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Title: Connecting the digital world and the physical world through light

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Master Thesis

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Abstract:

This master thesis with the title "Connecting the digital world and the physical world through light" is about working with lighting for augmented reality environments. Its goal is to develop a design framework for physical lighting in an augmented reality (AR) environment. The work is based on the theater play SKYG33N, directed by Mikael Fock. The theater play is a three-dimensional AR experience that uses a pepper's ghost illusion on stage. Through a series of practical experiments, including observations, on-site testing, and model trials, new design findings were developed. These findings are concluded in a "framework for creating an AR environment through a pepper's ghost illusion." Thereby, the whole process of this master thesis is working in the three knowledge areas of lighting design: natural science, social science and humanities. This thesis explores the background of lighting design in general and gives an overview of optical illusions. An important part of working in AR environments is understanding how to implement them. That is why it is explored how optical illusions work and how human beings perceive them. A particular focus is placed on the history and implementation of the pepper's ghost illusion.

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AALBORG UNIVERSITET

CONNECTING THE DIGITAL WORLD AND THE PHYSICAL WORLD THROUGH LIGHT

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INTRODUCTION

The everyday use of smartphones or computers is ubiquitous in everyday life. The digital world has found its way into almost all areas of modern life. How can this development be integrated into non-digital areas of life? For example, a tradition-rich culture such as theater, drama, or ballet. This question is posed by the theater play SKYG33N, which forms the starting point of this work.
It makes use of an optical illusion that is almost 200 years old – the pepper's ghost illusion.
This work is motivated by the idea of linking old techniques with new methods and utilizing the strengths of light in the creation of atmosphere.

MOTIVATION

My enthusiasm for light and designing with it goes back many years. I have always been particularly impressed by the countless possibilities that this medium gives the designer. Something that cannot be physically touched can have such an impact on people and the atmosphere around them has always held a great attraction for me. Light itself only becomes visible when it meets a physical object. This interplay of immaterial and material existence and the almost undisputed atmospheric power of light is something, I have always wanted to use in design. For this very reason, the first intention when finding a topic for this work was to deal exclusively with the atmospheric qualities and qualitative characteristics of light.
Another requirement I had for this work was to contribute to a subject area that had not already been analyzed in detail many times before. This is exactly the case with the atmospheric effect of light. I was also very interested in working on a topic that, in addition to design challenges, also involves challenges in its possible technical implementation.

In the field of lighting design, I am particularly enthusiastic about temporary and artistic works. Many of these designs take place on concert or theater stages, and their aim is to inspire and entertain people. I think that moments of great emotion, as they often take place in concerts or theaters, remain more in people's minds than the lighting of their everyday lives.

I also believe that academic work should always try to move with the times. In today's world, the digital and physical spheres merge. All virtual areas of our everyday lives are supported by digital systems or have been taken over by them. I therefore believe that lighting design itself should also become active at this intersection of worlds.

These different areas of motivation found many overlaps in one of the projects during my internship at the audiovisual artist collective Vertigo. The theater play SKYG33N forms the basis for this work.
The aim of this work is to go beyond the exclusive application of lighting design for augmented reality in the play itself and to develop insights that can be applied more generally.

The theater play - SKYG33N

One of the starting points for this work is the play “SH4DOW “or “SKYG33N” written and directed by Mikael Fock. It is a 3D production inspired by HC Andersen’s fairy tale “The Shadow”. It is played by a single actress. The play deals with the human attempt to discover oneself. This is attempted through the use of artificial intelligence. The piece is an anthropological experiment of a human being in a digital environment.

The play shows the conflict, that arises from the situation in which the AI collects human emotions. Both the actress and the audience interact directly with the AI. The AI is programmed by Cecilie Waagner Falkenstrøm. A large part of the play is improvised live by the actress in interaction with the AI. The AI responds in a humanized voice and is represented by a depiction of a digital neural network and other visual elements. These are designed by Carl Emil Carlsen (Falkenstrøm, n.d.).

The direct interaction between the digital world and the physical world is realized through the use of a pepper’s ghost illusion (Hösch, 2023). This thesis covers the performances presented in November 2023 by the Helsingborg Stadsteater and by the Theater de Veste in Delft in February 2024, both performed by Luise Skov.

PART 1: APPROACH

1. PROBLEM AREA AND FRAMING

In many areas, lighting design is not the main protagonist of the design but rather allows the effect of the entire situation to unfold (Sanders, 2018). For most theater plays, the light design is of minor relevance from the audience's point of view, especially in comparison to the play itself. One of the protagonists in SKYG33N is represented by a pepper's ghost illusion. It is the scenography and lighting design that make the performance possible. Therefore, the theater play is a strong basis for this work.

This approach being so closely connected to a practical project allows the interesting task of connecting the digital and the physical world on one stage within the same view. Secondly, it allows the very interesting challenge of using old techniques, like the pepper's ghost illusion, to create something new and potentially futuristic. The first time the Pepper's ghost illusion was presented on stage dates back to 1862, where it was first implemented on stage by Professor John Pepper (Groth, 2007).

Working within the area of theater lighting, the design allows a more creative way of thinking. There are no regulations on illuminance levels, which gives the chance to focus on the design aspects of the strengths of light in creating spaces and atmospheres.

The connection between the physical and digital world can have many different names. For example, a complete blending of the two worlds is often referred to as phytical. In addition, the phytical world is about the mixing of online and offline components. We can observe this aspect mostly in marketing businesses (Del Vecchio et al., 2023). Another type of blending of the two worlds is virtual production. Virtual production is often found in the area of moving images. In this case, real-time computer-generated imagery or other digital materials are mixed with live-action film productions (Breitman, 2024).

However, the way in which the illusion on stage connects the two worlds is more like a superimposition of layers. One reality is supplemented by another and vice versa. This project, therefore, operates within the framework of augmented reality (AR). The two worlds literally augment each other. According to this definition, in AR, it is still possible to see the real (physical) world, while a connection to the comprehensive digital world is also created (Doerner et al., 2022).

The main focus of the work is on the design of light, which is strongly influenced by three different areas (Figure 1). These have been precisely defined during the progress of the work.
In the first area, the design solution must be tailored to the practical implementation of the illusion and the physical possibilities. The physicality is directly linked to the medium of light, whereas the rigging of the design is only indirectly linked to the light view.
The second area is materiality. It distinguishes between which foundations and components of the design exist digitally, physically, or in both areas. These components are always directly linked to the light view.
The third area can be described as human experience or human study. It focuses on the impact of design on people. In particular, human studies examine the atmospheric effect and the viewer's experience. Furthermore, the area includes spatial theory. Light also has a direct influence on these three components of the human experience.

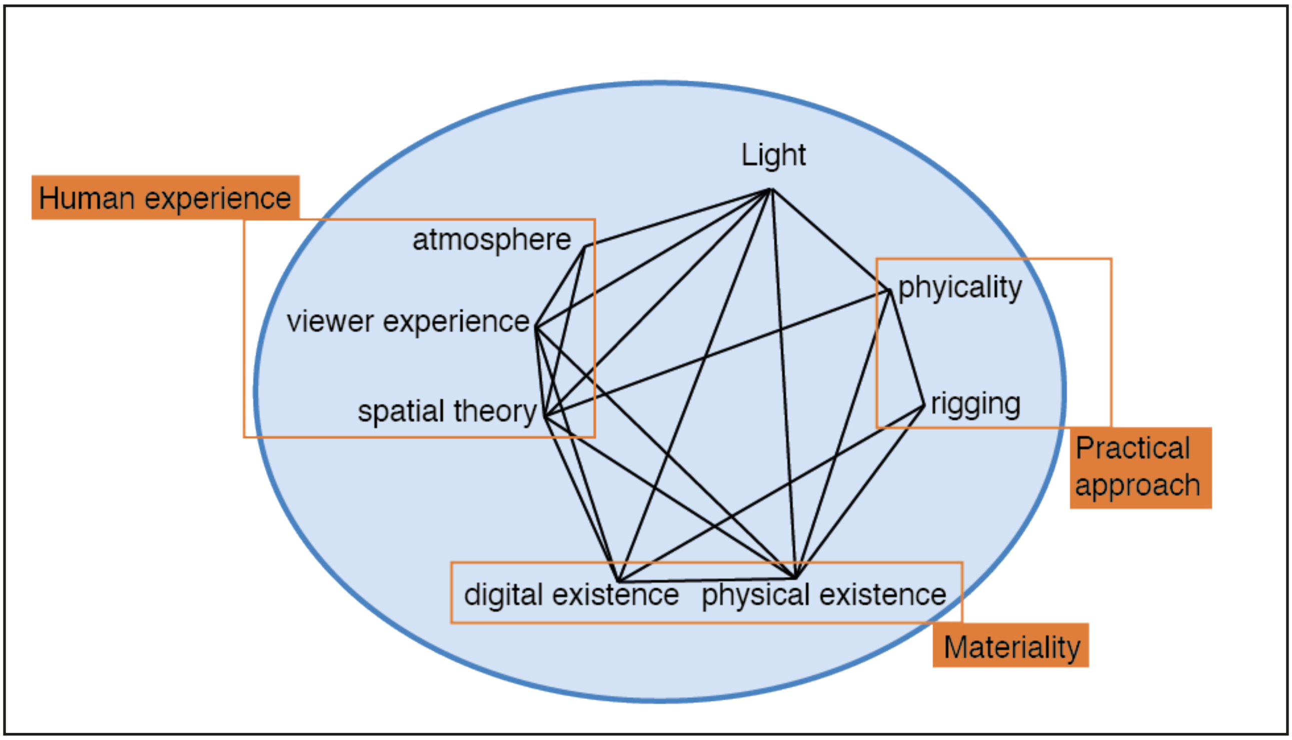


Figure 1: Framing of the topic: Hösch, 2024

2. INITIAL PROBLEM STATEMENT

The whole process of the project is led by a vision. This vision is created through personal motivation, the definition of the problem and the framing of the topic. The vision is described as:

Essentially, the vision is based on the idea that light in the physical world could connect this physical world to a digital world. The design of the light could thus merge two parallel worlds and improve the desired atmosphere of the space and situation.

In order to generate a structured objective, three hypotheses are developed from this vision. These hypotheses relate to the three research areas of humanities, social science and natural science.

Humanities:
Different light scenarios can create an all-embracing experience for the user based on cultural backgrounds.

Social Science:
Different light scenarios can create certain atmospheres, which are important for the different situations or scenes based on biological backgrounds.

Natural Science:
Lighting in the holographic visuals and the physical world around them need to have a certain relation to one another to achieve the effect.

The objective is to test these three hypotheses on the basis of the research and the experiments carried out.

The subsequently developed initial research question is:
How can physical light function as a medium to connect the physical and digital world in an augmented reality environment?

This work focuses exclusively on using physical light for the optimization of the light design. With this precise definition, the distinction between the design of a virtual production is clear.

3. METHODOLOGY

The project is based on the “Design Experiment Model” (Figure 2) developed by Ellen Kathrine Hansen. This design model addresses the multidisciplinary nature of lighting design. Whereby the research based-science of light will be integrated into interactive media technology. The aim of the “Design Experiment Model” is to combine knowledge from different disciplines and, thereby, gain new insights. The three disciplines of lighting design are natural science, social science and humanities. These are included in each of the five steps of the model: design vision, design intention, design proposal, design evaluation and design solution. The first step, the design vision, can be understood as an “entrance level”. The goal of this first step is to create a meaningful design vision across all three fields of knowledge. The result of this step is the initial research question. In the second step, the design intention, the three knowledge areas get further explored. This exploration results in an explicit statement or hypothesis. The third step, the design proposal, is about proposing preliminary design solutions (Hansen & Mullins, 2014). This is where this work is deviating from the structure of the Design Experiment Model. This work bases its design proposal on a series of observations and not alone on scientific research. In the forth step, the design evaluation, the design proposal is view critically. In this step, it is reflected on how the design meets the design intentions and criteria (Hansen & Mullins, 2014). As a design evaluation in this work, more experiments are conducted. The final fifth step, the design solution, aims on answering the hypothesis and the final research question. The final design should refer to the design vision and the design intention (Hansen & Mullins, 2014).

