "Light Box". He used the LED panels, implemented in Virtual Production Volumes and used a 9-foot cubic compound of panels. The three dimensional design in size of 6 x 6 x 6 meters gave them flexibility and made it possible to spin the light all around the character [Des12].
The Volume which was used in producing *The Mandalorian* and in other LED Virtual Productions is a setup made of individual LED modules. Depending on the model, the panels are either flexible for curved surfaces or rigid. With the help of trusses and other rigging methods, there are mostly limitless possibilities of geometric configurations. The more the Volume envelopes the scene, the higher the level ot realistic reflections and interactive lighting [Kad21, p. 52-56]. Walls in LED Volumes can go 5 m or higher, can have a sphericity or even go nearly all around a scene. A lot of VP studios also have a roof, made of LED panels hung over their Volume to be able to tilt or pan the camera in their shots as well as go on very low camera angles.

At a 3D event of *LEDcave* Frank Junghahn,VP Supervisor, mentions, that for the hard shadows, additional light is needed, but the rest of the lighting could be done image-based with the LED wall. With respect to the light emitted by the wall, he also mentions, that there is no green spill as when shooting with green screen. The reflections caused by the wall seem realistic and there is no time limit or physical restriction [Viv03].
Greig Fraser, DOP of *Disney+* series *The Mandalorian* reports, that shooting in the Volume was like walking out into nature, because they had got light bouncing from the desert shown on the wall. The round Volume, which was a circle of LED panels with a roof created a whole lighting scenario. Meanwhile, Roger Deakins questions if the lighting contrast in the Volume can be guaranteed [Alt21].

Having a huge LED wall beside or even all around a scene brings a lot of difficulties with it because it emitts light, that can only be controlled to a certain limit. Other lighting you could just regulate by e.g. adding an egg-rate, barn-doors, intensifier or simply flags or molton to take light away. In case of LED VP it is not possible to regulate a huge part of the wall, because it is seen in camera, which is the aim when using the LED wall.

When a group of differently color-emitting LEDs is merged together as a luminaire (Figure 1.2) and the intensity of each LED can be controlled, this group is able to produce millions of colors. The additive color model is used to produce several colors in a luminaire or fixture, since subtractive color models are applied with reflective surfaces[RK, p. 2-3].
LED walls are promised to be great for image-based lighting, they truly are great displays, but the light emitted by the wall offers a spiky light spectrum with peaks in Red, Green and Blue.

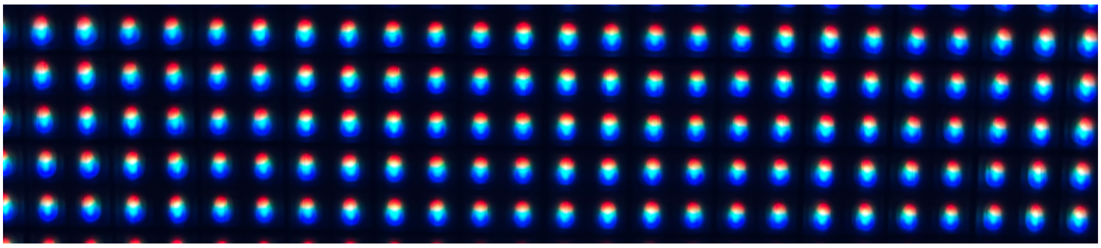

Figure 1.2: RGB LEDs of *ROE Ruby 2.3* LED Wall

As the LED wall is said to be a non plus ultra lighting tool, it should be measured in detail, how much light, emitted by the display can hit the scene without a harmful impact on the color rendition. To ensure a precise and descriptive measurement, it is important to use the right colorimetry.

1.4 Colorimetry

The Color Rendering Index (CRI, reference index: Ra), has been widely used for the assessment of color rendering characteristics of light sources. But color science has evolved remarkably since then. There are several recognized improvements for many components used in the CRI. Nevertheless, the CRI served moderately well for most of the light sources and was well accepted for

more than 40 years. Limitations relating the CRI, have been addressed recently, especially with solid-state lighting sources, where Ra values do not consistently correlate properly with the visual evaluation by a general user [Kwa18].
The Color Stimulus is an optical radiation which causes a sense of color perception in the human vision system. The color stimulus can be characterized by the tristimulus values X, Y, Z. For the calculation of these standard color values the spectral radiation density is being spectrally weighted and integrated in the visual spectral range between 380 nm and 780 nm [SBB16, p. 55-57] [Vos].
The demand and interest for the calculation of a color difference increased in 1931 when the CIE introduced a standard observer in colorimetry. The determination of the appropriate color spaces requires a perceptually change of these spaces and the tristimulus components X, Y, Z, which was achieved by the *International Commission on Illumination* (CIE, Commission Internationale de l'Eclairage), calculating the reference stimulus, ie.: $L^*a^*b^*$ or $L^*u^*v^*$. The CIE 1931 and CIE 1976 chromaticity diagrams can be seen in Figure 1.3. The idea in CIE 1976 UCS (Uniform Chromaticity Scale) was to create a linear color space in which the distance between the points defining individual colors would be proportional to the perceptual difference between them (perceptual color spaces) and to present colors with the coordinates describing one of their key attributes.
As color perception is highly crucial for human existence, color spaces were developed to describe on a mathematical base the color that an average person is able to perceive. A new need to distinguish colors, define them as similar, identical or completely different came up. Though a color-matching method is dependent on a color palette with characteristics that are perceptually linear [MT, p. 4-5].

The outer curvature is the spectral lotus, where the colors of the different monochromatic light sources are located. The absolute colors of the visual spectrum lay on this curve. The inner part and the curve of the horseshoe figure all the visual color values. The perceivable colors of the same chromaticity, but different luminance are displayed on the same point within this area.
The trichromatic color values X,Y,Z are not suitable for the perception-wise evaluation of colors. They aren't illustrative and tell little about the color

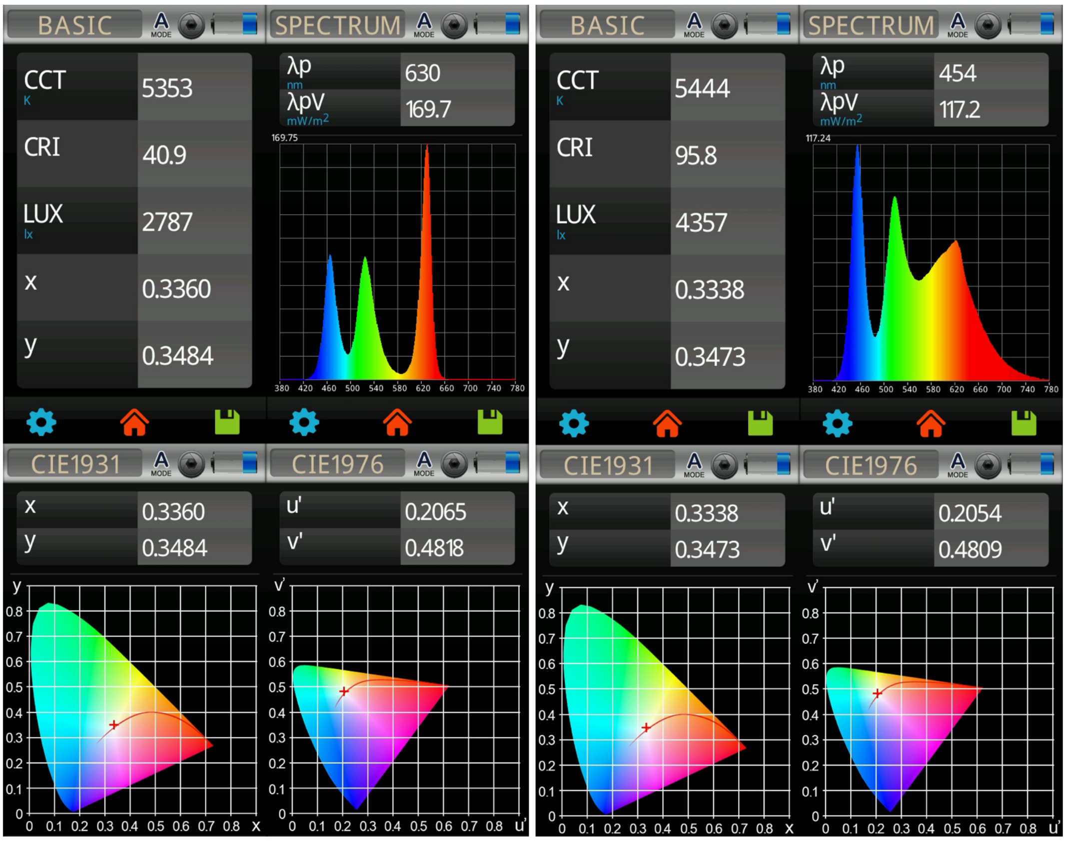

Figure 1.3: CIE 1931 and CIE 1976 Chromaticity Diagram of LED Wall and ARRI Skypanel

appearance of an object or an illuminant. They simply base on the principles of the additive mixture of color stimuli and don't relate to the psychology of color vision. The foundation of a perception-wise evaluation of color distance is the measurement of such color difference thresholds. If two colors differ in a just noticeable color difference, it is called color distance threshold.

The disadvantage of the MacAdam chromaticity diagram is that the differences aren't subject to perception. This can be seen when looking at the unsymmetrical color ellipses in a MacAdams chromaticity diagram.

As the MacAdams diagram is seen as inhomogeneous, the chromaticity diagram of CIE 1960 or CIE 1976 shows a compromise [Gre15, p. 79-83][RK, p. 2-3][Wal96].

The chromaticity diagram shows all the colors visually perceptible by an average person, at the same brightness those can be evaluated. To be able to judge differences of various hues, it is essential to assure an equidistant

representation of the color space. This can be achieved by the combination of the equidistant luminosity spectrum with the CIE chromaticity diagram. This color space with the coordinates L*u*v* was recommended in 1976 as the CIE LUV 1976 system [Gre15, p. 79-83][RK, p. 2-3] [MT, p. 4-5].
The even more approved system was recommended by the Commission Internationale de l'Éclairage (CIE) 1976 as the CIE LAB 1976, where the color values were definded with variables a and b and the psychometric brightness function L* was identical to CIE LUV. The color distances could be calculated according to the ΔE_{uv} with the formula [Gre15, p. 79-83] [RK, p. 2-3]:

$$\Delta E_{uv} = \sqrt{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2}$$

[MT, p. 15] [Gre15, p. 80-83]

There are two levels of visual divergence in color which are used to establish the margin: A minimal perceptual difference, which is defined as a visually barely noticeable difference between the sample and the pattern. A maximum in perceptual difference, which is defined as the highest eligible difference between sample and pattern. This type (level) of difference in color is important for the determination of the color. Any higher difference causes an exclusion of the sample. After defining those tolerance values, the following basic rules are also significant: People perceive, as most inappropriate, the difference in shades, whereas they often tolerate larger differences in chroma than in shades. While differences in brighter colors are accepted more easily than in chroma or in shade. The tolerance is greater for bright colors, and smaller for dark colors. The margin is based on the estimation measurement of unacceptable and tolerable samples, and an ideal standard for each color [MT, p. 4-5].

2 LED Walls in Virtual Production Environments and First Approaches towards Lighting

As in Virtual Production scenes the main goal is to create an illusion of reality, it is highly important to identify the main factors which could destroy the credibility of this virtually created new world. Since light is crucial for the sense of realism, we need to have a closer look on how scenes in Virtual Production studios are influenced by the emitted light of LED walls. Several light characteristics of the wall strongly reduce the sensation of reality in VP commercials or movies. Given that various light characteristics of the Wall can't be adjusted properly, it should be examined in detail to which extent image-based lighting influences the lighting of the scene and subsequently the sense of realism.