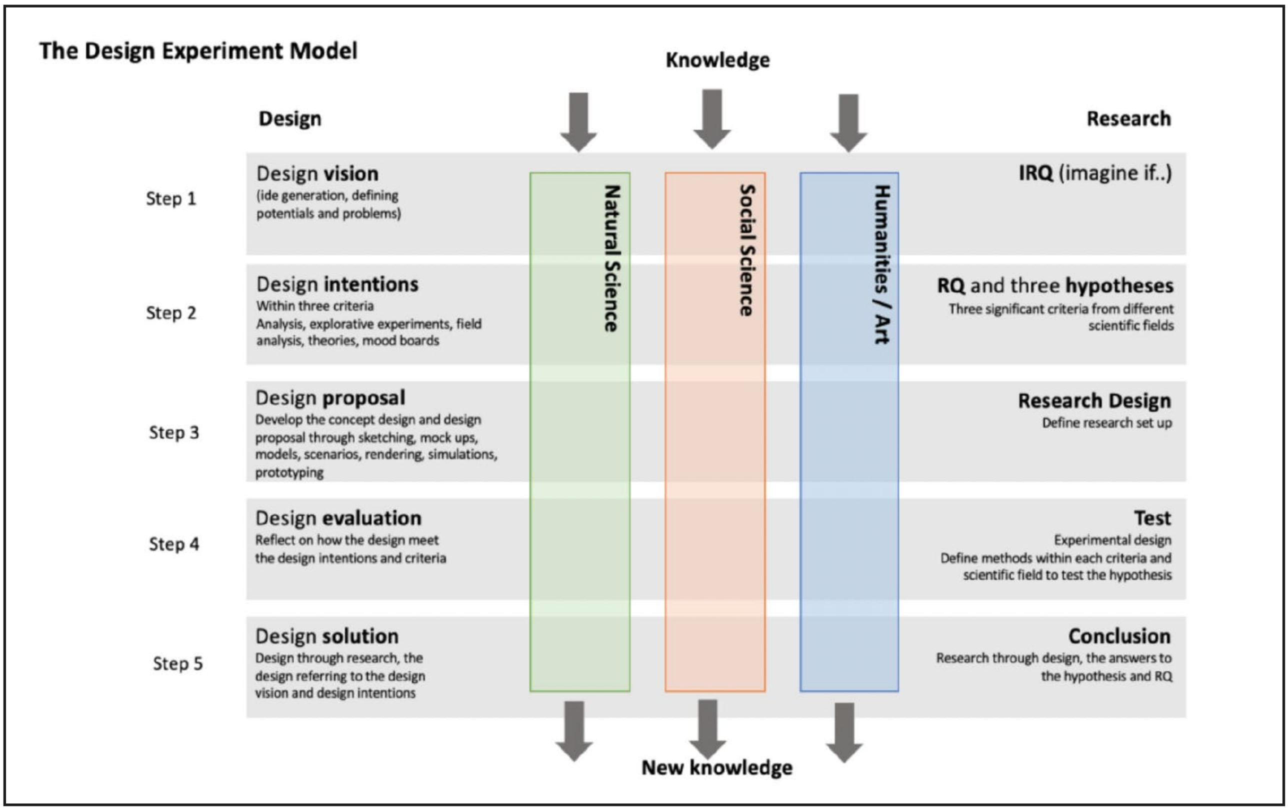


Figure 2: The Design experiment model: Hansen, Hvass 2019

Another method used is the explorative research model. The aim of this research is to explore and gather more insights on a topic that has not yet been widely studied. The explorative research model rather aims at defining the exact problem instead of searching for a final result. This offers the advantage of relatively inexpensive and flexible research. This type of research often remains without a general result. At the same time, the explorative research model can also be based on qualitative data. It is therefore difficult to generalize (Bhasin, 2023).

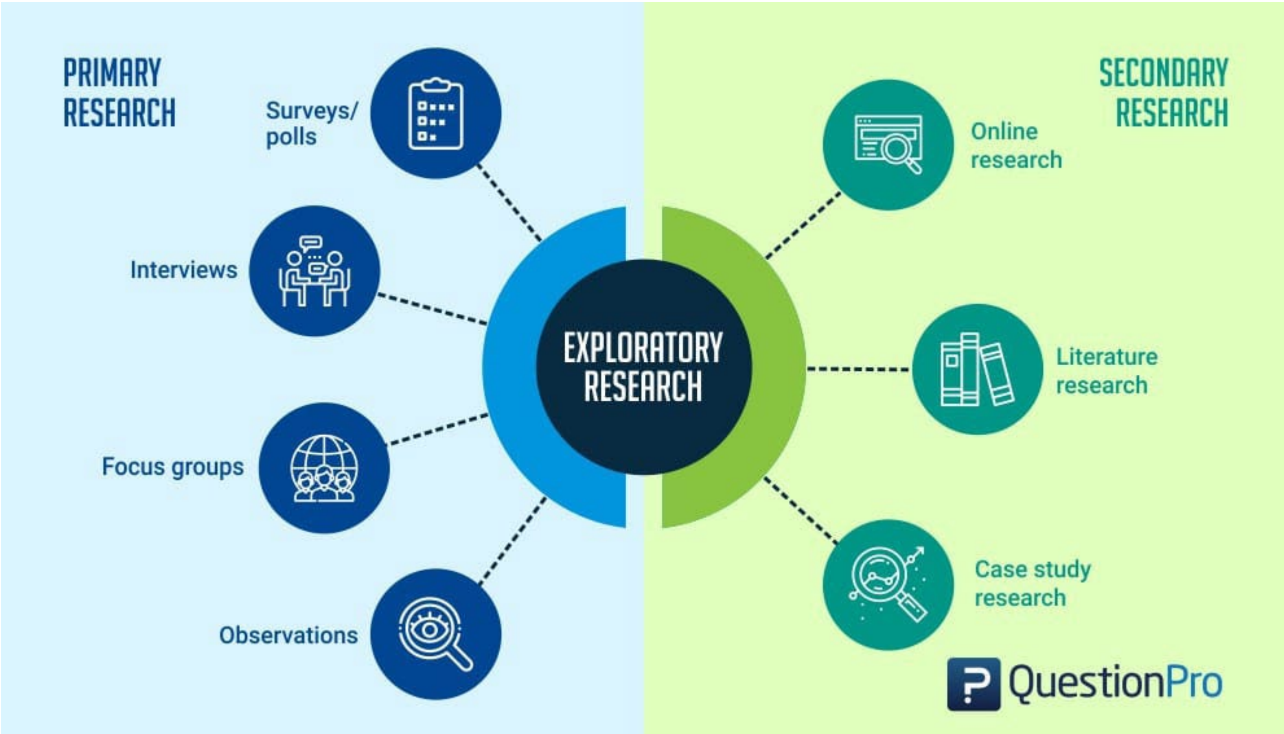


Figure 3: Explorative research model: Bhat, 2024

Due to the characteristics of this model, it is mainly used at the beginning of the research process. Nevertheless, the aim of this work is to develop a final result. The explorative research model will therefore be used mainly for the initial problem definition rather than for developing the final result. A final result is developed by following the design experiment model throughout the whole process of this work.

4. PROCESS MAPPING

Figure 4 shows a visual representation of the overall process for this project. Following the two method models, an initial problem statement is first formulated from the basic starting points and initial hypotheses. The initial problem statement, is followed by a literature research and first observations on the set of the play SKYG33N. From the literature research, the thematic framework of this work is developed, from which the final problem statement is drawn. The hypotheses developed can then be tested in a series of experiments consisting of three parts. The results obtained will then be summarized in a framework for lighting design in augmented reality in a pepper's ghost illusion.

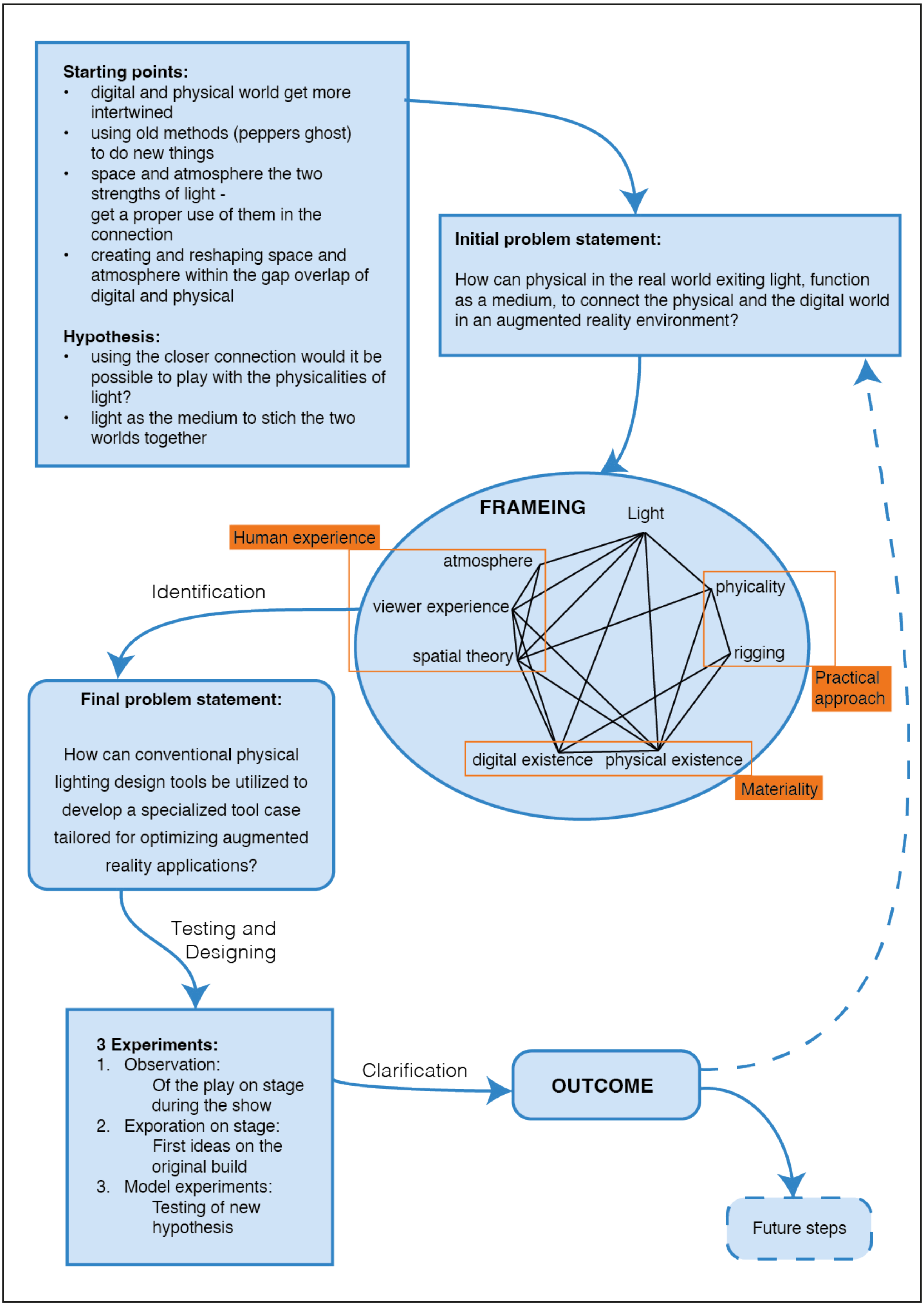


Figure 4: Process mapping: Hösch, 2024

5. DESIGN INTENTION

This type of work is in the fields of lighting design and augmented reality, with a focus on theater stages. The principal aim of this work is to develop the strengths and weaknesses of a production of this type and to make these accessible for subsequent designs. Furthermore, this work elaborates a framework for designers facing a similar design challenge. The focus here is not on a design solution for a specific project or problem but rather on providing new ideas for lighting design in augmented reality environments. The aim is to develop new and creative solutions that go beyond classic thought patterns.

PART 2: LITERATURE REVIEW

This section provides a comprehensive overview of the background of the project. The technical and theoretical background of each of the different areas is examined. In addition, this section provides an insight into the history of the most important aspects. A particularly important part of this background research is the relationship between the different areas and affected users. Therefore, each of the components is concluded with a connection to human perception. Finally, a conclusion is drawn for the entire field of backgrounds.

1. LIGHT

First, the background of the light is analyzed in more detail. Also, the technical aspects of electric light are discussed. The current implementation of the project relies on a perfect black box on a theater stage (see page 42). Thus, natural light is irrelevant. Therefore, whenever this work refers to light, it is always electrical light, unless stated differently. This is also the reason why a closer look is taken at the design of theater lighting. Then, the theory of light is explored in more detail, with a focus on color and the effect of light on atmosphere. The background of the theater is also included here. The human perception and effect on people of the different aspects of light are subsequently examined in more detail.

The last part of the section on light examines the use of projectors as a light source. Projectors are also used as a light source for the play SKYG33N and throughout the remainder of this work.

1.1 Technology:

A large proportion of the light sources used today are light-emitting diodes (LED) (Tregenza & Loe, 1998/2014). This first part will concentrate on the technical background of LED luminaires.

The light emitting diode

A LED generates light by electroluminescence. The visible light is caused by an electric current flowing through semiconductor connections. The different colors are then created by the semiconductor materials. An LED therefore always has a specific color, but often the individual colors are processed together in a pixel to cover different colors. As a result, the color rendering of LEDs is limited by the technical design of the system. However, color rendering has experienced massive improvements since the first LEDs emerged. In general, color rendering qualities are quantified by the color rendering index (CRI). Nevertheless, the CRI is not always a good indicator for the rendering performance of LEDs. The light emitted by a LED is not omnidirectional. Therefore, LEDs have small lenses to bundle or spread the light. Due to their small size, LEDs can be used in many different ways. In addition, LEDs can change colors very quickly. Naturally, the boundary between light and information displays is slowly becoming blurred (Tregenza & Loe, 1998/2014).

History

It took a considerable period of development before the flexibility of today's LED could be achieved. The first electric light, the carbon arc, was developed by Humphery Davy in 1810. It was not until 1880 that the widespread use of electric light was made possible by Joseph Swan and Thomas Edison. The next developments were high-fluorescent tubes and high-pressure discharge lamps in the middle of the 20th century. From then on, the development moved away from incandescent lights to compact fluorescent lights and finally to today's LEDs. In 1907, electroluminescence was discovered by H. J. Round. The first LEDs were manufactured in 1920. At that time, the technology was too expensive to be widely used in practice. Finally, at the beginning of the 21st century, bigger investments were made in the business for the development of LEDs, resulting in adequate performance and acceptable color rendering, which made the widespread use of LEDs possible (Tregenza & Loe, 1998/2014).
This chronological development shows how complicated the first realization of Pepper's ghost illusion must have been in 1863 (see page 31), when electric light was not widespread.

Quantitative data

To be able to analyze quantitative data when evaluating the experiments, the next section takes a closer look at the possibilities of measuring light.

Luminance:
The amount of light flowing from a certain direction from a surface is called luminance. Luminance is measured in candela per square meter. Sometimes luminance is described as the apparent brightness, but it is important to note that the apparent brightness is not only dependent on the lumiance. It is also influenced by how well the eye can adapt to the light/dark ratio at that moment and what the true brightness pattern is in the visual field (Tregenza & Loe, 1998/2014).
When using a luminance meter, it is important to consider the material used for the measurement. The reflection (see page 20) of the material has a large influence on the measured luminance (Tregenza & Loe, 1998/2014).