What subjectively looks real and what looks unreal in Virtual Productions has evolved rapidly throughout the last 10 years [Bar16]. Small irregularities can cause to be kicked out of the movie by the feeling of something being fake or having a leak of credibility. Most of the time it is that single part of a composite sequence that does not fit to the others, due to a change of continuousness in e.g. lighting. Due to the rapid evolution in the quality of computer generated imagery, we are not accepting low quality visuals anymore. There are virtually created images that look even better than in reality, which is all about the lighting design [Bar16].
As LED Virtual Production is a mix of virtual reality and real-life talents and props, it is crucial to adapt the lighting situations to each other.

2.1 Lighting Quality of LED Walls

The lighting quality of LED walls can roughly be divided into the criteria 'color rendition produced by the emitted light of the walls' and the characteristics of the radiant emittance of the panels.
Due to their characteristics of being a display rather than a lighting source, the LED wall has a wide angle of light being reflected in all directions. The light is soft and most of the commonly used indoor LED walls in VP generally don't go a lot brighter than 1500 nits [ROE]. Whereas usual film lights can be adjusted in direction, being tilted or panned, LED panels are as stiff as a wall is. These characteristics result in a diffuse sludge of light, which can neither be adjusted in hardness nor direction.The fall of the shadow also appears unnatural. Due to the close position of the wall as a light source, the shadows fall broad and a number of several shadows are occurring due to the light surrounding the scene from each side.

Daylight offers a nearly consistent spectrum across the visual area of the color spectrum, only having smaller irregularities, caused by the filtering of the sunlight in the atmosphere. The spectrum is also dependent on the daytime (Figure 2.1). The spectrum of halogen lamps and tungsten bulbs is likewise without perceivably gaps. Unlike daylight it is mostly weighted towards the longer, orange and red wavelengths [Gre21, p. 7-9].

Classic fluorescent lamps principally have a very incomplete spectrum, depending on their filling they have more or less peaks in their wavelength. The spectrum of RGBW LEDs is nearly continuous, but has a peak in the blueish area, and a weakness in cyan.
The spectrum of pure RGB LED light sources is concentrated on three peaks, which correspond to the three colors of the single LEDs.
Depending on their doping, LEDs can be divided into two type classes: The warmer types (red to amber) and the colder ones (green to blue). Single LEDs emit only a narrow-banded spectrum, which dominance in wavelength is determined by their doping. Meaning, single LEDs can't reproduce white light by their own. This is aimed by clustering various LEDs together, whereas one of each primary color of red, green and blue form a group [Gre15, p. 168-170].

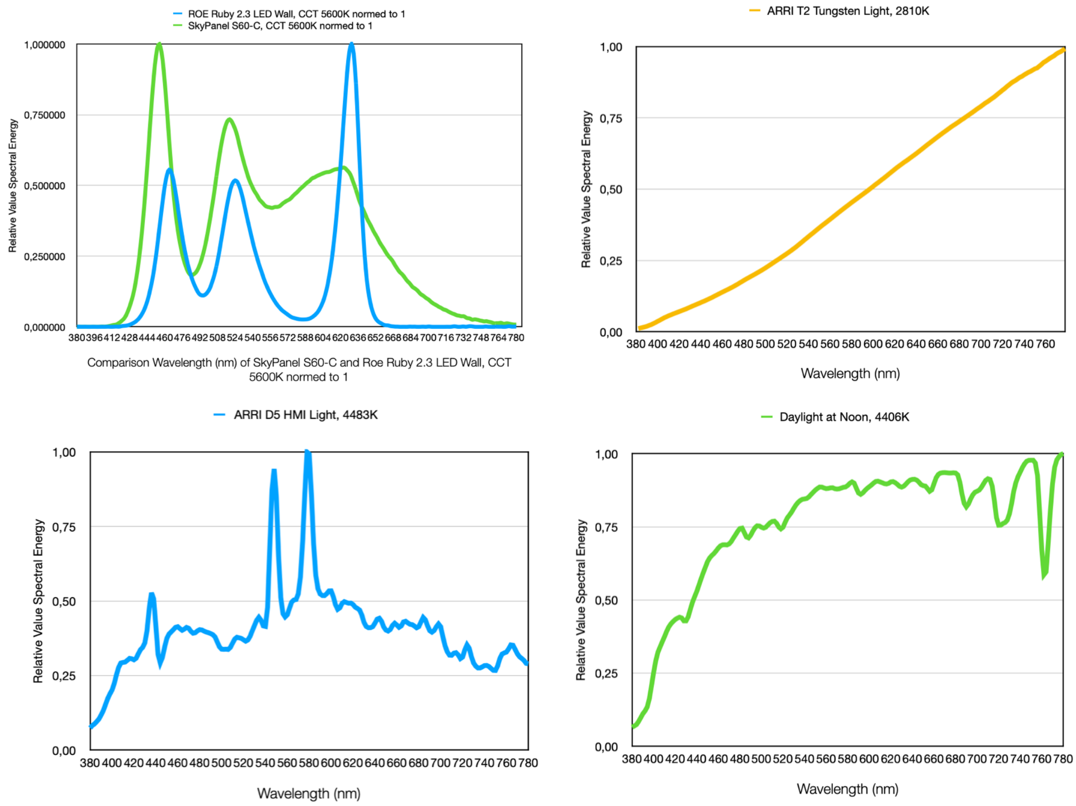

Figure 2.1: Spectra of Different Light Sources

Other colors than white are being generated due to the absorbance of parts of the spectrum. A wavelength which isn't part of the spectrum, can't be reflected either.

The problem of LED walls used in LED VP studios is, that they were made to be a good display rather than a good light source. There is a big section of color spectra missing, that is important for color rendition, especially concerning skintones. When the red LEDs were pushed deeper into the longer wavelength and the green LEDs pulled into the shorter wavelength this increased the color gamut but also caused gaps in the spectra. This made them a better display, but a worse light source [ETC]. As the spectrum of RGB LEDs is quite poor, several colors of a scene, which aren't part of the LED lights spectrum can't be reflected properly, as appearing in nature [DIN92] [DLL, p. 1-10].

2.2 Approaches by Netflix to improve LED Lighting in Virtual Production

Paul Debevec, Director of Research at *Creative Algorithms and Technology* at *Netflix*, did some research concerning lighting in LED VP studios. He had several approaches in terms of scene contrast and LED quality.

2.2.1 Increase of Scene Contrast

Debevec examined the scene contrast in various lighting environments with a workflow including HDRI maps.
As natural light in a cloudy environment resembles much more the LED lighting environment, since it is quite diffuse and is not too contrasty, it was quite easy to match the VP studio lighting.
The hardest lighting mood to match was the exterior sun lit environment. Only by showing the sun on the LED wall, the pixels would just burn out. Suggested in Siggraph 2002 Debevec used a seperate light source to immitate the sun, which was in his case a 30x30cm LED panel. He was able to reproduce the same key-to-fill-ratio he measured in the real-life scene, resulting that the lighting contrast was matching properly to the real lighting mood. Another benefit was, that the color rendition issue improved a lot. Resulting, that the skin tones matched quite well to the original situation and the costume almost looked the same, too. The reason was, that the LED lighting panel which was used for the sun light was a wider spectrum light source, than what the LED wall emitted [Deb].
Another problem was, that there was no light hitting from the camera side, or the other side of the wall, towards the scene. Considering this issue, it is reasonable, why many VP studios changed their stages in terms of geometry and developed the architecture of their wall towards a semi-circle or ellipse or even a nearly closed circle with a small opening for technical equipment and crew or cast.
In terms of the dynamic range of panels there is a limitation, as mentioned in chapter 2 section 1, because the real world lighting goes hundreds of times brighter than what LED panels are able to produce.
A clustering method, where Debevec tried to improve the dynamic range of LED displays, was to expose the pixels which had values over 1.0 and surround them

with bright pixels, additionally. Debevec put them to panels, which would result in a bigger bright light source, compared to the rest of the wall and have an improvement on the shadows and brightness. The shadows were still too soft and the light was too diffuse in general, but the light direction as well as the dynamic range were improved [ETC] [Deb]. This clustering method could be taken into consideration, when attempting to improve the dynamic range in terms of brightness. But it should be bared in mind, that such an increase of scene contrast could only be made in the *outer frustum*. The *inner frustum* marks the content of the wall, seen in-camera, whereas the *outer frustum* is the part around, which can be adjusted, whithout changing the background of the image.

2.2.2 Increase of Color Rendition

LED video walls are good for producing an ambient homogeneous level of light, but rather bad in color rendition, with the result that natural colors, such as skintones, are not being reproduced accurately [Bur]. Paul Debevec and Chloe LeGendre demonstrated, that the color appearance of materials under distinct indirect and direct illuminants could be matched much more accurate using five LEDs of different spectra for a multispectral lighting reproduction. He added additional LEDs to the existing spectrally deficient combination of red, green and blue. Using more than these five LEDs led to diminishing outcomes. An adjustment of the spectral illuminant and color appearance by metameric reflectance led to the same optimized set of five LEDs. Debevecs team used a circuit board with 11 distinct LEDs (including some duplicates) and measured their emitted spectra. They demonstrated the sufficiency of using five of those eleven commercially available LEDs. They published datasets of illuminant, spectral reflectance and spectral sensitivity cameras to prove that two distinct approaches of lighting reproduction, matching the illuminant spectra directly and matching the appearance of material color impression measured by one and more cameras or observed by a human being, all led to the same LED selections. The final proposal for the optimal set of five LEDs includes red, green, and blue with a narrow emission spectrum, together with a white and an amber with a broader spectrum [LYD, p. 1-2].
Debevec additionally examined image-based lighting situations in broad spectral lighting stages including LED nets, which could for now be a solution, if

image-based lighting is desired, and there are no displays with an sufficiently accurate color rendering. This would be an approach of optimizing image-based lighting and surrounding the object with an ambient light of the real scene in a studio [DLL, p. 1-10].
For now there hasn't been any pressure to develop multispectral LED panels, as the commercially available LED walls are seen as displays, which already can create about any color a person or camera can see. Adding LEDs isn't necessary to increase the color gamut. For the future it might be an issue to look at, that for future VP systems even larger VP stages are build. Stages, which allow good color rendition with enough dynamic range in lighting for light coming from every direction. Maybe LED panel manufacturers will be convinced to consider forming a broader spectrum LED pixels by adding additional LEDs in white or yellow into the package [ETC].
As there are many RGB LED VP Stages in use or under construction and RGBW/RGBY LED panels won't improve in the near future, as they need to be developed yet an optimal color correction needs to be evolved. Essentially, Debevecs team developed a system consisting of 3 matrices. The first one is what maps the HDRI map onto the LED Wall, the second to map the scene's pixels onto the LED panel colors, so that they look the same to the camera. They applied a 3×3 pre-correction matrix on the outer frustum content, while another 3×3 matrix was applied for in-camera-frustum content. At the end a three by three post-correction matrix was applied to the recorded image [DLL, p. 1-10] [ETC] [Deb].
The findings of Debevecs tests led us to the conclusion, that a full lighting kit should be used in addition. Problems were, that there was not enough angular coverage of all the directions light can come from, not enough dynamic range to go as bright as certain light sources in the scene can go up to and a poor color rendition. Due to this conclusion, this thesis focusses on additional lighting to be used apart from the LED wall. And to what extend people rely on the deficient color rendition. The arguments above prove, that the LED wall should not be used as the only lighting source on stage due to color rendition and scene contrast. In the following chapters is investigated, if the LED display could be really used as a key-light with additional higher spectral lighting sources, or if it should be kept as an additional fill-light. If the display is being used as a fill-light, it is to be examined to which extend it affects the color rendition of

the scene.
Additional lighting could be created for example with floating LED panels or by movie lights optionally connected to scenes via DMX or Network control. Projectors could even be used for special animated lighting like for example moving shadows [Kad, p. 39]. There are already VP stages, like *Dark Bay* that considered additional higher spectral lighting as an important lighting feature for ensuring scene contrast and color rendition [Bur].

3 Examination of Color Rendition under Specific Lighting Combinations and Spectra

3.1 Two Testing Scenes for the Evaluation of Color Shifts

To determine whether LED walls should be used as a key-light in order to realise image-based lighting or rather not, and if not to which extend it could be used as a fill-light, will be examined in the following chapters.

Below it will be shown how the testing setup and evaluation methods were developed. For the evaluation, the testing scene was mainly examined by a quantitive measurement method to create an overview for the different lighting setups and the impact of the quality of the light source in each one in particular. A qualitative method was used to check on several skintones and to identify disparities and similarities in both measurement results.

The recordings were made in a general LED VP setup, explained in chapter 1.1. In this thesis a *ROE Ruby* LED display was used, which consisted of 5 x 5 panels. Each panel consists of 216 x 216 pixels [ROE]. As a processor from *Brompton* was used, the settings were adjusted in *Tessera Software* by *Brompton Technology*.

Each of the tiles of the wall consists of four smaller panels, which are attached magnetically to the frame. On each panel, small pixels are placed, with a LED configuration of a 4 in 1 cathode and - from upwards down - a Red, Green and Blue LED. The pixels are surrounded by a black shader to realise a higher contrast and to prohibit that the pixels emit light on each other. Calibrated, the wall is able to get as bright as 1500 nits [ROE] [Sou22, p. 1-9].

Every evaluation of the color rendering characteristics of an illuminant is referred to a "reference illuminant". This reference illuminant can be a simple variable or an actually existent illuminant[DIN76].
In this thesis different types of the *ARRI SkyPanel* were used as a reference. As an even better light source in terms of color fidelity, for example a HMI could have been used as a reference. The decision on the *ARRI SkyPanel* was made due to the comparable characteristics of the wall and the *SkyPanel* and the *SkyPanel* being a higher qualitative common used on-set LED light source. in the further context, the reference will be called "optimum". The optimum is the lighting scenario, where the scene is lit with a *ARRI SkyPanel* from both sides.

In this thesis is examined to which extend the spectral power distribution is influencing the scene and to which extend it can be used to light the scene without drastically modifying the color fidelity of the scene. For accurate conditions of the test setup, the light sources need to be measured and balanced by different criteria to create the same basic conditions from where on the evaluation can take place [DIN82]. One of the main criteria is the luminous intensity, which has been measured directly in Lux with the *UPRtek MK350S* or for the creation of a specific scene contrast by a *Sekonic L-558* light meter.
The color of an illuminant can differ from one end to the other of the light source in reference to the emission angle. To assure a minimal half peak angle of the emitted light and also to avoid color variation of the respective illuminant a minimal distance was kept to the scene. The distance of 1.5m between LED display and scene was conform to the general distance to a LED wall in LED VP and assured a relatively frontal impingement of the light on each side [Gre15, p. 48] [DIN82].
The correlated color of the reference illuminant is recommended by *DIN 6169* to be around daylight. Therefore the correlated color temperature (CCT) of the light sources were kept at 5600 Kelvin in each testing setup [DIN93].
A lot of artificial and natural light sources have spectral power distributions, which chromaticities either are close to or coincide with a particular chromaticity on the Planckian lotus. Thus one can specify the color of such a light source simply by referring to its Planckian color temperature, which may differ significantly from its actual kinetic temperature. So if the chromaticity of a light source is placed off the Planckian lotus, the term CCT must be used

instead of color temperature [HALR]. The CCT was measured indirectly on a *GreyCard* from camera sight. The camera as the measurement tool was moved, together with the *GreyCard* around the light source. Due to the composition of the RGB LEDs, the color of the emitted light could differ in their variant radiation directions. From the measured values, a mean value was calculated to determine the polar distribution of the light color [DIN82].
As light sources emit light to various directions in differently intensities, it has so be checked, what is the luminous intensity distribution curve for fully characterizing the light source [SBB16, p. 26]. The polar luminous intensity distribution of a *SkyPanel S60-C* and a LED display can be seen as sufficiently similar, due to their mostly similar building design, as most of the LED panels.

A general basic lighting setup consists of three main lights. It is also called 3-point lighting setup. It consists of a key-light, a fill-light and a backlight, whereby the key-light and fill-light are the main lightsources hitting the face, when doing a portrait lighting [Gre15, p. 199].
In this thesis a simplified lighting setup of a key-light and a fill-light were used, to be able to display various lighting combinations.
The following methods were used to create a quantitive as well as a qualitative evaluation of the color differences created between a defined optimum and different lighting setups to analyse the impact on color rendition of a commonly used LED wall in VP studios.

3.1.1 General Color Differences in a Standard lit Scene using Keylight and Filllight

The test setup in the quantitive evaluation was created to visualize and examine several color shifts and artifacts. The test setup (Figure 3.1) contains a *ColorChecker Classic* by *X-Rite* with color patches in white, black, 4 neutral grays, primary and secondary colors as blue, green, red, yellow, magenta, cyan, miscellaneous colors as orange, purplish blue, moderate red, purple, yellow green and orange yellow, and natural colors as dark skin, light skin, blue sky, foliage, blue flower and bluish green [XR] [DMM, p. 95-99]. Furthermore a *Grey Card* and *Chrome Ball*, several different textiles such as fruits in different color shades, color wheels and costumes.

Figure 3.1: Setup of fixed Testing Scene

The recordings for the fixed testing scene were made with a ARRI Alexa Mini LF in ARRIRAW 3.8K, an approximately focal distance of 1.75m and an iris held by 4.0 and a White Balance of 5600K.
The scene was lit with a *SkyPanel S60-C* from both sides and with the LED wall from the right hand side. For each light source, one sequence was recorded. Three different images resulted from the test. The data was linearized as .EXR files and merged together in *Nuke* (Version 13.2v1), a compositing software by *The Foundry*, to create different lighting combinations in post production (Figure 3.2).
To assure a correct exposure balance and to avoid incorrect values later on in the analysis, the in-camera exposure tool as well as an additional white balance, calculated in *Nuke*. The Workflow in *Nuke* allowed to mix the light sources from each direction in various combinations and nuances. With this workflow it could be exactly calculated by which amount of light coming from the wall, relative to the *SkyPanel*, the colors of the scene were drifting apart.

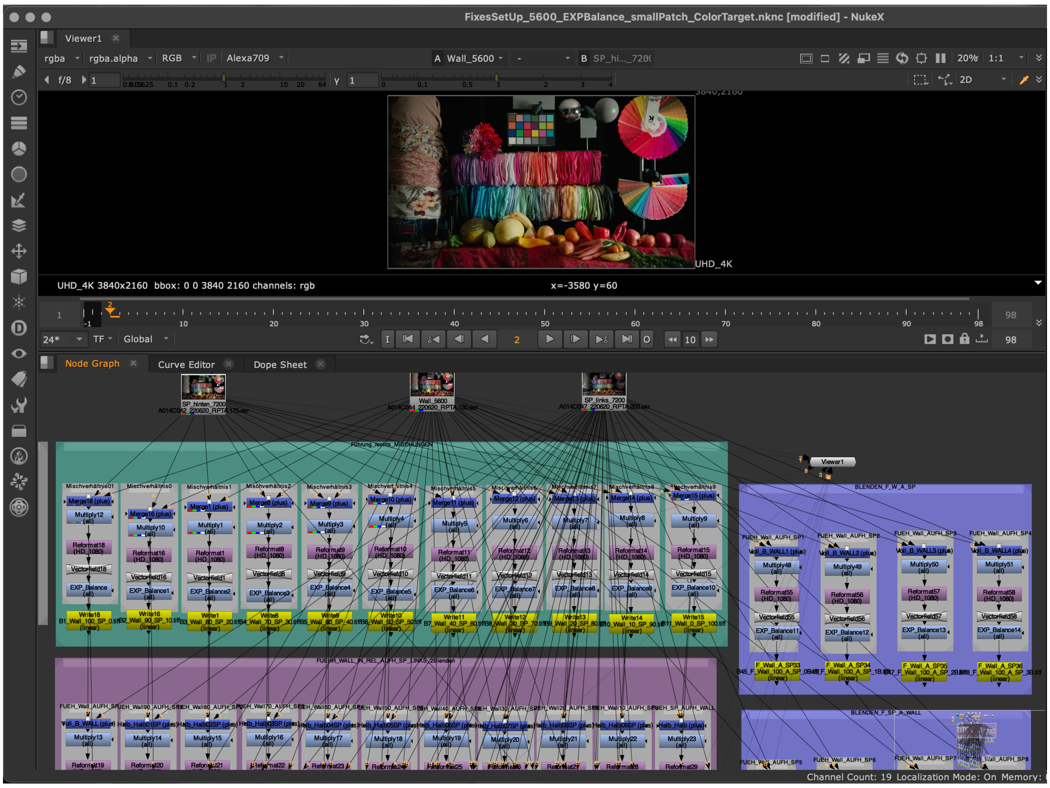

Figure 3.2: Nuke Project for Testing Scene

3.1.2 Influence of Lighting Combinations on Skintones

As real-life persons move and the images of the real skintones could not be overlayed accurately in terms of the exact same pixel in each image, the lighting had to be set up and mixed for each recording.

For the this method, to create diverse measurement values, five different skintones in terms of brightness or origin from women as well as men were recorded. An asian, elderly and younger caucasian, as well as a POC (People of Color) skintone were examined.

To examine the wall as a key-light with additional high quality fill-light coming from a *SkyPanel S60-C*, 4 different lighting setups were created (see Figure 3.3). To implement lighting situations, as created on a real set, lighting ratios from no contrast, with zero F-Stop difference to 3 F-Stops differences were lit. As the camera was set to an aperture of 2.8, the key-light was tweaked till the same value was measured with a light meter. Afterwards the *SkyPanel S60-C* was adjusted in Brightness on 26% for a F-Stop of 2.8, 16% for a F-Stop of 2.0, 9% for a F-Stop of 1.4 and 3% Brightness for a F-Stop of 1.0 for the four images.

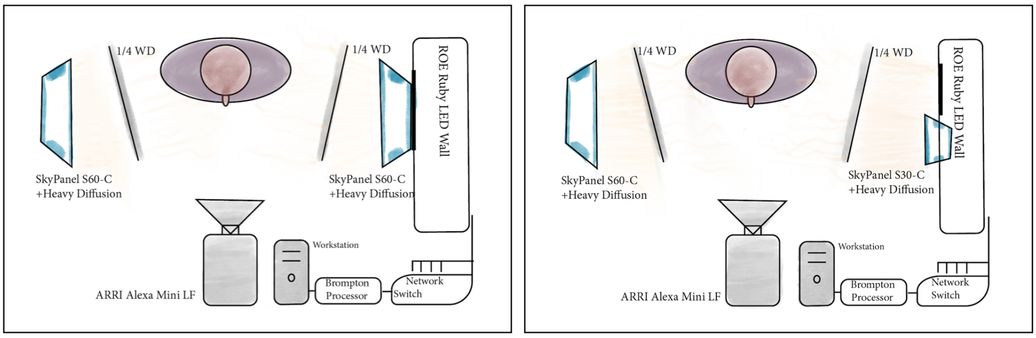

Figure 3.3: Setup for Skintones Testing Scene

For the images where the wall took over the role of a fill-light, whereas the *SkyPanel S60-C* lit the scene with 26% and a F-Stop of 2.8 as a key-light, the same F-Stop contrasts were created with the wall. The wall was set to 1485 Nits for F-Stop 2.8, 700 Nits for F-Stop 2.0, 350 Nits for a F-Stop of 1.4 and 200 Nits for a F-Stop of 1.0.