Since the luminance ratio between an object and its background is a good indicator of visual emphasis, luminance plays an important role in analyzing the planned experiments. An easy-to-implement method for measuring luminance is the use of false color images from high dynamic range images (HDRI). These images can be used to directly compare the luminance of different areas of the same scene at the same time (Tregenza & Loe, 1998/2014). At this point, it can be an

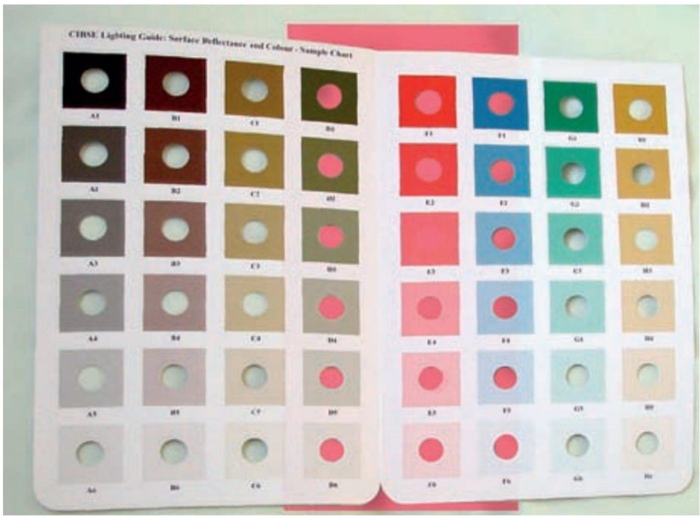
indicator of whether the viewer's attention is drawn to the desired areas of the scene. Since it can be assumed that brighter areas in the viewer's field of vision attract their attention more than darker areas (Studio CLC, 2019).
Through this literature research, a hypothesis can be developed, which is tested in the experiments. It is assumed that a certain ratio of luminance between the physical and digital world improves the visual connection between the two worlds.

Illuminance:
Illuminance is closely linked to lumiance. While luminance describes the amount of light flowing from a surface, illuminance defines the opposite direction. When illuminance is measured, the amount of light flowing onto a surface is measured in the unit lux (lx). The lux meter measures the total amount of light flux falling on the receptor. The large angle of incidence on the sensor can result in a large error rate in the measurements, which is why precise planning of the measurements is important (Tregenza & Loe, 1998/2014).
In the experiments to develop the design framework (see page 79), different illuminance measurements are carried out in different areas of the digital and physical world.
This practice follows the hypothesis that there is a connection between the illuminance of the illusion and its credibility for the viewer in connection with the physical world.

Reflectance
Every time light falls on a surface, it is reflected back. This reflection varies depending on the material. It can be defined as: Reflection is the ratio of the reflected light to the incoming light. Reflection is characterized by the Greek letter roh (ρ) and is always a value between 0 and 1. while rho = 0 describes a perfect black surface that absorbs all light, rho=1 describes a totally reflective material that throws all light back.
The reflection factor is the amount of light that is reflected as a percentage. For example, a white paper has a reflection factor of 80%.
Another factor is the type of material. If it has a shiny surface, the light is reflected back at the same and opposite angles as it hits the surface, just like a mirror. This behavior is referred to as specular reflection. If, on the other hand, the material is matte, the light is reflected in all directions. This is called diffuse reflection (Tregenza & Loe, 1998/2014).

Measuring reflection can be a complex task due to its intricate nature. There are various reasons for this. First of all, the reflection changes rapidly when the material is used in a three-dimensional space. By slightly changing the angle, the reflection of the material can change easily. Since reflection is the ratio of the reflected light to the incoming light, it can vary greatly. Reflection is therefore difficult to measure precisely, especially on large surfaces.

There are two methods of measuring reflectance.



The first method is a visual comparison. For this purpose, certain maps with different shades of gray or, in an extended version, shades of color are used for comparison. The material to be tested is then compared with these test cards (Figure 5) and brought together in the most similar area. The reflection can then be approximately determined. To have a simpler workflow, comparison cards with a glossy finish can also be used (Tregenza & Loe, 1998/2014).

Figure 5: Chart used to estimate reflectances:
Tregenza & Loe, 1998/2014

A second method obtains more accurate results. Here, the exact reflectance of a material can be determined using a formula with the help of a comparison card and a luminance meter (Tregenza & Loe, 1998/2014).
However, this type of measurement is beyond the scope of this work and therefore not discussed further.

Within this project, reflection is of particular interest, as it enables a better understanding of which materials are advantageous for the realization and effect of the illusion. The illusion works particularly well when it is possible to control exactly which components of the physical structure are visible to the audience. It is also important to understand which materials are particularly suitable for the illusion. By observing their reflection, it should be possible to better analyze which materials support the effect of the pepper's ghost illusion. This analysis only requires an approximate understanding of the reflection and not its perfect definition.

In theater

We assume to implement the results of this work in a traditional theater. These stages normally have a different setup of lights compared to the one used for the implementation of the illusion. The following section points out the major differences between classic theater stage lighting and the lights used for the implementation of the illusion. It will become clear why classic theater lighting cannot be used for the pepper's ghost illusion.

The first theaters in ancient Greece in the 5th century BC were illuminated exclusively by sunlight. Once electric light was developed, it also became established on the theater stage (Schiller, 2016). When Pepper's Ghost Illusion was first performed in 1862 (Groth, 2007), the carbon arc was the most modern type of theater lighting. Further development continued with the incandescent lamp and high-intensity discharge lights. Around 2008, LEDs also found their way into theaters (Schiller, 2016). Even nowadays, many spotlights consist of high-intensity discharge luminaires (VLTG, 2021).

There are different lighting concepts for theaters. The most widespread is the proscenium theater or a version of it (see figure 6). Here, the stage is illuminated from various, primarily suspended positions. Many of the spotlights are located in the auditorium and the direction of light roughly follows the audience's line of sight (Dunham, 2011/2016).

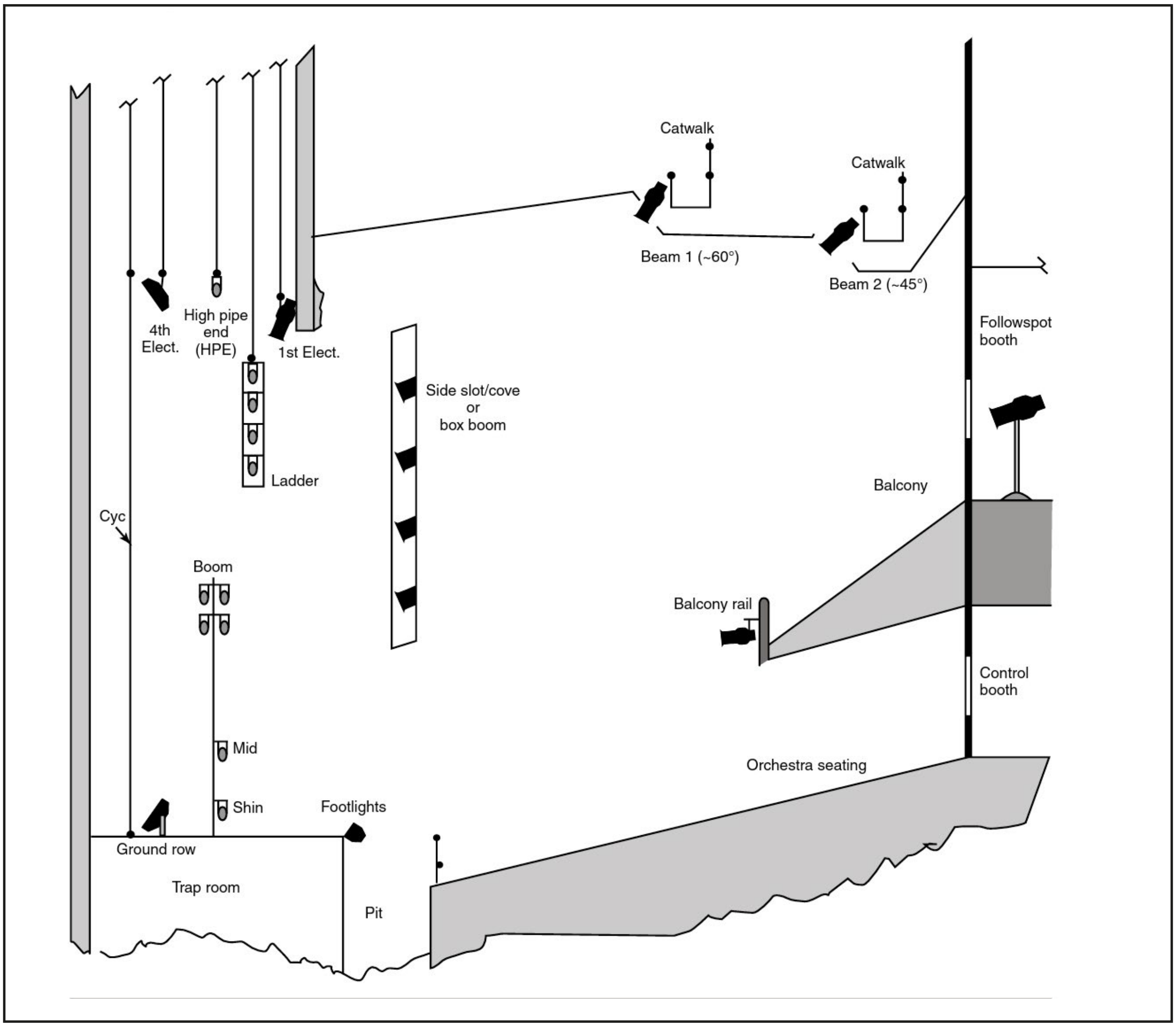
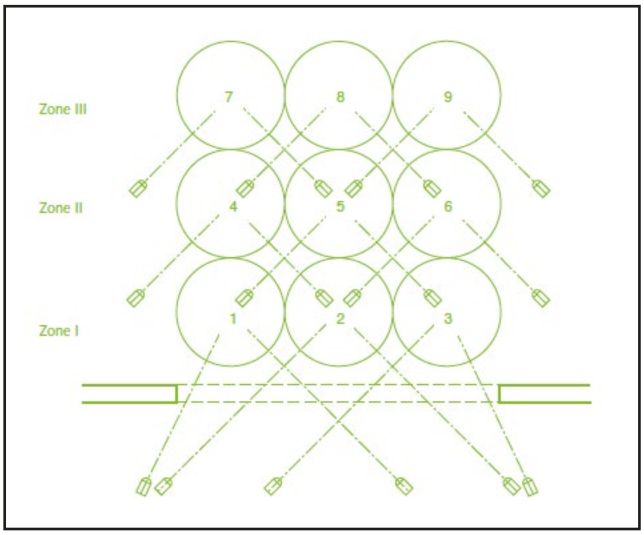


Figure 6: The proscenium theater: Dunham, 2011/2016



This setup creates a general illumination (see figure 7) of the stage, which is then adapted according to every single production. This standardized process enables fast, uncomplicated touring for theater productions (ADB GmbH, 2000).

Figure 7: General illumination of the stage: ADB Gmbh, 2000

As pointed out, classical stage lighting focuses on light from different directions. Generated by fixtures positioned in the auditorium and the side stages. This classical approach is not suitable for the implementation of the pepper's ghost illusion (see page 31). Instead, a different type of lighting has to be developed. For this lighting setup, it is difficult to use the existing theater lighting.

1.2 Theory

In addition to the technical background, the effect of light is also a decisive factor in the success of this project. The following section takes a closer look at color theory and the effect of light on the atmosphere in a room.

Color

Color and light cannot be considered separately. Every light has a color. The perception of the human eye depends on the wavelength of the light. However, this cannot be understood as a direct translation of light color. Instead, when looking at color in light, the following three parameters must be analyzed:

The hue, which describes the ratio of red and green in the color; the saturation, which defines the intensity of the pigment in the color; and the ratio of light and dark within that color.

Once these three variables have been determined, the colors can be specifically represented by different lamps. It is advantageous here if the lamps used have a CRI so that the colors are displayed in the desired way (Tregenza & Loe, 1998/2014).

Understanding how people perceive colors is important for the implementation of this project. It cannot be assumed that everyone perceives colors in the same way. The perception of colors is influenced by the physical adaptability of the eyes.
In addition, there are factors independent of the individual person that influence the representation of colors:

- The perception of color depends on the contrast between the surface and its surroundings. For example, colors often appear more saturated against a dark background.
- The perception of the saturation of the color strongly depends on the size of the surface on which it is displayed. This should be taken into account, especially when evaluating experiments conducted on different theater stages or smaller models.
- The preference for certain colors can be influenced by how long they are viewed. For example, the human vision has the tendency to be more easily distracted by bright surfaces than by dark ones.
- In addition, the perception of color is also influenced by experience. Short-lived objects often have brighter colors, whereas long-lasting walls tend to have duller colors. This experience is automatically incorporated into our perception when we look at colors (Tregenza & Loe, 1998/2014).

Atmosphere

When talking about atmosphere in rooms or on stages, most people have an idea of it. This idea is hard to define in a formal and generally valid way. One approach to describe atmosphere is character. In this context, character remains a very vague, intangible description of the phenomenon that everyone somehow knows, and that is very subjective.
The undisputed part of atmosphere is that it is strongly influenced by light. The moment light fulfills its main task of making things visible, it automatically creates an atmosphere.
The design of atmosphere can be approached from two sides. First, from the side of the object. For this work, the side of the object refers to looking into designing atmosphere through the theater scene. Secondly, the side of the subject. In this work, the side of the subject deals with the design of atmosphere for the theater audience (Böhme, 2013).
For this project, the aim is to create a certain atmosphere on stage, both in the physical and the digital world. Böhme (2013) formulates how this is possible: To design atmosphere it is important "that the artist does not see his actual goal in the production of an object or work of art, but in the imaginative idea the observer receives through the object." (Böhme, 2013).
This statement shows how atmosphere is created through perception and can be individual for each viewer. Due to the multi-layered nature of atmosphere, it is difficult to determine exactly how atmosphere will be in a room. For example, every theater audience is slightly different and therefore influences the atmosphere of the entire play in a different way.

1.3 Projectors as light source

An important part of the project is the use of projectors, To create the digital world, but also as a source of light itself. In the following, both the history and the different uses of modern projectors are therefore discussed in more detail.

History

At first, it seems surprising that the first projectors were used before the development of the first electric light. The “magic lanterns,” which were documented as the first projectors in 1659 by Christiaan Huygens, were powered by candles or oil lamps. Images were projected through painted glass. The episcope was developed around 100 years later. Here, additional mirrors, prisms, or lenses were used to focus the image. In 1872, a projector was powered by an oxyhydrogen lamp for the first time. This development made it possible to present a large-scale projection in the Philadelphia Opera House with 3500 seats (Aleksandersen, 2019).

For the first time, moving images were presented in 1879 using a zoopraxiscope; the moving images were generated by rapidly rotating glass panes. In 1895, the brothers Auguste and Louis presented the first real film projector, which was a film camera, projector and printer all in one.

These analog film projectors continued to be developed until the late 2000s. In the 1950s, cathode ray tube (CRT) projectors became much more popular. The projectors had three separate CRTs, each with one lens to display colors. Between 1990 and 2000, the development of digital projectors began. Due to a number of new technologies, the projectors became smaller and cheaper, which finally caused their breakthrough (Aleksandersen, 2019).

Applications

The difference between a conventional light source and a projector is evident. The task of a projector is to project images, ideally at the highest possible resolution. This makes it possible to play creatively with light. Sharp light edges and laser-like beams can be realized with projectors. Video mapping allows light to be shaped into a wide variety of forms. This great flexibility is mainly restricted by the size of the devices. Only large and heavy devices can produce light at high intensity. In addition, large lenses are needed to make focusing possible. Depending on the use case, these options can be a creative stylistic element. Depending on the project, either a projector or LED fixture might be the better choice. Whereby the LED can easily be equipped with a gobo or barn doors (Fine, 2016).

1.4 Practical implementation

Control system

This chapter provides an overview of the interaction between different components, such as spotlights and projectors. In particular, the control systems for projects working with projectors and conventional lighting are reviewed. It is assumed in this project that the design results will be used for the implementation of temporary installations, which is why only control systems for this type of production are considered.

The different lighting fixtures used in a theater lighting setup (page 21) are usually controlled through digital multiplex 512 (DMX). DMX is a standardized protocol for the transmission of digital control data. Bit signals are sent from a transmitter, a lighting console, to the receivers, the light fixtures. To receive the signals, each of the fixtures is addressed with corresponding channels in the universe. Because of this individual address, a certain number of fixtures can be wired one after another. This practice is called a daisy-chain and makes it possible to feed several fixtures through only one output out of a lighting console. The setup is relatively simple and, therefore, can be prepared up to the last detail during the planning stage. It is therefore the standard in the event industry (Dunham, 2011/2016).

Using additional hardware, image material can be sent from a lighting console to a projector. The control gained through this practice does not enable to use the full flexibility of a projector. This is why a different type of lighting control is used for this project.

The main program used here is MadMapper. The choice of using this program is based on the personal preferences of the video- and light-operators of the theater play SKYG33N. MadMapper is a video mapping software, which means that it is designed to adapt visual content output via projectors to different surfaces.

This program is used as an example of the wide variety of video mapping software. In addition, programs of this type also have the option of playing out DMX protocols, which is why they are well suited for a project of this type (MadMapper Features, n.d.). By controlling the different technical components of the project through one singular program, the different components interact better with each other. The projectors in the production can be seen as the digital world, and the physical fixtures as the physical world. We assume that controlling both worlds through the same software can lead to a more satisfying result in the final design.

2. HOLOGRAMS AND OPTICAL ILLUSION

This section discusses holograms and optical illusions. First, an explanation of a real hologram is given. Additionally, it is shown why its implementation poses great challenges. A brief digression into its history is also made to show the relation between holograms and optical illusions in detail. Subsequently, optical illusions in general are presented. Their practical implementation over the years is discussed. The human perception of an optical illusion is what makes it an illusion in the

first place. A detailed description of this phenomenon is given in this section.
The pepper's ghost illusion plays a decisive key factor in the play SKYG33N and in this work. Therefore, it will be explained in detail, including its history and technical implementation.

2.1 True hologram

When it comes to floating images made of light and also when looking at the visual material from the SKYG33N theater piece discussed here, they look like holographic images. It quickly becomes apparent that the existence of a real hologram and its creation involve special challenges.

A hologram is a three-dimensional image that is generated by the interference of laser beams. A real hologram is created by incorporating image material into a so-called light modulator. The light modulator is then irradiated with the help of a laser and thus generates the same wavelengths of light as the original object would. These can then be recognized by the human eye as a 3D image (Habernig, 2022). The technology was developed by Dennis Gabor in 1940. He received a Nobel Prize for his work in 1971 (Odelberg, 4 C.E.).
The advantages of holography are, for example, the generation of 3D images or the possibility of reconstructing phases and amplitudes (Osten & J. De Groot, 2022).
A detailed explanation of the technology and functionality of real holography would go far beyond the scope of this work. The images shown in this work are not real holography but stereoscopic images that appear three-dimensional to the human eye (Habernig, 2022).

2.2 Optical illusions

As already described, the creation of a real hologram is technically very complex; therefore, stereoscopic illusions are used for the project. The same technology is applied for the holographic effect in this work.
To gain a better understanding of the different possibilities of optical illusions, these are examined in the following. As a background for understanding illusions, the six categories of Bach and Poloschek (2006) are used:

- Luminance and contrast
- Motion
- Geometric or angle illusions
- 3D interpretation: size constancy and impossible figures
- Cognitive/gestalt effects
- Color

Why optical illusions appear in all six areas has not yet been completely understood by researchers. However, it is known that illusions occur when one or more of the human sensors for perceiving the environment fail (Bach & Poloschek, 2006).

History

The experience of optical illusions and the interest in them are almost as old as human philosophy itself. Researchers agree that Aristotle already tried to explain optical illusions (Zaykova, 2023), (Bach & Poloschek, 2006). He described an illusion that is often referred to as the waterfall illusion in modern literature. If one looks at a waterfall for a while and then looks at the still surroundings, it appears as if the surroundings are falling upwards in the opposite direction to the water (Bach & Poloschek, 2006). This type of optical illusion is also referred to as a motion aftereffect (Wade & Ziefle, 2008).
Similar to the waterfall illusion, many more illusions were recognized and described as such. The development of modern technology had a great impact on this process (Bach & Poloschek, 2006). Technical implementability therefore plays an important part when investigating and creating illusions.

Human perception

One of the most important parts of an illusion is how people perceive it. Illusions are an example of the difference between reality and the perception of reality (Gregory, 1996).
What a person sees, i.e., how an object appears, is based on her perception and does not necessarily correspond to reality, for example, the objects' physical characteristics. It is particularly interesting, that research is not sure to what extent perception is linked to the cognition of an object (Pylyshyn, 1999). The special thing about illusions in this case is that they have the ability to show how perception works in certain cases (Bach & Poloschek, 2006).

As the waterfall illusion has already shown, there are physiological reasons for peoples' perception. In the illusion of aftereffect motion, the visual cortex adapts to the movement (Wade & Ziefle, 2008). Another physiological effect occurs by looking at a colored surface or pattern for a long time and then turning to a bright surface. In this case, the pattern still appears to be visible. The perception of color is also altered. The illusion is often referred to as a negative afterimage or afterimage (Berrebi, 2019). This change can be explained by the structure of the human eye. The retina contains rods and cones. The rods are responsible for the perception of illumance, and the cones are responsible for the perception of color. If we look at a certain color for a long time, the rods are overstimulated and their function decreases, resulting in the afterimages (Lamb, 2015).

In general, the rods that are responsible for color perception are not well adaptable compared to the cones. This also applies to changing light conditions. In situations with particularly low illumance, shapes can still be recognized relatively well due to the good adaptation of the cones, whereas there is low luminance for the rods to function (Lamb, 2015).
This brief excursion into the structure of the human eye is far from complete. However, a more detailed analysis would go beyond the scope of this work. In addition, the main interest here is to understand which components can be influenced by an illusion and their effects on a possible design solution.

Accordingly, it can be stated here for the experiments that different lighting conditions and color schemes can be used to make certain areas of the scene visible to the human eye or to hide them.

In addition to the physiological components, however, psychology also has a major influence on human perception. Seeing does not only consist of the physical sequences of events. Recognition is what makes the illusions work. This can be seen particularly well in the example of the hollow mask.

Figure 8: The hollow mask: Gregory, 1996

If one looks at the first picture of the mask (Figure 8), it looks like a normal face curved forward. However, if it is turned, it becomes clear that it is actually hollow on the inside. Nevertheless, the face is recognized in the same way as previous experiences have shown. A person's previous experiences have a great influence on what they see (Gregory, 1996).

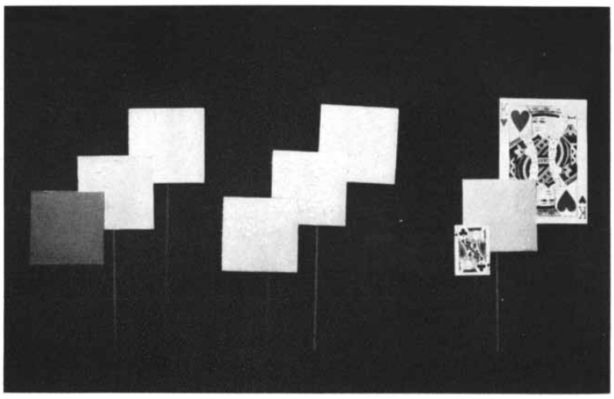


Figure 9: The card illusion: Ittelson & Kilpatrick, 1951

Another example of human experiences influencing humam perception is distances. In figure 9, the smaller card on the left appears closer, whereas in reality (Figure 10), the larger card on the right is closer (Ittelson & Kilpatrick, 1951).

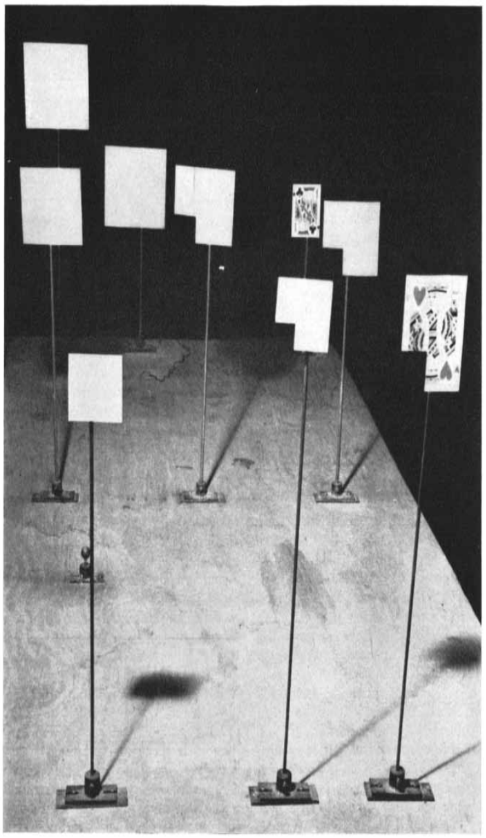


Figure 10: The card illusion: Ittelson & Kilpatrick, 1951

Humans see what they know, not necessarily what's physically in front of them. A theater stage can be an exception here. The boundary of what is perceived is, by a moderate amount, looser because the audience knows that they are watching a production. Nevertheless, perception passes through the filter of lifelong experience (Tregenza & Loe, 1998/2014).

Technical background

As the presentation of optical illusions shows, these phenomena are not created by a special technical realization but rather by human perception - or by its malfunction.
Of course, the creation of illusions has become much easier through the use of digital methods, but this is not necessarily required. Optical illusions are also created naturally.

2.3 The pepper's ghost illusion

The optical illusion created for the SKYG33N is the pepper's ghost illusion. It is also used for further investigation of the research question about the connection between the digital and physical world. A major advantage of this illusion is that it is relatively easy to implement in different sizes. This becomes clear when comparing it to other illusions that have a similar holographic effect, such as the 3D hologram-projector (Figure 11) and the reflection pyramid (Figure 12). The projector are fast-spinning, illuminated strings that make a picture visible. The reflection pyramid uses reflective material to reflect visuals from four different directions upward.

Figure 11: 3d hologram-projector: itatouch.com, n.d.

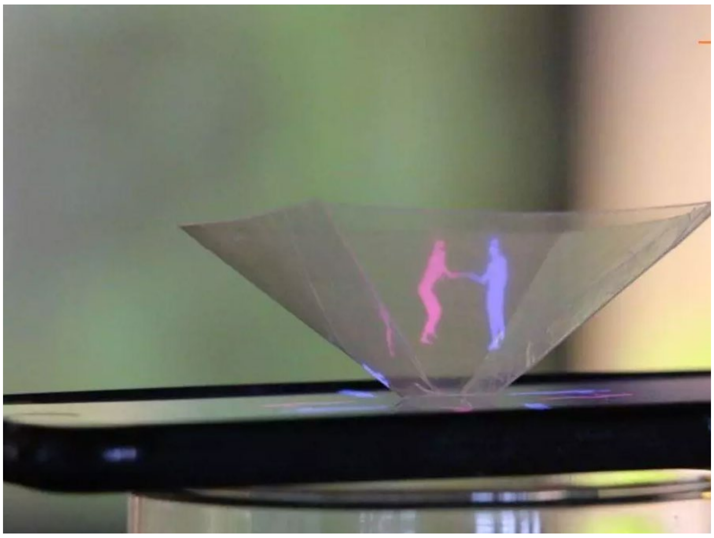


Figure 12: Refelction pyramid: science.lu, 2017

Interestingly, there is not much literature on this particular illusion and its implementation, which gives the impression that it is not widely used. On closer inspection, however, it is noticeable that the illusion or a version of it is regularly used both in a historical context and today (Burdekin, 2015).