To use the wall only as a partial fill-light, three fill-light proportions were created. This was realized with the same patch on the wall as before, but in half the size. The other half of the fill-light was provided by a *SkyPanel S30-C* which was attached to the wall, right beside the half-sized patch as used before. The *S30-C* could be attached to one of the frames, of which the wall consists. The four panels which are magnetically attached to on of the frames of the LED wall, need to be disconnected and taken off this frame. As a result, the frame above and the frame beneath need to be connected in terms of network signal and power cable. The *SkyPanel S30-C* could now be attached to the frame with a prototype clamp, developed at ARRI for general lighting attachments to LED walls in future.

The first lighting proportion was a half/half one, meaning setting the brightness of each light to a value to which they produce the exact same amount of light and matching together having an output of a 2.8 F-Stop. A *251 Quarter White Diffusion* roll of *Rosco* was used to create a better blend of both lighting sources. As a result of this lighting setup, the foil was used for all the other lighting setups to implement the exact same conditions for all the lighting compositions and also for key-light and fill-light to have the same basic characteristics.

The other two fill-light combinations were created first with 25% brightness output for the SkyPanel and 75% for the wall and afterwards 75% brightness output for the wall and 25% for the SkyPanel.

3.2 Evaluation Methods

The .EXR files, that were imported to *Nuke* and merged together to diverse lighting situations led to around 60 TIFF (Tagged Image File Format) documents of the fixed test scene, which were afterwards read into *Matlab* and the color patches could be read out. The measuring results were calculated in *Matlab*, picking the average RGB values in linear wide gamut of each of the 24 *ColorChecker* patches of each image created in *Nuke* [XR] [The93].

The linear RGB values could then be transferred by a matrix to CIE 1931 XYZ color space [Bre12, p. 10]. The ALEXA Wide Gamut RGB to CIE 1931 XYZ conversion matrix is as follows:

Later on, the XYZ values were transferred to L*a*b* color space which was

0.638008	0.214704	0.097744
0.291954	0.823841	-0.115795
0.002798	-0.067034	1.153294

Table 3.1: Alexa Wide Gamut RGB to CIE 1931 XYZ [Bre12, p. 10]

necessary to do the calculation in CIE DE 2000. In case of the L*a*b* space, the ΔE difference between two colors is calculated by the formula:

$$\Delta E_{Lab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \text{ [MT, p. 15]}$$

3.2.1 Calculation of ΔE in *CIE DE 2000*

As discussed in chapter 1 section 4, there are different systems to evaluate color differences, depending on the application area. As color differences between the individual lighting scenarios shall be examined, it is important to determine color difference values, called ΔE, to reach precise and expressive values. The expression ΔE is a compound of the letter "E" which stands for “Empfindung“, which is German and means "sensation". Delta is the Greek word for a variable being gradually converted. Overall, ΔE can be defined as a discrepancy in sensation. ΔE as a metric is seen as the groundwork for precision in colors. It is used as a quantification method beside subjective views and opinions. The measurement type ΔE has been developed by the CIE (International Commission on Illumination or Commission Internationale de l'Eclairage) and via this method the color difference between two types of color shown on a screen can be quantified. The optimum is to keep the ΔE value located as close to zero as possible [Vie21]. ΔE_{2000} is measured on a scale from 0 to 100, where 0 is the lowest color divergency, and 100 is seen as a complete distortion. In other words, high ΔE_{2000} values indicate a crucial mismatch, whereas lower values stand for higher accuracy. The indication of the values can be described verbally as written in table 3.2.

Due to the fact that CIE L*a*b* space is nonuniform, the ISO recommends to use instead of ΔE_{Lab} a different formula: ΔE_{2000} is mathematically expanded. ΔE_{2000} was standardized by the CIE in 2000 and compensates some errors that occurred in CIE 1994 and CIE LAB formulas [Tré08, p. 8-9] [MT, p. 15-19].
ΔE_{2000} values between the optimum lighting situation lit with the reference illuminant and all the other lighting combinations transferred to LAB could now be calculated in CIE DE 2000 (see Figure 6.1) and plotted in a Microsoft Excel chart for a detailed evaluation. ΔE_{2000} levels are the difference between the displayed color and the original color standard and the displayed color of an input content.

Two samples which have under the same lighting by an illuminant the same color, but differ in their spectral reflections or transmission curves, cause most likely under different illuminants an unequal color impression. This existing color distance can be described by the metamerism index. It describes

<= 1.0	Not perceptible by the human eye
1-2	Perceptible through to close observation
2-3	Unexperienced observer also notices the difference
3-5	Perceptible at a glance, clear divergence in color
>5	Observer notices two different colors
11-49	Colors are more similar than the opposite
100	Colors are exactly the opposite

Table 3.2: Indication of ΔE Values [Vie21] [MT, p. 15]

quantitively the color difference with a measurement for color difference. The metamery index M_T for difference between illuminants is the color distance ΔE_{ab} , which the sample shows under the testing light, when the reference illuminant is equal to zero: $Delta E*_{ab} = 0$ [DIN93].

3.2.2 Visual Evaluation and Survey

For the Visual Evaluation, 21 pairs of images have been shown to Florian "Utsi" Martin, a professional Senior Colorist at ARRI. The pairs consisted of an image which was lit only with *SkyPanels*, and defined as the optimum for the skincolor reproduction. To each slide another image was added. All in all, every pair was approximately shown twice, to calculate an average value of the chosen indication for each image.
The images had to be categorized to one of the following descriptions, which are conform to the indications of ΔE_{2000} values and start at the color distance threshold. The indication for the colorist to be used as evaluation the images are shown in table 3.3.

1	<1	“No perceptible color difference to optimum.“
2	1-2	“Just perceptible color difference to optimum.“
3	2-3	“Small color differences to optimum.“
4	3-5	“Clearly noticeable color difference to optimum.“
5	>5	“Huge, unacceptable color difference to optimum.“

Table 3.3: Indication of ΔE_{2000} Values for a Visual Evaluation

4 Results

4.1 ΔE_{2000} in CIE DE 2000

Especially notable throughout the results of the technical examination is that there exist high color difference values in all color patches (see Figure 6.8), except foliage, yellow green and green, which had in all cases not markable divergence. This is quite reasonable, as the spectrum in the green wavelengths is mostly solid. Cyan has ΔE_{2000} values that maintain also beyond or just around 1, which means, that on close observation or as an experienced observer, there are perceptible color differences. Using the LED wall as an only key-light leads to ΔE_{2000} values which imply that the observer notices two different colors and huge color differences with ΔE_{2000} reaching values until 8.31.
This improves, when adding 40% light from the *SkyPanel S60-C* to the key-light, especially for the darker skin tone, but still remains at a color difference which is noticed even by an unexperienced observer. Additionally the lighter skin tone, such as blue flower, orange, moderate red and purple remains at values between three and five.
Taking those slightly better color differences with an additional light source in the key-light and a *SkyPanel S60-C* as a fill-light, with a scene contrast of 2 F-Stops and a relative light output of 25% to the key-light, the critical color patches named before still remained in between ΔE_{2000} 2.2 and 4.3, but the initial ΔE_{2000} values decreased by 13%.
When using the wall and the *SkyPanel S60-C* half/half as a key-light and add a *SkyPanel S60-C* as a fill-light with zero F-stops of contrast, meaning there was hitting the same amount of light from the other side, light skin, blue flower, purple, orange yellow, red and magenta still had ΔE_{2000} values between 3.34 and 3.85 (see Figure 6.2, B22), meaning color divergences perceptible at a glance.
A three F-stops contrast of fill-light in relation to the key-light, reached a color difference value as high as 7.78 (see Figure 6.4, B48).

Given that using the wall as any key-light in various combinations resulted in quite unsatisfactory ΔE_{2000} values, it is interesting to analyze, setting the *SkyPanel S60-C* as a key, whereas the LED display is used as fill-light with zero F-stops of scene contrast.
Even if the *SkyPanel S60-C* is used as a key-light and the fill-light is lit half by the LED wall and half by the *SkyPanel S60-C* there are ΔE values up to 2.78 (see Figure 6.3, B44) in the reddish patches of the *ColorChecker*, whereas the other color differences already result quite acceptable, including moderate red, with a ΔE_{2000} value of 1.97.
Another case was when the *SkyPanel S60-C* was set as a key-light, when the LED wall was used as a fill-light with a scene contrast of 3 F-stops (see Figure 6.4, B52), which still had a ΔE_{2000} value of 2.53 in the light skin patch and a value of 2.28 in orange it's worst ΔE_{2000} values. The other patches remained around values of color differences which were only perceptible through to close observation or if it is watched by an experienced user. Generally can be observed that the average ΔE_{2000} values of the light skintone patch is 41,73% higher than the dark skintone. As the patch of the *ColorChecker* is an approximate value of an average lighter such as darker skintone, this might not be sufficiently expressive. What can be observed, is due to the fact that skintones either are a little more a greenish or reddish, this might be when the LED wall has a greater impact on color fidelity in skintones.

Further observations of the test images resulted in the following (see Figure 6.9 and 6.10):
The fruits and vegetables in the test image have strong color shifts. The orange paprika shifts completely towards the color of the red one, whereas the red one gets a purplish and louder red. The carrots shift rather to red than being orange and get a strongly unnatural color hue, at which the shadows are clearly more affected and turn into artifacts. Reddish or orange patterns on the pear and the melon get louder and kind of blurred out and don't look pleasing anymore. Remarkably especially for costume designers and fashion brands is that patterns of the costumes make a totally new impression, as the colors of the several elements turn into totally new directions and differ a lot from the color rendition in the optimum lighting situation.
The several differently red colored swatches merge together to nearly one color.

The different shades of red shift together as one and get pinkish. The brown turns more to orange and the violett turns pinkish whereas pink gets glaring and unpleasant, like the tablecloth. The same happens with the flower bouquet. The bouquet consisting of blossoms in various hues, just melt together as one ball. The same can be observed in the color fans: Nearly one half of the entire upper color fan turns to a mostly similar hue.

4.2 Skintone Evaluation by Colorist Florian 'Utsi' Martin

The five video sequences were provided as Rec.709 HD and watched on a correctly calibrated monitor.
Elderly caucasian and POC skin had comparable good results, whereas skintones of the caucasian adult and young person were rated worse (see Figure 6.11 and 6.12). The evaluation of the asian skintone lies in between.
Generally key-lighting with the wall results in perceivably bad color rendition. Even the 0 F-stops contrast (see Figure 6.6, lighting scene 7) with additional fill-light by the *SkyPanel* was evaluated with small color differences to the optimum, in case of the elderly and the younger caucasian skin. The POC skintone was evaluated with small to clearly noticeable color differences, and the asian and adult caucasian skin had clearly noticeable color differences to the optimum. In all cases of the different skintones, a key-light by the LED wall with a low fill-light using the *SkyPanel* and a scene contrast of 3 F-Stops (see Figure 6.6, lighting scene 6) resulted in an evaluation of "huge unacceptable color differences" and was one of the worst evaluated lighting situations. Which has as a result that the wall even used in a scene with a strong fill-light and no scene contrast results in a perceivably bad color rendition. This confirms the findings in chapter 4.1.