History

Although the use of augmented reality may seem modern, the foundations for this particular case, such as pepper's ghost illusion, were laid much earlier. Descriptions of the phenomenon of reflective glass can be found in the collection "Magiae Naturalis" by Giambattista della Porta, which dates back to 1584. It describes a phenomenon that can be experienced regularly in everyday life. If one looks out of an illuminated room into the darkness, one can recognize not only the surroundings outside but also one's own reflection in the glass of the window. The first public presentation of the phenomenon in the form of an optical illusion did not take place until 1862.

The first successful presentation of the illusion was a polytechnic lecture at the Royal Polytechnic Institute on Regent Street in London. John Henry Pepper presented the story "The Haunted Man and the Ghost's Bargain" by Charles Dickens from 1848 with the use of the first known pepper's ghost illusion. The performance of the story made Pepper a celebrity in polytechnic circles and, among other things, ensured the financial security of the polytechnic institute through its great success.

Initially, the lecture was only shown on the Royal Polytechnic's so-called small stage, but subsequent performances of the play were quickly staged on the institute's larger stage. Even at this stage, the developers of the lecture, John Henry Pepper and Charles Dickens, agreed that the perception of such an illusion is closely linked to the experiences already made by the audience. And that these are always subjective and unpredictable for the creator of an illusion (Groth, 2007).

Technical background

For a better overall understanding of the technical implementation of the pepper's ghost Illusion, the original implementation from 1863 is described first. For this purpose, reference is made above all to the patent registered by Pepper. The technical implementation of the illusion today is thereafter described. This section mainly refers to the technical background for the realization of the play SKYG33N by the audiovisual artist collective, Vertigo.

A two-story construction is required to create the illusion on a large stage. The upper stage is at a normal height, while the lower stage below is not directly visible to the audience. The lower stage is strongly illuminated by an artificial light source and must be completely independent of the visible upper stage. Its lighting is provided by the normal stage lighting. A glass screen is placed in front of both stages. The pane in front of the normal stage is positioned in such a way that the audience does not notice it and can see the actors on stage as normal. The pane on the normal stage shows the reflection emulated upwards by the pane under the stage. This only happens when the lower stage is illuminated. If the lower stage remains dark, the screen on the stage also shows no reflection. The two glass panels are also mounted in a frame that allows them to be moved. This allows them to be aligned for optimum use.
As can be seen in the drawing (Figure 13, page 27), the use of only two panes of glass may not be enough to create the desired effect of the perfect illusion. Therefore, additional panes of glass may be required on the lower stage (Pepper, 1890).

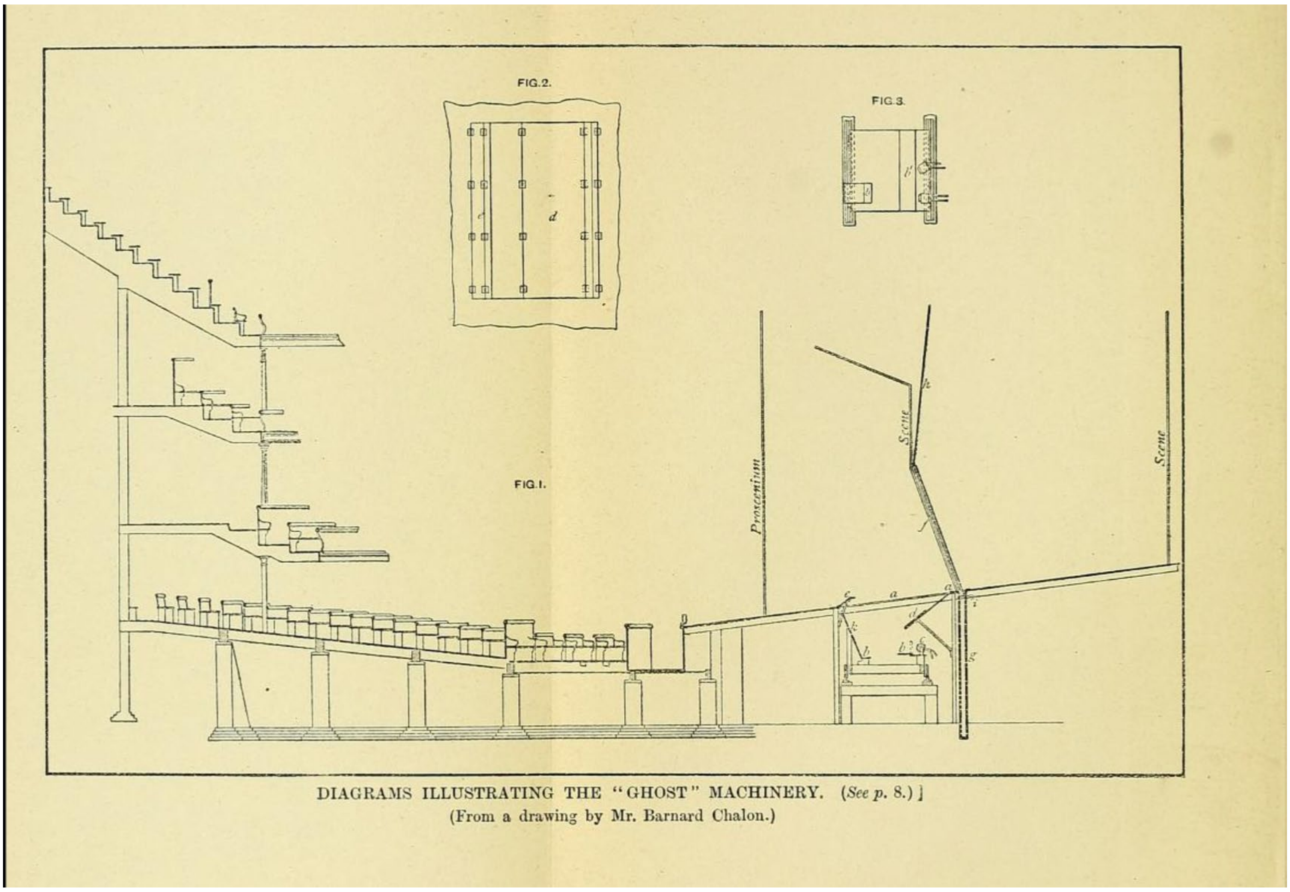


Figure 13: Drawing of the first pepper‘s ghost illusion: Pepper, 1890

Pepper does not describe exact angles for the individual panes in the patent text. He points out that a group of people is needed to set up the illusion who view the stage from different locations in the theater to determine the optimal angle of the glass panes to each other. He also describes that the actors on the lower stage have to be particularly brightly lit, as otherwise they are not visible through the reflection. Another difficulty is that the illusion does not work for the actors on the normal stage. This means that they cannot see the positions of the actors in the illusion, which is why Pepper recommends markings for the actors on the ordinary stage.

Despite these many considerations and precautions, it is assumed today that the illusion only really worked perfectly in a few places in the theater, most likely in the middle (Burdekin, 2015). However, at the time of the first performances, the press only had positive comments to make about the realization (Groth, 2007).

Comparing the implementation at that time (Figures 13 and 14) with today's technical possibilities, a major development has taken place.

The biggest development is in the materials used. Whereas the first implementations of the illusion probably used very heavy glass screens, these can now be replaced by a thin plastic film. This plastic film is stretched within a rectangle of truss with the help of stretchers and ratchet straps. This film is then mounted at a 45° angle in front of the stage. If the film is not illuminated, it is not visible to the audience. The use of these lighter materials makes it possible to transport and set up the entire set in just a few days.

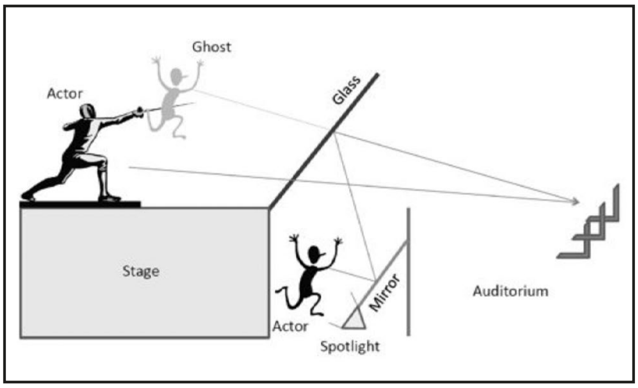


Figure 14: Schematic of the Installation: Burdekin, 2015

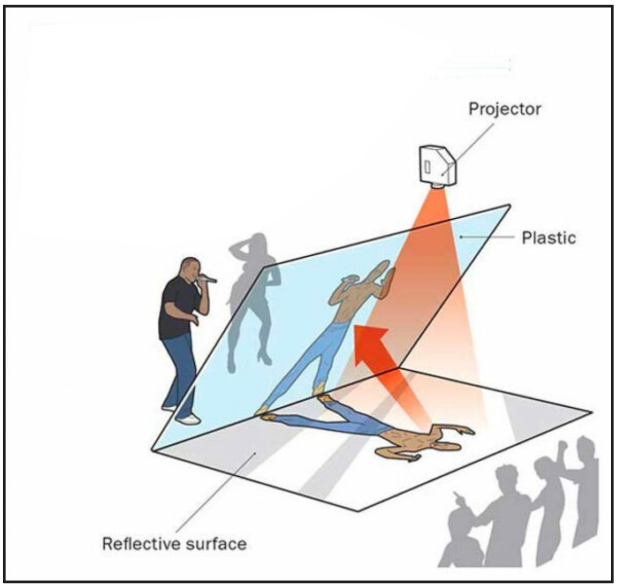


Figure 15: Schematic of the installation nowadays: Groove Jones, 2023

Another enormous development that makes the introduction of a "real" digital world possible is the use of projectors. Instead of two live actors and several panes of glass, today the "ghost" is replaced by a projector image (Figure 15). In the modern version, the second lower stage is located in front of the actual stage. A white, highly reflective material is laid out on the lower stage. Images are projected from above at a 45° angle on this reflection surface. The images then reflect onto the film above at a 45° angle. For the viewer, the image then appears as if it were on the actual stage at a 90° angle. The more modern implementation of the illusion offers greater artistic freedom. In addition, the reduced height of the lower stage saves a lot of space, which improves the overall appearance of the performance (Vertigo Aps & Hilmer Svanholm, 2022).

The exact structure of the set for the SKYG33N play, which is used to develop the first hypotheses for the research question, is explained in more detail on page 42. A further implementation of the illusion in model size is discussed on page 59. This model is used in the third round of the experiments – the model trials.

3. SPACE

The third part of the background relates to the room. This is interesting for this work, as the aim of the design is to connect two actually separate spaces or worlds - the physical and the digital world. First, the definitions of these two worlds are presented, which are the basis for this work. Then, once again, the human being is embedded within them.

One of the most important components of this work is augmented reality (AR), as the connection between the physical and digital world takes place exactly in this reality, and the design starts right there. In this section, augmented reality is defined, its history explored and its use explained. The chapter also takes a look at the opportunities and risks of AR. Once again, special attention is paid to the human perception of the technology. In addition, the ethical question of designing with AR is addressed. Design itself is never neutral, which is why ethics need to be looked at (Lindberg et al., 2024).

3.1 Physical space and digital space

Physical world:

The physical world refers to all components of the production that are physically present on stage and can be seen by the audience (Hösch, 2023).

Meaningfully, a large part of the technical components of the production are also physically located on the stage, but these should not be perceived by the viewer and are used to implement the design. Therefore, these technical components are not counted into the experienced physical world of the scene.

Digital world:

The term “digital world” in this work refers to the elements of the stage play that are not physically present but are created using a digital device (Hösch, 2023).

In SKYG33N and the experiments in this work, the digital world is implemented by the pepper’s ghost illusion.

3.2 Augmented reality

Definition

This work follows the definition of AR by Ronald T. Azuma from 1997, which is one of the most widely used definitions of AR.

AR is a reality that allows the viewer or user to experience the digital world while still being connected to the real environment.

The special feature of AR is that the digital world does not completely replace physical reality but rather extends it with an additional layer (Doerner et al., 2022).

History

To show why there is comparatively little literature in this area of lighting design, that deals with light in augmented reality environments, a digression into the history of augmented reality is conducted.

The concept of a digital world could only emerge with the corresponding technological development of computers. The first video games were launched on the market in the 1970s. Their development took place around 20 years earlier. The possibility of complete digital worlds is therefore only 50 to 70 years old (Bodmer, 2022).

The basis for AR as it is known today was laid by Ivan E. Sutherland. In his article “The Ultimate Display” (1965), he describes the idea of a kinetic dual potential display. The particular display should make it possible to live in reality, but to expand it with digital content that is aligned with reality. Another possibility that could arise from this ultimate display would be to create a kind of window that creates a reality in which the normal rules no longer exist.

Sutherland never used the term AR, but it is exactly what he described with his thought processes. Following this idea, various developers have designed the concept and technology of today’s AR over the years (Efrat, 2022).

Applied Cases

To outline the widespread use and variable possibilities of AR, the following section briefly presents two typical AR projects.

Figure 16: Hello, We’re from the Internet: DeGeurin, 2018

MoMAR: Hello, We’re from the Internet

The mobile application “MoMAR: Hello, We’re from the Internet” developed by Damjan Pita and David Lobser is an unauthorized exhibition concept and AR app. The app deals with the deconstruction of the authority of certain places. In this specific case, the Jackson Pollok Gallery at MoMA in New York in 2018.

When the artworks are viewed through the camera of a smartphone, they are supplemented by various components (Figure 16). The aim of the app is to highlight power structures and social hierarchies in specific locations (Fabric of Digital Life Archive: Moving Image: MoMAR: Hello, We’re From the Internet, 2020).

Jeff Koons' Snapchat Sculptures

Another app-based AR example is the collaboration between Jeff Koons and Snapchat. As part of the Snapchat project "Art all around you" in 2019, six of the artist's sculptures were digitized and geo-localized in popular locations. Using the app, these could then be found and viewed without the sculpture being present in real life. The result is an experience of the sculptures in a similar way to a material exhibition (Fabric of Digital Life Archive: Moving Image: Jeff Koons' Snapchat Sculptures, 2020).

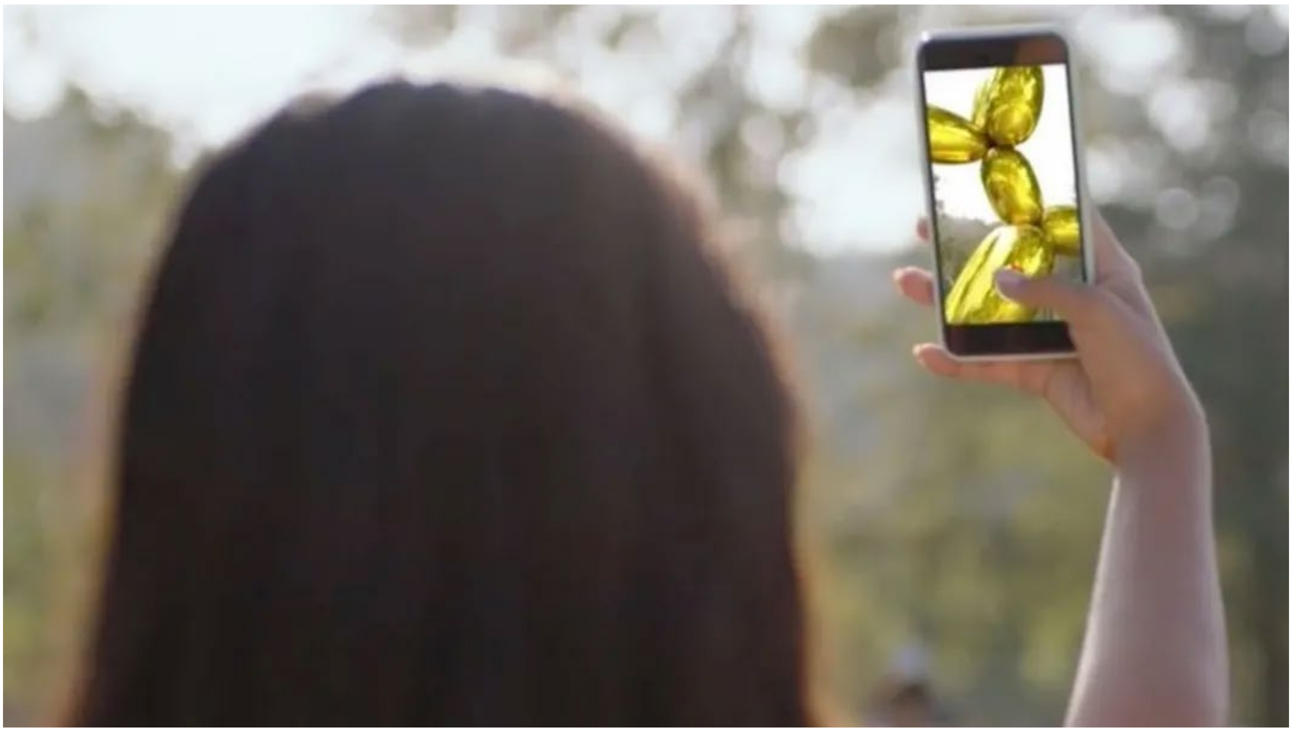


Figure 17: Jeff Koons' Snapchat Sculpture: Kelion, 2017

Chances and risks

As can be seen from Jeff Koons' collaboration with Snapchat, AR offers the opportunity to make art and culture easily accessible to a greater number of people. Instead of taking the considerable effort of transporting the sculptures, everyone can see them on their own smartphone. Similarly, productions such as the theater piece SKYG33N would not be possible without the technology. AR also offers the opportunity to make planning processes for architecture, technology, or other areas more realistically tangible and therefore easier to evaluate (Doerner et al., 2022).

How much AR applications bind people becomes clear when analyzing the AR example of Jeff Koons work. In a way, people are separated from each other again during the shared experience, and the physical world around them becomes secondary to the augmented reality that takes place on their smartphone. The possibilities of AR call the physical production of art objects into question. From economic and environmental point of view the added value of physical art production is rather limited and could be replaced by human-computer-interaction (HCI). Nevertheless, the cultural value and the spiritual elements of tangible art can not be replaced by HCI.

The extent to which the resulting phenomena can be assessed as positive or negative depends on the situation. It also remains the personal opinion of each designer and user of AR experiences.

Human perception

If the human perception of AR is considered, it is noticeable that it has certain similarities with that of optical illusions (see page 27). Even if the viewer consciously knows that it is an optical illusion, he cannot unsee it (Gregory, 1996). This phenomenon can also be observed in the perception of AR. A good example of this is the effect of light on people. For sensory stimulation, it does not matter whether it is a purely physical world or an AR; the effects on people are the same (Papadaki, 2015). The same applies to the atmospheric effect of light, where there is likewise no difference in the effect on people (Edensor, 2015).

The atmospheric effect can be seen even more clearly in virtual reality (VR). Here, viewers show exactly the same reactions to situations as they would if they were in physical reality (Sanchez-Vives & Slater, 2005). Of course, VR cannot be directly transferred to AR, but it shows how easy it is to influence human perception.

It is important to emphasize that the correct use of light and darkness in the creation of digital realities plays a decisive role in their credibility (Wang, 2022). The correct use of light and shadow in particular makes an artificial reality real for the viewer (Konttinen et al., 2007).

This leads to the conclusion that a key factor in the effective application of the augmented reality illusion is the appropriate use of light and shadow. It turns out that augmented reality can take advantage of light's previously established atmospheric strengths

Ethical challenges

As designers, in addition to developing the design, we always have a duty to question its impact and ethics. Every design decision that is made for published projects will have an influence on the people experiencing that design (Lindberg et al., 2024). The question is particularly important for this work because the viewer's perception is deliberately manipulated. AR that can be experienced via a mobile device is always recognizable as AR to a certain extent. It is easy for the viewer to take the device aside and experience the environment without the device. And even performances in a theater or similar situation are obviously perceived as an art form or entertainment. They can therefore not easily be confused with reality. The technology can also be used in a less obvious way or in a setting that is not evidently an art form, for example, in a political setting. In this case, such a strong manipulation of reality has a much stronger impact. The use of technologies of this kind is of importance nowadays. When developing and improving such technologies, their great opportunity to manipulate reality should always be kept in mind.

4. FINAL PROBLEM STATEMENT

With the evaluation of the literature review, a final problem statement can now be formulated. It's stated in the following:

How can conventional physical lighting design tools be utilized to develop a specialized tool case tailored for optimizing augmented reality applications?

This statement is used as a guideline for the creation of the final design product. The goal of this is to develop a set of design frameworks in order to simplify the design of further projects of this type.

PART 3: PRACTICAL AND EXPERIMENTAL APPROACH

1. STUDY CASES

1.1 State of the Art

The design research focuses on the AR installations, implemented with a pepper's ghost illusion. Therefore, two comparable projects are presented in the following:

Enchanted Tale of Beauty and the Beast – Disney Land Tokyo

A contemporary example of the pepper's ghost illusion is its use in theme parks. For example, the "Beauty and the Beast" attraction at Disneyland in Tokyo. In the attraction, spectators are transported through the building on fixed seats. By having the spectators seated on fixed seats, their viewing angle can be predefined. Since the pepper's ghost illusion works best at certain viewing angles, the predefined seating supports the overall experience.

In the attraction, the pepper's ghost illusion is utilized to show moving figures (Figure 18) in combination with video mapping technology (Clark, 2021).

Figure 18: Enchanted Tale of Beauty and the Beast - Disney Land Tokyo: Clark, 2021

Tupac hologram

Another example of the pepper's ghost illusion is the performance of the American rapper Tupac at the Coachella Valley Music and Arts Festival in 2012 (Dodson, 2017). The special aspect of this case is that Tupac died in 1996 (Universal Music Group Deutschland, n.d.). During Snopp Dogg's performance, the pepper's ghost illusion served to "bring him back to life" (Figure 19) for one final time. If one views the entirety of the stage during the performance, the slanted truss frame for the screen can be discerned. It is, of course, impossible for the illusion to look perfect in front of such a large audience. The size of the stage is too big to hide all the technical requirements for the illusion. The question of whether it is justifiable to resurrect artists who have already passed away in this manner is a pertinent one (Dodson, 2017).

Figure 19: Tupac Illusion at the Coachella Valley Music and Arts Festival in 2012: Lipshutz, 2013

1.2 SKYG33N

The series of experiments to develop new design solutions is fundamentally based on the theater play SKYG33N. The technical implementation of the play was designed and executed by the Vertigo collective in the performances discussed here. For this reason, the technical and artistic implementation will first be examined. The plans shown in this work are from previous productions, whereby the positions of the projectors and fixtures in the performances examined here also correspond to those on the plan. Only the exact implementation of the rigging varies between the different venues.

The aim of the lighting design was to illuminate the actress in a way that would make her visible to the audience. At the same time, she should not stand out too much from her surroundings to maintain a visual connection with the digital world surrounding her. The digital world in SKYG33N represents the antagonist for the actress. This antagonist is played by an AI and is visually present on stage in the form of a neural network or a particle cloud. (Hösch, 2023).

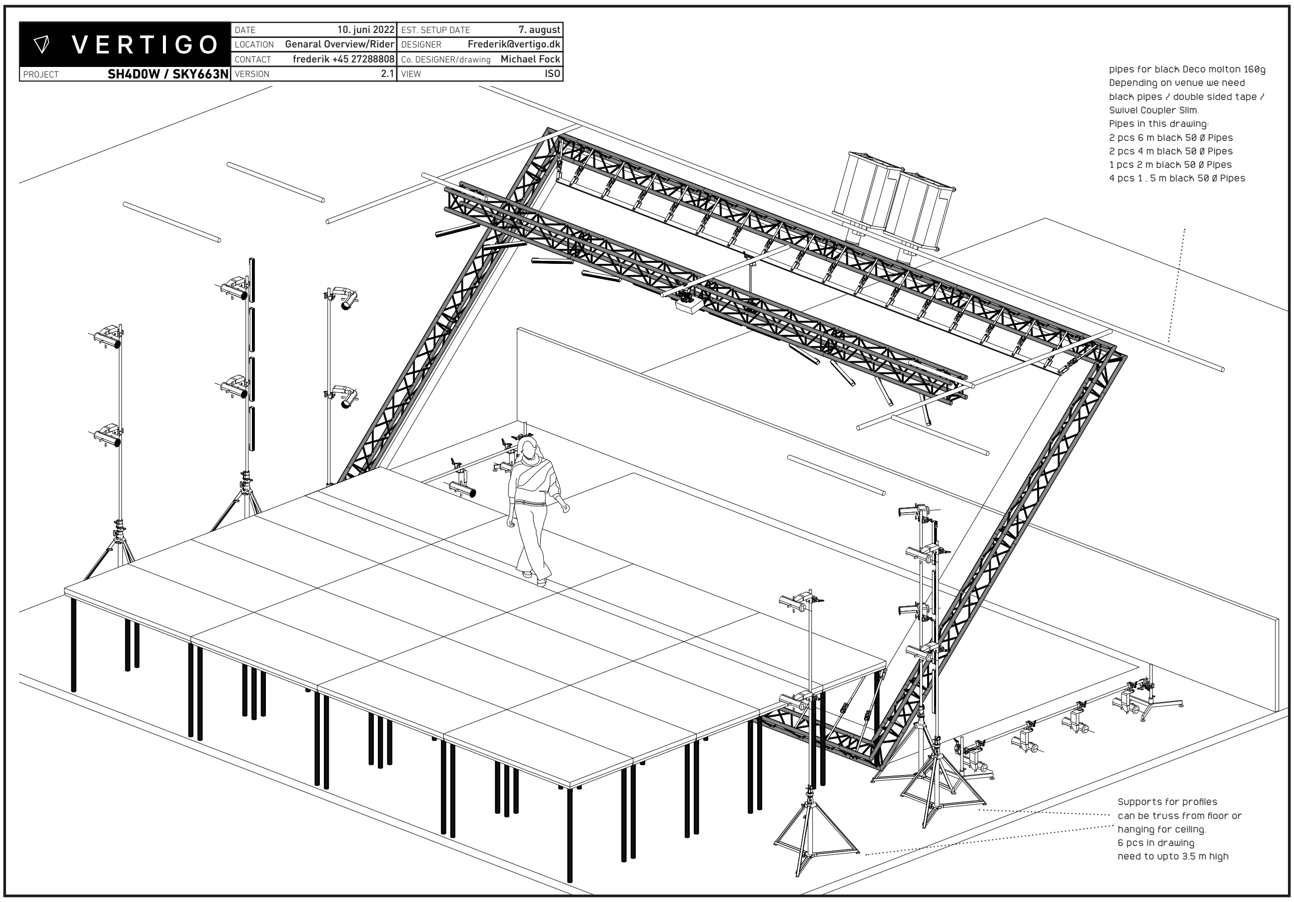
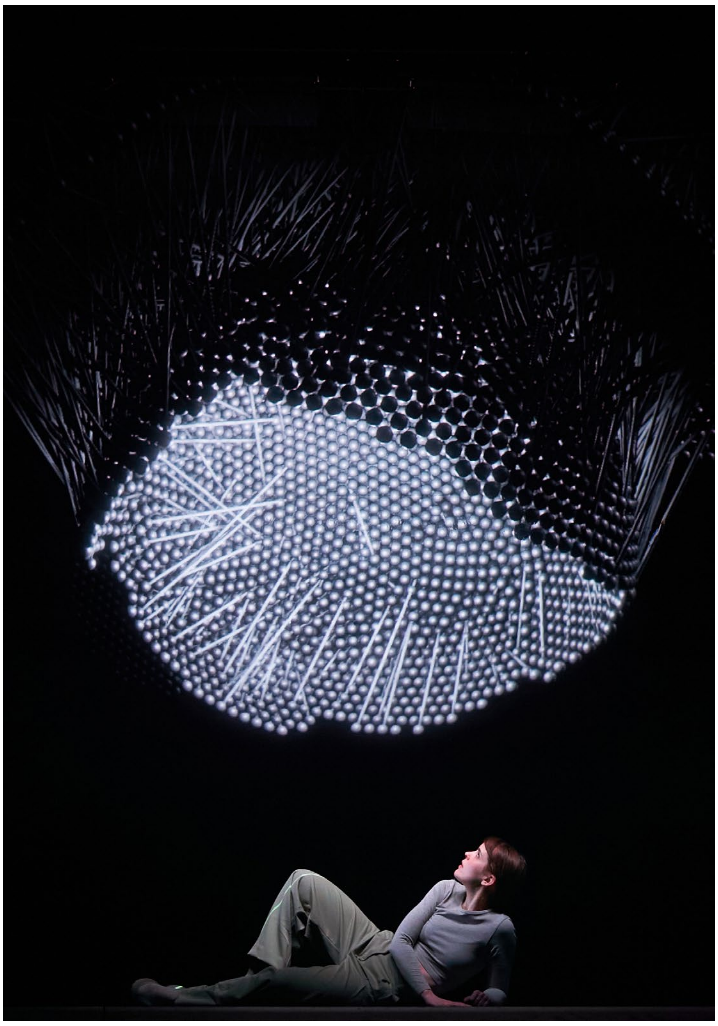