When the *SkyPanel* was used as a key-light with the LED wall as a fill-light with a scene contrast of 3 F-Stops (see Figure 6.6, lighting scene 11), the results were quite better. In all skintones, the color differences were maximally perceived as small. The elderly caucasian skin had the best evaluation with a just perceivable color difference to the optimum.

A lower scene contrast with the *SkyPanel* used as a key-light and the LED wall used as a fill-light in a scene contrast of 2 or 1 F-Stops (see Figure 6.6, lighting scene 9,10), resulted in "clearly noticeable color differences to the optimum".

Florian 'Utsi' Martin added some valuable comments, towards his impression on skin appearance in VP lighting situations which are dominated by the LED wall. Concerning the asian skintone he added that in his eyes resulted clearly two different skintones. The lips seem to be pale and the skintone made an unhealthy impression. Additionally the skin appears blotchy.
Regarding the elderly caucasian skintone, he mentioned, the colors appear spiky and wrinkles are much more noticeable. In his opinion, the neck seemed more wrinkled and the lips make an unhealthy impression. All in all the skin seems less charming.
The younger caucasian skintone was described as blotchy, too. The light almost seemed to pass differently through the skin, which was seen especially in the area of the inner nose, where the skin appeared reddish. The eye color changed from green to blue and the eye bags appeared desaturated. The nose seemed unhealthy and generally skin impurities were more noticeable.
The lips as well as a skin impurity of the adult caucasian appeared supersaturated. The beard became bluish.
The skintone of the person of color made a sunburned impression and the hair color had a red cast.

5 Discussion

5.1 Evaluation in Summary

All in all, the most acceptable ΔE_{2000} values resulted in the following lighting setups: The lowest ΔE_{2000} values were given in lighting situations, where the LED wall was used as a fill-light in a 3 F-Stops contrast to the *SkyPanel* (see Figure 6.4, B52), with the highest ΔE_{2000} value for the lighter skintone patch, and 2.28 in the orange patch. Still, those values indicate that also an unexperienced user might notice the color difference. The remaining values for the other patches were below 2.0

The second most tolerable lighting situation in concern of ΔE_{2000} values was, when there was no scene contrast and the *SkyPanel* was used as a key-light. The fill-light was mixed by using half the output of the *SkyPanel* and half of the LED wall.

The evaluation of the professional colorist resulted in the following:
A *SkyPanel* used as a key-light with a partial fill-light by the LED wall mixed with an additional *SkyPanel* results in acceptable color differences: The scene contrast was set to a difference of 0 F-Stops, where key-light and fill-light both measured an iris of 2.8 (see Figure 6.6, lighting scene 12). When the fill-light was set to 25% using the *SkyPanel* and 75% using the LED display, all skintones were added to the category "clearly noticeable color differences to optimum". Except the POC skintone, which was perceived as having only small color differences to the optimum.
When the fill-light was set to 50% using the *SkyPanel* and 50% (see Figure 6.11 and 6.12) using the LED display, the color differences were still described as small. Except in the adult caucasian skin tone, which was added to "clearly noticeable color difference to optimum.“ Showing, that a partial fill-light can

result in acceptable color rendition, when keeping a minimum of 50% or lower as a partial fill-light.
All in all, the quantitive evaluation clearly proves the results of the qualitative evaluation calculated with 2000.

5.2 Outlook

Concerning the color rendering issue in Virtual Production Volumes, there are several approaches to achieve a better image quality:
As the results in chapter 4 show, the commonly used LED walls in Virtual Production should not be used in a wider extend than as a relative low or partial fill-light. Therefore it should be considered to use a broader spectral lighting kit additionally, such as HMI, Halogen or 6 and more poled LED lights. In terms of color rendition, as well as scene contrast, LED Volumes should be planned and build with an external lighting setup. Additional lighting could be added with floating movie lights or LED panels which are connected via DMX or Network control.

For now there hasn't been any pressure to develop broader spectral LED panels, as the commercially available LED walls are seen as displays. But with the growth of the Virtual Production industry and a requirement and higher demand it could be seen as a possibility in future.

Another perspective would be, that the available color workflow could be adapted to the LED wall. The LED wall would function as a base, where additional lights would be adapted to. The LED wall, the camera and additional light sources would be coordinated with each other to optimize not a single component, but the whole system.
The improvement of Color Processing in digital motion picture could also improve the overall image quality and therefore the lighting quality itself. In-Camera or in the post production process. With the introduction of the new ALEXA35 camera I was able to test the new AWG4 (Arri Wide Gamut 4) processing with the Arri Reference Tool (ART) and apply it to the images recorded with the ALEXA Mini LF. This showed, that the color reproduction is

much better, compared to common color processing or AWG3. As it is possible to apply AWG4 to every already recorded ARRIRAW image, it is much easier to reach an even better image than already before.
There is a large number of new opportunities and advantages provided by Virtual Production. VP can be seen as the following step in the evolution of filmmaking [PS1, p. 52-58]. As a new, sustainable way of filmmaking with numerous of creative possibilities VP will for sure be developed further in future and implemented in more film productions than ever before. When solutions for technical difficulties will be found, there will be produced a wide range of impeccable pictures captured in LED Volumes.

6 Appendix

Appendix Chapter 3.2.1

ΔE_{2000} changes participation of L^* depending on the brightness of the color value range. Measuring pattern has the form:

$$\Delta E_{2000} = \sqrt{(\frac{\Delta L'}{K_L S_L})^2 + (\frac{\Delta C'}{K_C S_C})^2 + (\frac{\Delta H'}{K_H S_H})^2} \tag{3}$$

where:

$\overline{L'} = (L_1 + L_2)/2,$
$\Delta L' = L_2 - L_1,$
$C_1 = \sqrt{a_1^2 + b_1^2},$
$C_2 = \sqrt{a_2^2 + b_2^2},$
$\overline{C} = (C_1 + C_2)/2,$
$G = (1 - \sqrt{\frac{\overline{C^7}}{\overline{C^7} + 25^7}})/2,$
$a_1' = a_1(1 + G),$
$a_2' = a_2(1 + G),$
$C_1' = \sqrt{a_1'^2 + b_1^2},$
$C_2' = \sqrt{a_2'^2 + b_2^2},$
$\overline{C'} = (C_1' + C_2')/2,$
$\Delta C' = C_2' - C_1',$
$\Delta H' = 2\sqrt{C_1' C_2'} \sin(\Delta h'/2),$
$S_L = 1 + \frac{0.015(\overline{L}' - 50)^2}{\sqrt{20 + (\overline{L}' - 50)^2}},$
$S_C = 1 + 0.045\overline{C}',$
$S_H = 1 + 0.015\overline{C}'T,$
$\Delta\theta = 30 \exp\{-(\frac{\overline{H'} - 275^o}{25})\},$
$R_C = \sqrt{\frac{\overline{C^7}}{\overline{C^7} + 25^7}}),$
$R_T = -2R_C \sin(2\Delta\theta),$
$K_L = 1 - default,$
$K_C = 1 - default,$
$K_H = 1 - default.$

Figure 6.1: Chapter 3.2.1, Formula ΔE_{2000} [MT, p.19]

Appendix Chapter 4.1

The lighting situations in "Figure 6.2: Chapter 4, ΔE_{2000} Values 1/4" have been mixed as following:
Images with B1 till B11 in their naming are keylight combinations of the *SkyPanel* and the LED wall, where B1 is totally lit with the wall and B11 has 50% additional light coming from the *SkyPanel*.
B12 to B22 are the keylight combinations of B1 till B11 with a aditional maximum filllight of the *SkyPanel* with no scene contrast and a zero F-stops difference.
B23 till B33 (Figure 6.3) are ΔE_{2000} values of images, where the keylight came from the wall, whereas the filllight was increased. B23 equals B1 and has no additional filllight, whereas B26 has a 23% of filllight by the *SkyPanel* in relation to the keylight, which more or less is equal to 2 F-Stops difference. B33 equals a 50% of filllight in relation to the whole lighting, which equals to 0 F-Stops in contrast to the keylight.
B45 to B48 is a scale of F-Stops, where the LED display is a keylight and the *SkyPanel* a filllight. B45 equals a 0 F-Stops of scene contrast, whereas B48 equals a 3 F-Stops.
B34 to B44 are lit with a *SkyPanel* as a keylight, whereas the fillight is a mix of *SkyPanel* and LED display. B44 in this case has a filllight, which is half/half lit by the *SkyPanel* and the LED wall.
B49 to B52 is a scale of F-Stops, where the *SkyPanel* is the keylight and the wall acts as a filllight. In this case B49 has a 0 F-Stops of scene contrast, whereas B52 equals a 3 F-Stops scene contrast.

	1	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18						
'B55_Optimum,tiff'	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Keylight Combinations																			*					
'B1_Wall_100_SP_0,tiff'	4,27	7,20	3,76	0,90	8,10	1,71	8,29	2,70	5,16	7,37	1,29	8,31	2,70	1,36	6,65	5,00	7,78	3,33	6,43	3,90	3,25	2,74	2,53	2,10
'B2_Wall_90_SP_10,tiff'	4,02	6,68	3,45	0,85	7,47	1,57	7,66	2,42	4,75	6,83	1,16	7,56	2,51	1,23	6,15	4,57	7,20	3,04	6,20	3,57	2,98	2,56	2,32	2,01
'B3_Wall_80_SP_20,tiff'	3,74	6,28	3,20	0,81	6,92	1,46	7,10	2,25	4,39	6,39	1,04	6,97	2,34	1,12	5,74	4,21	6,70	2,86	6,03	3,35	2,79	2,40	2,18	1,95
'B4_Wall_70_SP_30,tiff'	3,54	5,86	2,98	0,79	6,43	1,36	6,63	2,08	4,08	5,98	0,95	6,45	2,21	1,06	5,38	3,89	6,27	2,69	5,87	3,10	2,61	2,29	2,06	1,81
'B5_Wall_60_SP_40,tiff'	3,31	5,55	2,81	0,74	6,03	1,29	6,23	1,95	3,81	5,63	0,87	6,02	2,12	0,99	5,06	3,63	5,90	2,52	5,75	2,94	2,48	2,17	1,90	1,72
'B6_Wall_50_SP_50,tiff'	3,14	5,25	2,67	0,70	5,67	1,21	5,85	1,83	3,58	5,30	0,80	5,62	2,00	0,94	4,76	3,40	5,58	2,38	5,64	2,81	2,34	2,09	1,81	1,65
'B7_Wall_40_SP_60,tiff'	3,03	5,00	2,54	0,70	5,34	1,16	5,50	1,74	3,37	5,01	0,73	5,31	1,90	0,88	4,50	3,20	5,29	2,25	5,56	2,71	2,24	2,02	1,73	1,54
'B8_Wall_30_SP_70,tiff'	2,89	4,77	2,44	0,68	5,08	1,11	5,22	1,65	3,18	4,75	0,68	4,99	1,82	0,86	4,27	3,02	5,03	2,12	5,48	2,58	2,12	1,94	1,69	1,52
'B9_Wall_20_SP_80,tiff'	2,75	4,56	2,35	0,67	4,87	1,08	4,97	1,57	3,01	4,50	0,63	4,71	1,74	0,83	4,06	2,87	4,80	2,00	5,40	2,50	2,04	1,89	1,61	1,50
'B10_Wall_10_SP_90,tiff'	2,61	4,37	2,26	0,65	4,62	1,04	4,73	1,50	2,86	4,30	0,58	4,47	1,67	0,81	3,87	2,73	4,59	1,90	5,34	2,41	1,96	1,84	1,57	1,44
'B11_Wall_0_SP_100,tiff'	2,51	4,21	2,19	0,64	4,40	1,00	4,52	1,42	2,72	4,12	0,55	4,26	1,61	0,79	3,70	2,61	4,40	1,80	5,30	2,32	1,87	1,75	1,51	1,39
Keylight Combinations + Filllight Skypanel																			*					
'B12_F_Wall_100_ASP,tiff'	3,84	6,52	3,08	0,73	7,12	1,47	7,32	2,39	4,68	6,59	1,17	7,25	2,35	1,25	6,04	4,33	6,89	2,88	5,18	3,27	2,69	2,27	2,09	1,70
'B13_F_Wall_90_ASP,tiff'	3,56	6,02	2,85	0,69	6,54	1,35	6,74	2,17	4,30	6,10	1,05	6,63	2,18	1,14	5,59	3,95	6,35	2,68	4,93	3,00	2,46	2,11	1,92	1,59
'B14_F_Wall_80_ASP,tiff'	3,30	5,58	2,62	0,66	6,05	1,24	6,26	2,00	3,98	5,70	0,95	6,09	2,05	1,03	5,20	3,62	5,92	2,48	4,71	2,79	2,31	1,97	1,82	1,53
'B15_F_Wall_70_ASP,tiff'	3,10	5,23	2,48	0,61	5,56	1,15	5,83	1,87	3,69	5,33	0,88	5,62	1,93	0,96	4,86	3,36	5,55	2,33	4,54	2,62	2,15	1,85	1,72	1,43
'B16_F_Wall_60_ASP,tiff'	2,90	4,95	2,32	0,58	5,20	1,08	5,45	1,73	3,45	5,01	0,80	5,22	1,83	0,88	4,57	3,14	5,20	2,20	4,40	2,46	2,00	1,76	1,57	1,32
'B17_F_Wall_50_ASP,tiff'	2,71	4,68	2,21	0,55	4,89	1,01	5,13	1,65	3,24	4,72	0,74	4,88	1,73	0,82	4,30	2,94	4,91	2,06	4,29	2,35	1,89	1,67	1,48	1,26
'B18_F_Wall_40_ASP,tiff'	2,57	4,43	2,12	0,54	4,60	0,96	4,83	1,56	3,06	4,45	0,69	4,58	1,63	0,76	4,07	2,78	4,65	1,93	4,19	2,25	1,81	1,60	1,37	1,21
'B19_F_Wall_30_ASP,tiff'	2,46	4,22	2,05	0,52	4,37	0,92	4,56	1,48	2,89	4,22	0,65	4,30	1,56	0,73	3,87	2,62	4,42	1,84	4,11	2,14	1,72	1,54	1,27	1,22
'B20_F_Wall_20_ASP,tiff'	2,34	4,01	1,95	0,50	4,13	0,87	4,33	1,40	2,73	3,99	0,61	4,06	1,48	0,69	3,68	2,48	4,21	1,74	4,03	2,05	1,67	1,49	1,24	1,15
'B21_F_Wall_10_ASP,tiff'	2,24	3,87	1,88	0,49	3,90	0,84	4,12	1,34	2,59	3,81	0,57	3,85	1,42	0,66	3,50	2,35	4,02	1,61	3,96	1,96	1,59	1,44	1,18	1,12
'B22_F_Wall_halb_ASP,tiff'	2,15	3,68	1,80	0,47	3,72	0,80	3,93	1,28	2,46	3,63	0,53	3,67	1,36	0,63	3,34	2,24	3,85	1,53	3,91	1,89	1,52	1,39	1,12	1,11

Figure 6.2: Chapter 4, ΔE_{2000} Values 1/4

Keylight Wall _ Fillight SP left 10-100																		*						
'B23_Wall_100_SP_0,tiff'	4,27	7,20	3,76	0,90	8,10	1,71	8,29	2,70	5,16	7,37	1,29	8,31	2,70	1,36	6,65	5,00	7,78	3,33	6,43	3,90	3,25	2,74	2,53	2,10
'B24_Wall_100_SP_10,tiff'	4,07	6,89	3,47	0,84	7,68	1,60	7,88	2,56	4,94	7,03	1,24	7,84	2,57	1,30	6,39	4,70	7,39	3,14	5,90	3,61	3,02	2,53	2,34	1,92
'B25_Wall_100_SP_20,tiff'	3,89	6,64	3,19	0,77	7,30	1,52	7,50	2,45	4,76	6,73	1,19	7,44	2,41	1,27	6,15	4,45	7,05	2,97	5,43	3,38	2,80	2,34	2,17	1,77
'B26_Wall_100_SP_30,tiff'	3,75	6,39	2,99	0,72	6,97	1,43	7,17	2,35	4,59	6,45	1,15	7,08	2,28	1,23	5,93	4,21	6,73	2,79	4,96	3,17	2,59	2,20	2,00	1,60
'B27_Wall_100_SP_40,tiff'	3,58	6,17	2,85	0,64	6,62	1,36	6,88	2,24	4,43	6,20	1,11	6,74	2,21	1,21	5,73	3,99	6,44	2,68	4,53	2,98	2,44	2,09	1,88	1,50
'B28_Wall_100_SP_50,tiff'	3,46	5,98	2,70	0,61	6,31	1,31	6,58	2,15	4,29	5,96	1,10	6,41	2,13	1,20	5,55	3,79	6,15	2,58	4,19	2,80	2,29	1,95	1,79	1,42
'B29_Wall_100_SP_60,tiff'	3,31	5,76	2,55	0,57	6,04	1,24	6,33	2,10	4,16	5,74	1,07	6,13	2,04	1,18	5,38	3,60	5,90	2,46	3,91	2,63	2,12	1,87	1,69	1,32
'B30_Wall_100_SP_70,tiff'	3,22	5,56	2,41	0,55	5,78	1,18	6,08	2,05	4,03	5,54	1,06	5,90	1,95	1,19	5,21	3,44	5,69	2,37	3,63	2,50	1,99	1,77	1,59	1,25
'B31_Wall_100_SP_80,tiff'	3,12	5,40	2,27	0,53	5,50	1,14	5,85	2,00	3,91	5,33	1,03	5,67	1,88	1,18	5,05	3,29	5,48	2,30	3,38	2,40	1,87	1,65	1,47	1,16
'B32_Wall_100_SP_90,tiff'	3,03	5,22	2,14	0,52	5,27	1,09	5,61	1,95	3,79	5,16	1,00	5,44	1,81	1,18	4,91	3,17	5,28	2,19	3,14	2,26	1,77	1,56	1,35	1,10
'B33_Wall_100_SP_100,tiff'	2,93	5,06	2,04	0,51	5,01	1,05	5,43	1,92	3,69	5,00	0,98	5,24	1,73	1,17	4,77	3,05	5,09	2,11	3,01	2,15	1,65	1,47	1,26	1,05
Keylight Wall _ Fillight SP left 0B-3B																			*					
'B45_F_Wall_100_A_SP_0B,tiff'	2,93	5,06	2,04	0,51	5,01	1,05	5,43	1,92	3,69	5,00	0,97	5,24	1,73	1,18	4,77	3,05	5,09	2,11	3,01	2,15	1,65	1,47	1,26	1,05
'B46_F_Wall_100_A_SP_1B,tiff'	3,47	5,98	2,70	0,60	6,31	1,30	6,58	2,16	4,31	5,97	1,08	6,41	2,13	1,21	5,56	3,78	6,16	2,59	4,21	2,81	2,29	1,95	1,79	1,42
'B47_F_Wall_100_A_SP_2B,tiff'	3,84	6,52	3,08	0,73	7,12	1,47	7,32	2,39	4,68	6,59	1,17	7,25	2,35	1,25	6,04	4,33	6,89	2,88	5,18	3,27	2,69	2,27	2,09	1,70
'B48_F_Wall_100_A_SP_3B,tiff'	4,01	6,82	3,39	0,82	7,59	1,58	7,78	2,52	4,90	6,94	1,23	7,74	2,54	1,29	6,33	4,63	7,30	3,11	5,78	3,58	2,96	2,49	2,29	1,92
Keylight SP _ Fillight WALL + SP																			*					
'B34_F_SP_AWALL_100,tiff'	2,88	5,02	1,99	0,54	4,99	1,07	5,32	1,89	3,70	5,00	0,95	5,23	1,74	1,14	4,78	3,05	5,09	2,04	3,12	2,08	1,58	1,47	1,23	1,08
'B35_F_SP_AWALL_100_SP_10,tiff'	2,63	4,68	1,80	0,50	4,59	0,97	4,87	1,75	3,40	4,62	0,86	4,76	1,60	1,04	4,42	2,76	4,69	1,88	2,85	1,88	1,43	1,32	1,06	0,94
'B36_F_SP_AWALL_100_SP_20,tiff'	2,42	4,38	1,72	0,44	4,25	0,89	4,50	1,59	3,15	4,26	0,78	4,36	1,45	0,96	4,10	2,52	4,33	1,72	2,63	1,71	1,32	1,23	0,98	0,86
'B37_F_SP_AWALL_100_SP_30,tiff'	2,24	4,09	1,64	0,40	3,96	0,82	4,19	1,47	2,93	3,98	0,72	4,03	1,31	0,90	3,83	2,32	4,04	1,57	2,46	1,58	1,22	1,15	0,92	0,76
'B38_F_SP_AWALL_100_SP_40,tiff'	2,15	3,85	1,56	0,38	3,67	0,77	3,90	1,39	2,74	3,71	0,66	3,73	1,24	0,85	3,59	2,15	3,77	1,47	2,30	1,48	1,16	1,09	0,84	0,70
'B39_F_SP_AWALL_100_SP_50,tiff'	2,00	3,62	1,42	0,36	3,42	0,71	3,66	1,29	2,58	3,49	0,62	3,48	1,15	0,80	3,38	2,01	3,53	1,36	2,17	1,38	1,08	1,01	0,79	0,66
'B40_F_SP_AWALL_100_SP_60,tiff'	1,92	3,40	1,31	0,31	3,20	0,67	3,46	1,23	2,43	3,32	0,58	3,27	1,09	0,74	3,20	1,88	3,33	1,27	2,05	1,30	1,02	0,95	0,75	0,63
'B41_F_SP_AWALL_100_SP_70,tiff'	1,77	3,22	1,22	0,29	2,99	0,63	3,25	1,16	2,29	3,14	0,55	3,06	1,01	0,70	3,03	1,78	3,15	1,21	1,95	1,21	0,96	0,90	0,70	0,61
'B42_F_SP_AWALL_100_SP_80,tiff'	1,66	3,06	1,14	0,27	2,84	0,60	3,07	1,10	2,17	2,98	0,52	2,89	0,95	0,66	2,88	1,69	2,98	1,14	1,87	1,16	0,89	0,83	0,66	0,57
'B43_F_SP_AWALL_100_SP_90,tiff'	1,58	2,91	1,11	0,26	2,68	0,57	2,92	1,05	2,06	2,83	0,49	2,74	0,89	0,63	2,75	1,59	2,83	1,08	1,77	1,10	0,85	0,80	0,62	0,55
'B44_F_SP_AWALL_100_SP_100,tiff'	1,53	2,78	1,08	0,26	2,56	0,54	2,78	1,00	1,97	2,71	0,46	2,61	0,86	0,60	2,63	1,52	2,69	1,03	1,71	1,06	0,80	0,74	0,58	0,54