Figure 20: General overview / Rider SKG33N: Vertigo Aps & Hilmer Svanholm, 2022

Figure 20 is a plan drawing of the general overview of the setup.

The three projectors are used for developing the pepper's ghost illusion. The two bigger projectors generate the image, which is going to be visible to the audience as an illusion. This process is described in more detail on page 31. The third projector projects onto the stage. Where orientation marks are projected for the actress. The image of the third projector is also used to project onto the actress in some scenes.

The lighting arrangement consists of two areas: on stage and in front of the stage. The performance mostly takes place on stage, with the actress interacting directly with the AI.
A row of 12 LED spot bars is placed above the screen. Additionally, four gallery profilers are placed on either side of the stage. In theater, this position is called booms or ladders (Dunham, 2011/2016) (see figure 6, page 22). The LED spot bars and the booms are the fixtures that illuminate the actress on stage. Depending on the scene, the lighting setup is adjusted.



When the actress interacts with the AI visible through the illusion (Figure 21), the LED bars are mainly used. The idea is that the AI is perceived as a light source for the viewer (Hösch, 2023).

Figure 21: The AI-network as a light source – SKYG33N: Vertigo Aps, 2023

In other scenes, the actress has predefined positions. For those scenes, the galery profilers are used as the light source, as the LED bars would cast too diffuse light (Hösch, 2023).

Figure 22: The kitchen szene – SKYG33N: Vertigo Aps, 2022

Four gallery profilers are placed on the lower stage in front of the screen, next to the reflective surface, situated 40 cm above the floor. The light from these fixtures is not immediately visible to the audience. It is reflected through the pepper's ghost illusion and used for the final scene of the play (Hösch, 2023).
In that scene, the actress becomes a part of the pepper's ghost illusion. She is floating across a digitally created environment.
By using a rolling board, she is moving across the reflective surface on the lower stage while lying on her back. The gallery profilers on the sides are lighting her up. The profilers can be compared with the oxygen-hydrogen spotlight utilized at the first pepper's ghost illusion (Hösch, 2023).
When compared to a traditional theater setup, this layout is no longer practical. Any light on the screen would disrupt the pepper's ghost illusion. Therefore, a perfect black box on the stage is required (Vertigo Aps & Hilmer Svanholm, 2022).

2. EXPERIMENTS

To develop findings for the final design framework, a series of experiments are conducted. The experiments are divided into three rounds. The first round, the observation, focuses on collecting qualitative data by observing the dress rehearsals and performances of the play SKYG33N. The result will be used for the second round of experiments. In the second round, the on-site testing, a series of experiments will be carried out on the set of the play. The structure of the theater setup will not be changed. This provides the opportunity to work in a full-size model. Due to the time restrictions on the use of the full-size model, flexibility is limited. This limitation needs to be taken into account when evaluating the second phase of the experiments.

The third round of the experiments, the model trials, will be conducted in a 1:10 scale model. The results of the two first rounds will be further processed. The aim of the model trials is to support the hypotheses of the first two rounds with quantitative data, as well as to develop design findings, solutions and recommendations that were not possible in the first two phases.

2.1 First Round - Observations

The performances considered, for the observations, are the dress rehearsal and performances of the play from November 7 to 10, 2023 at Helsingborgs Stadsteater, Sweden and the dress rehearsals and performances from February 14 to 17, 2024 at Theater de Veste Delft, Netherlands. As these observations were carried out during ongoing theater operations, they focus on the collection of qualitative data.

The observations mainly test the two hypotheses related to humanities and social studies. The hypotheses related to natural science is still considered.

Humanities:
Different light scenarios can create an all-embracing experience for the user based on cultural backgrounds.

Social Science:
Different light scenarios can create certain atmospheres, which are important for the different situations or scenes based on biological backgrounds.

Natural Science:
Lighting in the holographic visuals and the physical world around them need to have a certain relation to one another to achieve the effect.

The observations are carried out under the following four questions:

Observation criteria:

- What works great as a scene and why?
- What does not work as good yet and why?
- What are the techniques that are used, and what do they do?
- What could be improved, parts that could be actively changed?

These four questions are also used in the follow-up experiments in order to establish comparability.

Scenes that work well:

In the following, two scenes from SKYG33N are presented. The two scenes are examples of lighting design that already connects the digital world and the physical world well.

The picture wall:

Figure 23: Picture wall – SKYG33N: Vertigo Aps, 2022

Description of the scene:	Subjective assessment
In this scene, the actress stands in front of a wall of flickering pictures that represent her photo album. The AI can be heard in the form of a voice and the wall moves to the rhythm of the AI's speech.	The overall picture on stage looks rounded. There is no question of whether and how the interplay between the physical world, the actress and the digital world of the screen can come together.

Humanities	Social Science	Natural Science
In this day and age, it is nothing unimaginable to stand in front of a screen several meters in size or an LED wall (Seitinger, 2010). This is something that viewers are probably very familiar with. The illusion works because what is seen is already known and, therefore, recognized (Gregory, 1996).	The direction from which the scene is illuminated is not necessarily recognizable to the viewer. This does not call the scene into question. On the one hand, there is a general illumination; on the other hand, the picture wall also appears to radiate light. Both a general illuminated room and a space illuminated by a display do not draw special attention. This insight into the direction of light can be used to explain both social science and natural science.	The light color (not measured in this case due to ongoing production) of the digital world and that of the light in the physical world are in a similar spectrum. This leads to a better visual connection between the two.

The bathroom scene:

Figure 24: Bathroom scene – SKYG33N: Vertigo Aps, 2022

Description of the scene:	Subjective assessment
In this scene, the protagonist is in a bathroom created in the digital world. This is obviously recognizable to the viewer due to the pixel-like structure. The AI is also represented by the movement of the bathroom walls.	The closed off room, which is created in the digital world, creates a good visual connection between the digital and the physical world.
In the same scene, the protagonist is also sitting in a bathtub. That bathtub is also created in the digital world.	While the protagonist sits in the bathtub, only the part of her body that looks out of the top of the tub is illuminated from the side. As a result, the part that is in the bathtub disappears into the dark and thus visually disappears into the bathtub.

Humanities	Social Science	Natural Science
A bathroom is something familiar to the audience. Its authenticity is not questioned, especially on a stage. The same situation of viewers seeing familiar things is also evident when the protagonist sits in the bathtub. This is something quite natural for the viewer and is therefore less questioned (Gregory, 1996).	The indirect, soft light of the scene is often found in domestic bathrooms. Again, the direction of the light plays a decisive role in the success of the illusion. Similarly, in a large part of the scene, the actress is situated between two walls created by the illusion. In this area, she stands out against the darkness. The same applies to the illusion on either side of her. The viewer's eye adjusts to the luminance of the illusion and the actress. Therefore, the viewer focuses on these two areas. (Tregenza & Loe, 1998/2014).	To the human eye, the two colors look very similar, which creates a good visual connection between the digital and the physical world. The extent to which the environment within the illusion is illuminated has an extremely strong influence on how much the two worlds merge. If the physical world within the illusion is too bright, it is no longer visible. If it is not illuminated, the physical world is invisible. A great example is the selective illumination of the upper part of the actress.

Observation results:

It can be concluded that when the colors of the physical and digital worlds are visually aligned, the two worlds merge better. In addition, the use of indirect light supports the connection between the digital world and the physical world. The same applies if the illuminance of the two worlds appears similar. If the direction of the light in the digital and the physical world appear to be the same, the two worlds are visually better connected.

A particularly good connection between the digital world and the physical world is created when the components of the two worlds contrast strongly from the dark background of the stage in the same way, thereby attracting the attention of the audience.

Scenes that do not work yet:

In the scenes in which the actress interacts with the neural network, the neuronal network is supposed to represent the light source in the situation. In these scenes, the AI, in the form of the neuronal network, and the actress should stand out from the dark background. However, it is not always entirely clear that the network is supposed to represent the light source. This could be due to a number of factors.

Firstly, the situation is unfamiliar to the viewer. Therefore, the viewer cannot recall previous experiences to perceive the situation.

Secondly, the light in these scenes is not as direct as would be expected from such a large light source. As a result, it is not clear that the network is representing the light source. That's why the two worlds appear as if they exist side by side. Additionally, shadows seem to be missing in some of these scenes.

Figure 25: Neuronal network as a light source – SKYG33N: Vertigo Aps, 2022

2.2 Second Round - On-site testing

The findings from the first observations were used to develop the following round of experiments. The experiments were carried out in the stage setup of the play. It was therefore not possible to change the positioning of the spotlights or projectors.

The following goals for the experiments were developed from the observations:

- Creating targeted shadows
- Incorporating different colors to understand their exact function in connecting worlds and creating atmosphere
- Get a better understanding of why indirect light seems to work better for connection
- Get a better understanding of other factors influencing the success
- Understand why some visuals work better in the illusion than others

Since the different goals do not necessarily refer to all three areas of humanities, social science and natural science, only the relevant hypotheses are considered.

Creating targeted shadows:

One idea was to create physical shadows by placing physical objects on the stage (Figures 26 and 27). The objects were then illuminated to create shadows and transformed into a desired object by the pepper's ghost illusion.

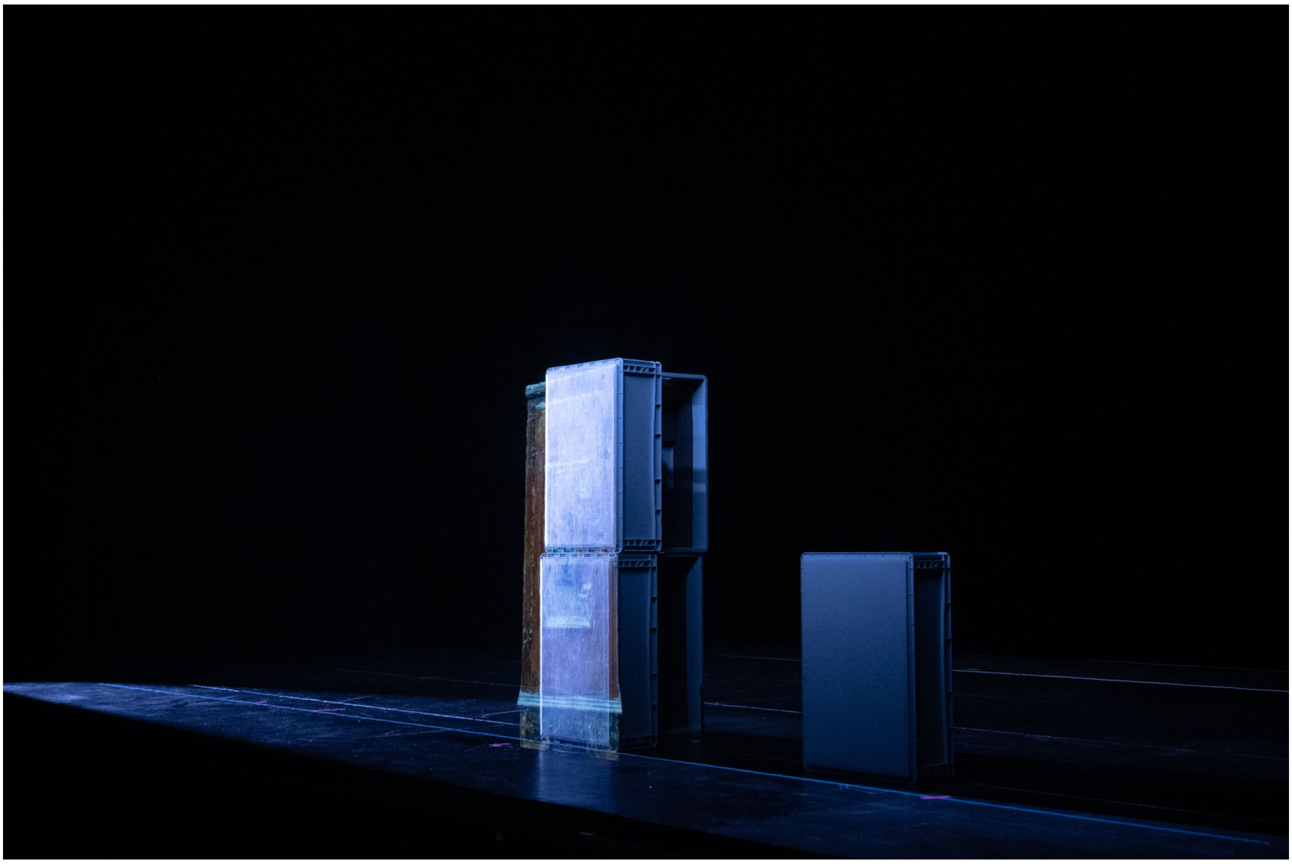


Figure 26: First test to create shadows with physical objects on stage: Hösch, 2024

This test brought up several different results:
Firstly, the shadows created by the spotlights were present on the stage but not visible to the audience. The attempt to cast the shadow directly on a person did not lead to a successful result either.