Figure 6.3: Chapter 4, ΔE_{2000} Values 2/4

Keylight SP _ Fillight WALL 0B-3B																			*					
'B49_F_SP_100_A_WALL_0B,tiff'	2,93	5,06	2,04	0,51	5,01	1,05	5,43	1,92	3,69	5,00	0,98	5,24	1,73	1,17	4,77	3,05	5,09	2,11	3,01	2,15	1,65	1,47	1,26	1,05
'B50_F_SP_100_A_WALL_1B,tiff'	2,26	4,07	1,33	0,48	3,52	0,86	4,13	1,58	2,93	3,69	0,80	3,83	1,19	1,22	3,77	2,12	3,73	1,50	3,04	1,34	0,95	0,85	0,70	0,61
'B51_F_SP_100_A_WALL_2B,tiff'	1,80	3,08	1,04	0,52	2,05	0,83	2,95	1,33	2,17	2,39	0,69	2,40	0,72	1,33	2,71	1,24	2,33	0,88	5,03	0,74	0,68	0,28	0,17	0,18
'B52_F_SP_100_A_WALL_3B,tiff'	1,47	2,53	1,06	0,50	0,88	0,94	2,28	1,21	1,57	1,29	0,56	1,30	0,49	1,47	1,81	0,59	1,23	0,55	7,38	0,69	0,90	0,32	0,38	0,43
'B53SP_links_100,tiff'	1,41	2,24	1,48	0,63	0,82	1,16	2,14	1,20	0,80	0,71	0,45	0,26	0,81	1,70	0,58	0,50	0,89	0,71	11,62	1,35	1,54	1,00	1,07	1,07
'B54_SP_rechts_100,tiff'	0,84	1,35	0,89	0,43	0,51	0,69	1,28	0,71	0,45	0,28	0,31	0,13	0,50	0,97	0,32	0,25	0,50	0,41	4,63	0,74	0,78	0,75	0,42	0,52
																			*					

Indication	<1	No perceiptable difference
	1-2	Perceptible through to close observation or by experienced observers
	2-3	Unexperienced observer also notices the difference
	3-5	Perceptible at a glance, clear difference in color is noticed
	>5	Observer notices two different colors
	>8	
In F-Stops	* note	The White Patch was not analyzed, as there was in some lighting situations a shadow on the patch, The ColorChecker should be held completely in the foreground, maybe even recorded completely separate to avoid such issues,

Figure 6.4: Chapter 4, ΔE_{2000} Values 3/4

Wall Keylight Mix																			*						Keylight	Filllight	
'B60,tiff'	3,79	6,52	3,36	0,86	7,25	1,52	7,41	2,38	4,64	6,67	1,03	7,30	2,36	1,16	6,01	4,37	7,00	2,90	6,12	3,45	2,87	2,48	2,18	1,96	+12,5% SP		
'B61,tiff'	3,34	5,77	2,92	0,77	6,31	1,34	6,44	2,05	4,00	5,84	0,85	6,24	2,08	1,00	5,26	3,75	6,14	2,55	5,80	3,02	2,55	2,21	1,96	1,76	+25% SP		
'B62,tiff'	2,43	4,22	2,24	0,57	4,42	1,01	4,49	1,42	2,73	4,14	0,53	4,24	1,54	0,76	3,71	2,61	4,42	1,74	5,26	2,29	1,86	1,73	1,54	1,31	+50% SP		
+ Add SP to Key																											
'B63,tiff'	3,57	6,15	3,03	0,74	6,70	1,40	6,88	2,24	4,39	6,24	0,98	6,77	2,17	1,10	5,68	4,01	6,54	2,65	5,38	3,16	2,59	2,20	1,96	1,69	+12,5% SP	Links 12,5% SP	
'B64,tiff'	2,78	4,97	2,30	0,56	5,16	1,07	5,42	1,76	3,51	5,01	0,77	5,21	1,72	0,88	4,60	3,09	5,20	2,09	4,09	2,40	1,96	1,67	1,49	1,30	+25% SP	Links 25% SP	
'B65,tiff'	1,58	2,81	1,12	0,26	2,54	0,53	2,84	1,02	1,98	2,71	0,45	2,63	0,84	0,60	2,62	1,51	2,71	1,04	1,57	1,10	0,82	0,76	0,60	0,57	+50% SP	Links 50% SP	
Wall Key + Fill SP																											
'B66,tiff'	3,91	6,77	3,35	0,84	7,54	1,57	7,71	2,54	4,92	6,94	1,14	7,68	2,44	1,26	6,32	4,56	7,28	2,97	5,71	3,54	2,86	2,41	2,27	1,94	Wall 100	Links 12,5% SP	2 Stops
'B67,tiff'	3,62	6,33	2,93	0,73	6,81	1,40	7,04	2,33	4,57	6,37	1,08	6,97	2,19	1,19	5,88	4,09	6,63	2,63	4,81	3,07	2,47	2,14	1,92	1,68	Wall 100	Links 25% SP	1 Stop
'B68,tiff'	2,89	5,07	2,10	0,54	5,02	1,05	5,44	1,96	3,72	5,02	0,93	5,25	1,72	1,17	4,79	3,05	5,11	2,05	3,08	2,15	1,63	1,46	1,27	1,05	Wall 100	Links 50% SP	0 Stops
SP Key + Fill Wall																											
'B69,tiff'	1,53	2,52	1,04	0,51	1,13	0,91	2,37	1,18	1,67	1,65	0,48	1,36	0,39	1,50	2,01	0,64	1,40	0,63	6,59	0,68	0,88	0,30	0,30	0,34	SP links 100	Wall 12,5%	85,5% Skypanel
'B70,tiff'	2,03	3,48	1,13	0,52	2,72	0,82	3,39	1,37	2,53	3,12	0,65	2,95	0,87	1,32	3,21	1,60	2,95	1,16	3,90	0,94	0,78	0,44	0,34	0,55	SP links 100	Wall 25%	75% Skypanel
'B71,tiff'	2,98	5,09	2,03	0,54	4,97	1,05	5,42	1,86	3,73	5,02	0,91	5,20	1,70	1,17	4,81	3,01	5,12	2,14	3,13	2,10	1,65	1,42	1,24	1,04	SP links 100	Wall 50%	50 % Skypanel

Figure 6.5: Chapter 4, ΔE_{2000} Values 4/4

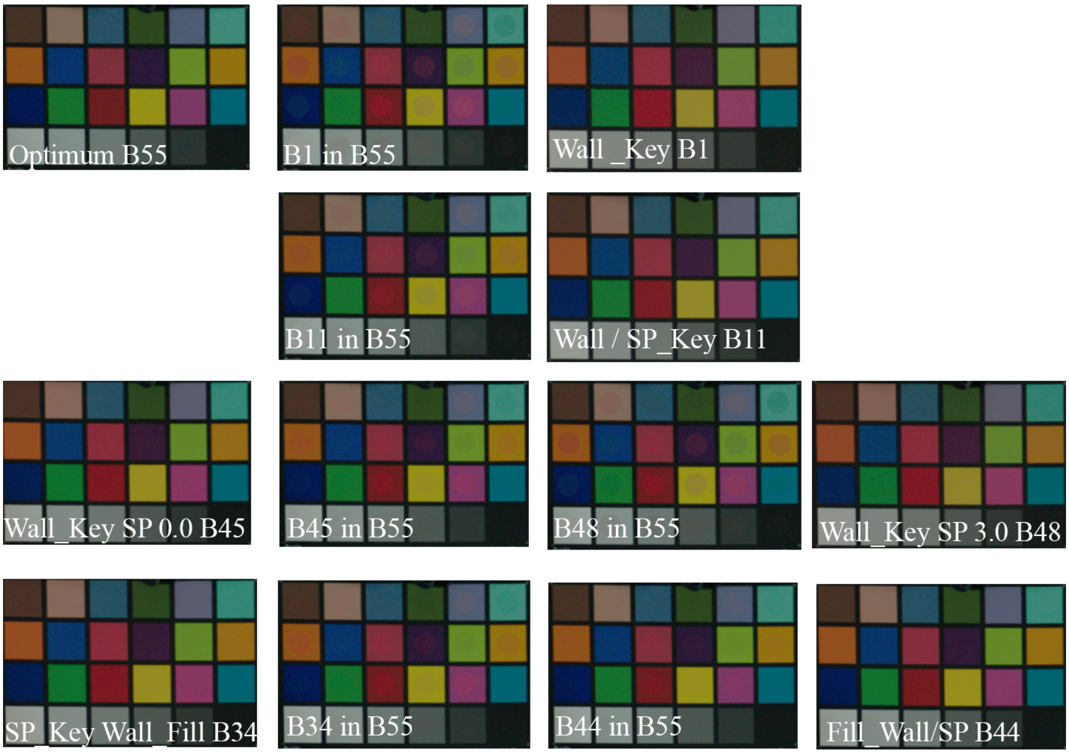

Figure 6.6: Comparison of Differently lit ColorChecker Charts

The ΔE_{2000} values for the lighting situations shown in Figure 6.8 are plotted in Figure 6.2 to 6.5.
B55 shows the optimal lighting scenario, lit with *Skypanels*.
B1 shows the lighting situation, using only the LED wall as a key-light.
B11 shows the lighting scenario, when the *Skypanels* and the LED wall are used half/half to form the key-light.
For the key-light in B45 was used the LED wall with a scene contrast of 0 F-Stops, whereas B48 has a scene contrast of 3 F-Stops.
B34 shows the *ColorChecker* lit by the *Skypanel* as a key-light and the LED wall as a fill-light. Whereas the fill-light in B44 is lit half/half by the *Skypanel* and the LED wall.

Figure 6.7: Comparison of the SkyPanel lit Scene (Left) and the LED wall lit Scene (Right) 1/2

Figure 6.8: Comparison of the SkyPanel lit Scene (Left) and the LED wall lit Scene (Right) 2/2

Appendix Chapter 4.2

Results of a personal correspondence with Colorist Florian 'Utsi' Martin.
A survey called "Color Rendition of Skintones in VP Scenes a Survey with Florian 'Utsi' Martin".

Summary of Survey Documentation

			Asian Skin	Elderly Caucasian Skin	Young Caucasian Skin	Caucasian Skin	POC Skin		
2. „Just perceptible color difference to Optimum due to close observation."		<2		11					
____________									
		2					11, 13		
3. „Small color differences to Optimum."	Perceptible through close observation	2-3	10, 11, 14	4, 7, 9, 12	11, 12, 4	11	10, 11, 12, 13, 14		
____________									
		3	9, 12	5, 14	7, 9	4, 14	7		
4. „Clearly noticible color difference to Optimum."	Perceptible at a glance	3-5	5, 4, 7, 13	13	5, 10, 13, 14	5, 6, 7, 9, 10, 12, 13	9, 4, 5		
____________									
		5							
5. „Huge, unacceptable color difference to Optimum."		>5	3, 6	3, 6, 13	3, 6	3	3, 6		
Lightning Scenario									

1	Skypanel Left Side, Measured 2.8 aperture with light meter	
2	Skypanel Right Side, Measured 2.8 aperture with light meter	
3	Wall Right Side 1485 Nits, Measured 2.8 aperture with light meter	
4	Wall 2.8 Right Side 1485 Nits, 1 T-Stop Contrast, SkyPanel left Side with 2.0	Wall as Key
5	Wall 2.8 Right Side 1485 Nits, 2 T-Stop Contrast, SkyPanel left Side with 1.4	
6	Wall 2.8 Right Side 1485 Nits, 3 T-Stop Contrast, SkyPanel left Side with 1.0	
7	Wall 2.8 Right Side 1485 Nits, 0 T-Stop Contrast, SkyPanel key left Side with 2.8	
9	Wall 2.8 Right Side 700 Nits, 1 T-Stop Contrast, SkyPanel key left Side with 2.8	SP as Key
10	Wall 2.8 Right Side 350 Nits, 2 T-Stop Contrast, SkyPanel key left Side with 2.8	
11	Wall 2.8 Right Side 200 Nits, 3 T-Stop Contrast, SkyPanel key left Side with 2.8	
12	Wall Right Side 1300 Nits, SkyPanel Right Side 15% 50/50// 0 T-Stop Contrast, SkyPanel Left Side with 2.8	Wall partial as Fill
13	Wall Right Side 1000 Nits, SkyPanel Right Side 12% 25/75// 0 T-Stop Contrast, SkyPanel Left Side with 2.8	
14	Wall Right Side 1200 Nits, SkyPanel Right Side 7% 75/25// 0 T-Stop Contrast, SkyPanel Left Side with 2.8	

Figure 6.9: Subjectively indicated ΔE_{2000} Values. Results of survey "Skintones in VP Scenes" with Colorist 1/2

3	Wall Right Side 1485 Nits, Measured 2.8 aperture with light meter	Wall as Key
6	Wall 2.8 Right Side 1485 Nits, 3 T-Stop Contrast, SkyPanel Left Side with 1.0	Wall as Key, SP Fill
4	Wall 2.8 Right Side 1485 Nits, 1 T-Stop Contrast, SkyPanel Left Side with 2.0	Wall as Key, SP Fill
5	Wall 2.8 Right Side 1485 Nits, 2 T-Stop Contrast, SkyPanel Left Side with 1.4	Wall as Key, SP Fill
7	Wall 2.8 Right Side 1485 Nits, 0 T-Stop Contrast, SkyPanel Left Side with 2.8	Wall as Key, SP Fill
9	Wall 2.8 Right Side 700 Nits, 1 T-Stop Contrast, SkyPanel Left Side with 2.8	SP as Key, Wall as Fill
10	Wall 2.8 Right Side 350 Nits, 2 T-Stop Contrast, SkyPanel Left Side with 2.8	SP as Key, Wall as Fill
11	Wall 2.8 Right Side 200 Nits, 3 T-Stop Contrast, SkyPanel Left Side with 2.8	SP as Key, Wall as Fill
13	Wall Right Side 1000 Nits, SkyPanel Right Side 12% 25/75// 0 T-Stop Contrast, SkyPanel Left Side with 2.8	SP as Key, Wall/SP Fill
12	Wall Right Side 1300 Nits, SkyPanel Right Side 15% 50/50// 0 T-Stop Contrast, SkyPanel Left Side with 2.8	SP as Key, Wall/SP Fill
14	Wall Right Side 1200 Nits, SkyPanel Right Side 7% 75/25// 0 T-Stop Contrast, SkyPanel Left Side with 2.8	SP as Key, Wall/SP Fill
Comments		
Asian Skintone	Deutlich verschiedene Hauttöne, verblasste Lippen, ungesund, Sehr fleckige Haut	
Elderly Caucasian Skintone	Spiky Colors, Falten kommen mehr zur Geltung, Hals sieht faltiger aus, Lippen ungesunde Farbe, wirkt uncharmant	
Younger Caucasian Skintone	Als würde Licht tiefer eindringen, Hautunreinheiten kommen stärker zur Geltung, Nase sieht ungesund aus, in der Nase sieht man rot, als würde Licht anders durch die Haut gehen, Augenfarbe wird grün zu blau, Mehr Fleckigkeit, Entsättigtere Augenringe	
Adult Caucasian Skintone	Lippen übersättigt, Bart wird blaustichig, Hautunreinheit auf Nase fliegt weg, Lippen besser, weniger Spikeyness, Lippen wieder blasser	
POC Skintone	Haut sieht verbrannt aus, Haare bekommen Rotstich	

Figure 6.10: Subjectively indicated ΔE_{2000} Values. Results of survey "Skintones in VP Scenes" with Colorist 2/2

Figure 6.11: Skintone Comparison of the LED Wall and SkyPanel lit Scene 1/2

The recordings shown in 6.11 and 6.12 are (from left to right) lit with the LED wall and the *SkyPanel*. The third image shows a mix of both light sources. The *SkyPanel* is used as a key-light, whereas the fill-light is a mix of half *SkyPanel* and half LED wall.

Figure 6.12: Skintone Comparison of the LED Wall and SkyPanel lit Scene 2/2

Bibliography

[Alt21] AlterCine: *The Future of Cinematography: Virtual Production | Greig Fraser & Roger Deakins*. https://www.youtube.com/watch?v=F5_N_1SUE0Y. Version: 2021

[Bar16] Bardi, Joe: *3D Modeling: Realism and Lighting for Augmented Reality and Virtual Reality*. 2016

[BC14] Bennett, Joel ; Carter, Chris: Adopting Virtual Production For Animated Filmaking. In: *7th Annual International Conference on Computer Games Multimedia and Allied Technologies (CGAT 2014)*, Global Science and Technology Forum, 2014, S. 1–8

[Bre12] Brendel, Harald: *ALEXA Log C Curve: Usage in VFX*. 27.06.2012

[Bur] Burns, Michael: Everything you need to know about Virtual Production. In: *Guide Virtual Production* , Nr. 2022, 33–41. www.broadcastnow.co.uk/broadcasttech

[Deb] Debevec, Paul: *Virtual Production: Getting the Lighting Right*. https://fmx.de/en/program-2022/detail/event/23280

[Del20] Deloitte.: The future of content creation: Virtual production: Unlocking creative vision and business value. In: *Deloitte.* (2020)

[Des12] Desowitz, Bill: *Reverse Engineering 'Gravity'*. https://www.awn.com/vfxworld/reverse-engineering-gravity. Version: 2012

[DIN76] DIN Deutsches Institut für Normung e.V.: *Farbwiedergabe: Farbwiedergabe-Eigenschaften von Lichtquellen in der Beleuchtungstechnik*. Teil 2. Berlin, 01.02.1976

[DIN82] DIN Deutsches Institut für Normung e.V.: *DIN 5033 T.8: Farbmessung: Messbedingungen für Lichtquellen*. Berlin, 08.04.1982

[DIN92] DIN Deutsches Institut für Normung e.V.: *DIN 5033 T.4: Farbmessung: Spektralverfahren.* 01.07.1992

[DIN93] DIN Deutsches Institut für Normung e.V.: *DIN 6172: Metamerie-Index von Probenpaaren bei Lichtartwechsel.* Berlin, 1993

[DLL] Debevec, Paul ; LeGendre, Chloe ; Lepicovsky, Lukas: *Jointly Optimizing Color Rendition and In-Camera Backgrounds in an RGB Virtual Production Stage*

[DMM] Davidson, J. G. ; Marcus, H. ; McCamy, C. S.: A Color-Rendition Chart, S. 95–99

[ETC] ETCenterVideos ; Weaver, Eric (Hrsg.): *Virtual Production Getting the Lighting Right Paul Debevec.* https://www.youtube.com/watch?v=SJxEWQYAbVg

[Gre15] Greule, Roland: *Licht und Beleuchtung im Medienbereich.* Carl Hanser Verlag München, 2015. – ISBN 978344643479

[Gre21] Greule, Roland: *Licht und Beleuchtung: im Medienbereich.* 2. Carl Hanser Verlag München, 2021

[HALR] Hernández-Andrés, Javier ; L. Lee Jr., Raymond ; Romero, Javier: Calculating correlated color temperatures across the entire gamut of daylight and skylight chromaticities, S. 1–7

[Jun] Junghahn, Frank: *LEDcave - How Virtual Production has started in Germany.* https://fmx.de/en/program-2022/detail/event/24489

[Kad] Kadner, Noah: *Virtual Production Field Guide.* https://cdn2.unrealengine.com/vp-field-guide-v1-3-01-f0bce45b6319.pdf

[Kad21] Kadner, Noah: The Virtual Production Field Guide: Volume 2. (2021), 1–152. https://cdn2.unrealengine.com/Virtual+Production+Field+Guide+Volume+2+v1.0-5b06b62cbc5f.pdf

[KK22] Kwok, Andrei O. J. ; Koh, Sharon G. M.: COVID-19 and Extended Reality (XR). In: *Current Issues in Tourism* (2022), S. 1–3

[Kwa18] KWAK, Youngshin: *CIE Research - Addressing Color Quality of Light Sources Related to Perception and Preference.* 2018 http://files.cie.co.at/LpR%2066%20CIE%20RESEARCH%20Special%20-%20CIE%20Research%20Addressing%20Color%20Quality%20of%20Light%20Sources%20Related%20to%20Perception%20and%20Preference.pdf

[Lux21] LUX MACHINA CONSULTING: *Lux Machina | What Goes into Building an LED Virtual Production Volume - Extended Version.* https://www.youtube.com/watch?v=jKrpwtW2WsY. Version: 2021

[LYD] LEGENDRE, Chloe ; YU, Xueming ; DEBEVEC, Paul: *Optimal LED selection for multispectral lighting reproduction*, SIGGRAPH '16, July 24-28, 2016, Anaheim, CA. http://dx.doi.org/10.1145/2945078.2945150. – DOI 10.1145/2945078.2945150

[Mar22] MARCHÉ DU FILM (Hrsg.): *Today, Cannes Next announced a new partnership with Epic Games, developer of Unreal Engine, for the innovation-driven program of the Marché du Film, taking place this year in Cannes from 17-25 May.* https://www.marchedufilm.com. Version: 2022

[McG22] MCGOWAN, Chris: Into the Volume: Five Innovative Firms with LED Stages Eye Year of Growth. In: *The VES Handbook* (2022)

[MT] MOKRZYCKI, Wojciech ; TATOL, Maciej: Color Difference Delta E: A Survey, S. 1–28

[Net22] NETFLIX: *1899 - Behind the Scenes.* https://www.youtube.com/watch?v=5vWt49oXINg. Version: 2022

[PS1] PRIADKO, leksandr ; SIRENKO, Maksym: Virtual Production: a New Approach to Filmmaking. In: *Bulletin of Kyiv National University of Culture and Arts. Series in Audiovisual Arts and Production* 4 (1), S. 52–58. http://dx.doi.org/10.31866/2617-2674.4.1.2021.235079. – DOI 10.31866/2617–2674.4.1.2021.235079

[RK] R., Srividya ; KURIAN, Dr.Ciji P.: *White Light Source Towards Spectrum Tunable Lighting: A Review.* India,

[ROE] ROE Visual Co., Ltd.: *Specifications RB2.3.* https://www.roevisual.com/uploads/files/Product%20File/Ruby/ruby-1.52.3-specification1.pdf

[SBB16] Seifert ; Barfuss ; Baer: *Beleuchtungstechnik.* 4. Berlin : Huss-Medien GmbH, 2016

[Sou22] Southern, Richard: *A comparison of LED panels for use in Virtual Production: Findings and recommendations.* 2022

[The93] The Foundry: *Nuke.* https://www.foundry.com/products/nuke-family/nuke. Version: 1993

[Tré08] Trémeau, Alain: Color in Image and Video Processing: Most Recent Trends and Future Research Directions. In: *EURASIP Journal on Image and Video Processing* (2008), Nr. Volume 2008

[Vie21] ViewSonic: *What is Delta E? And Why Is It Important for Color Accuracy?* https://www.viewsonic.com/library/creative-work/what-is-delta-e-and-why-is-it-important-for-color-accuracy/. Version: 2021

[Viv03] *LEDcave OPEN: We're hosting an open-door day this June!* https://ledcave.vivents.io/. Version: 2022-06-03 (LEDcave OPEN)

[Vos] Voss, Olaf von: *What You Need to Know About the History and Physics of Film Lighting.* https://www.cined.com/

[Wal96] Walker, John: *Colour Rendering of Spectra.* https://www.fourmilab.ch/documents/specrend/. Version: 1996

[XR] X-Rite, Inc.: *ColorChecker® Classic.* https://www.xrite.com/categories/calibration-profiling/colorchecker-classic