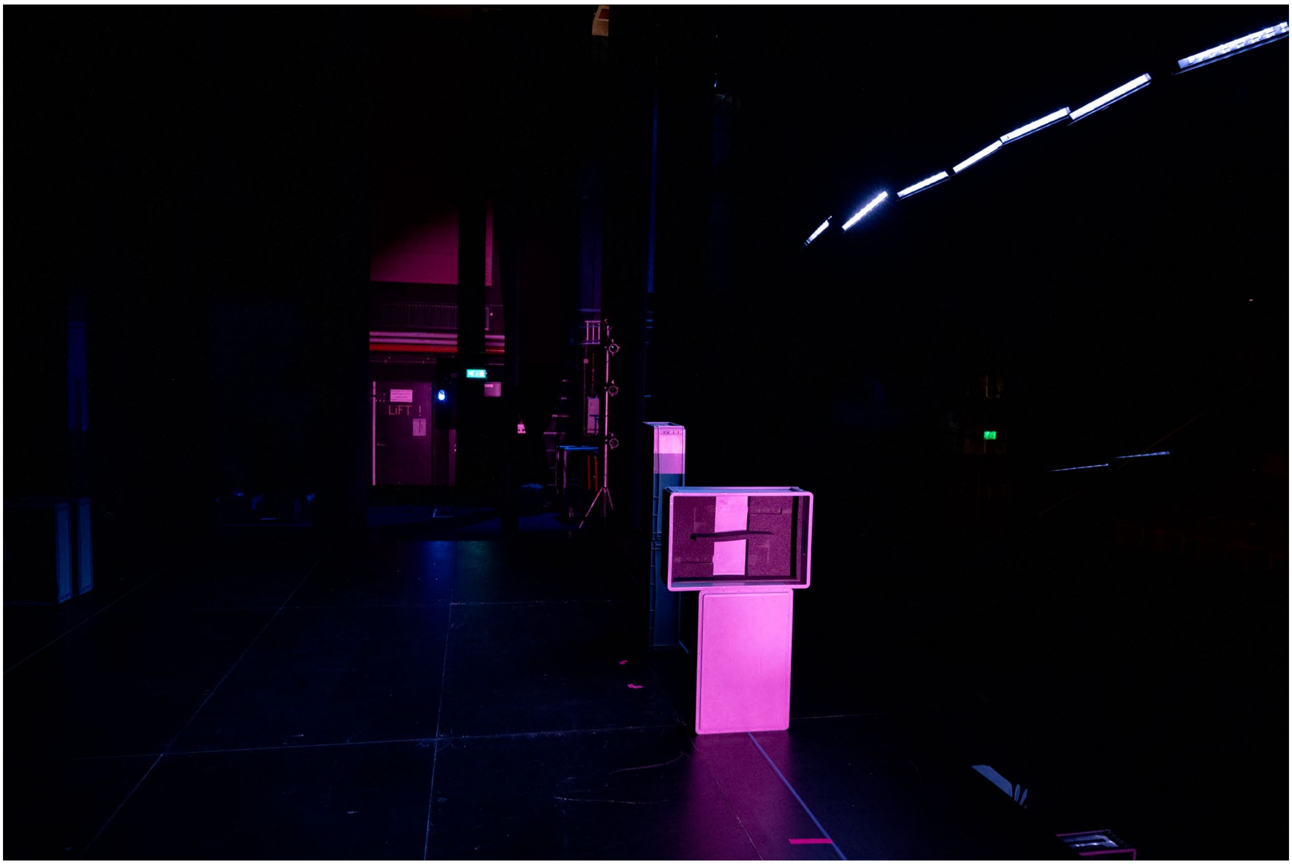


Figure 27: Test to cast shadows onto an object on stage; view from the stage: Hösch, 2024

With that current setup, the shadows were not clearly visible from the auditorium here either. Every object on the stage must have a certain basic brightness in order to be visible. The shadows on these brightly illuminated objects were not recognizable.

Another insight gained from this test setup was that the pepper's ghost illusion can only develop its full effect when the stage is completely dark in the area of the visuals. Otherwise, the physical objects on stage shine through the illusion (Figure 28).

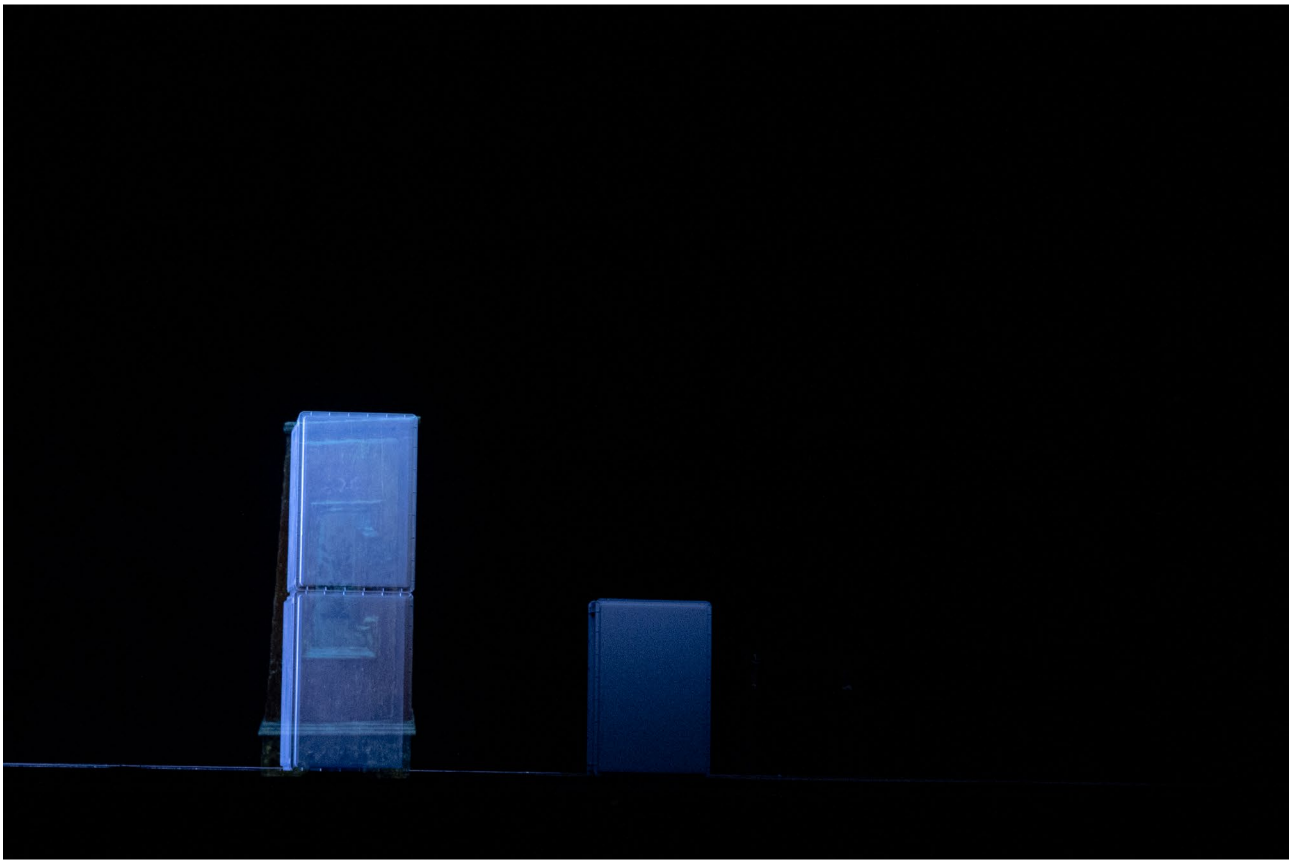


Figure 28: The projection of the illusion is invisible due to high illuminance: Hösch, 2024

That possibility to blend over the illusion can be kept in mind and possibly used for other purposes.

The experiment shows that it is very difficult to create shadows for this lighting situation since they need to be visually meaningful.
A practical implementation could involve the use of a different lighting setup with stronger spotlights, as well as the use of a projector as a light source.
Another possibility to create shadows would be the use of the digital world through the pepper's ghost illusion. These potential design solutions will be further investigated in the model trials.

Indirect light:

The attempts to create targeted shadows showed why indirect light seems to create a better connection between the physical world and the digital world.

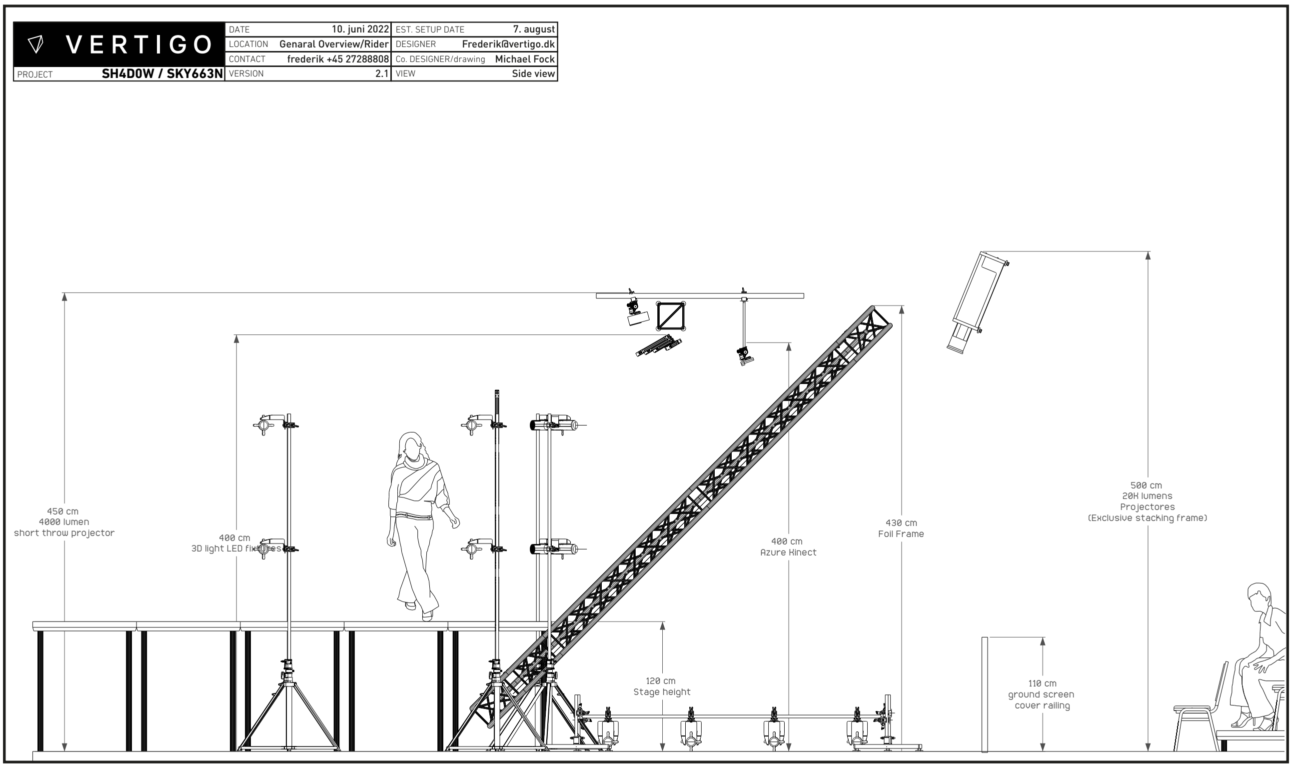


Figure 29: General overview / Rider SKYG33N: Vertigo Aps & Hilmer Svanholm, 2022

As shown in figure 29, the lamps arranged in a semi-circle above the stage seem to be indirect for the audience since they cast a soft light. This soft light makes the actress recognizable on stage, but it does not create sharp edges of light. Due to the way the pepper's ghost illusion works (see page 31), the edges also appear somewhat softer here. The similar looking soft edges make the digital world and the physical world connect well (Figure 30).

Figure 30: Soft edges make the two worlds work better together: Vertigo Aps, 2022

The scene in figure 30, is a great example why the stage has to be a perfect blackbox in order to create the pepper's ghost illusion. A perfect blackbox in this context means that no light from the surrounding fixtures should fall on the screen. If light, other than the images of the digital world, hits the screen, the plastic material of the screen becomes visible to the audience. This would destroy the perception of the pepper's ghost illusion. Similarly, the entire rigging of the build must be disguised in order not to reveal the large structure. These requirements create limited positions and angles in which the lighting fixtures can be mounted. During the on-site testings, the positions of the lighting fixtures where fixed to the lighting setup used by for SKYG33N. To find new design solutions it would be interesting to see other mounting positions for the light fixtures is shown in figure 31 and 32.

Figure 31: Testing: Fire from the bottom, light from the top: Hösch, 2024

Figure 32: Testing: Fire from the top, light from the top: Hösch, 2024

The visual of the fire going upwards is already visually connecting the digital world and the physical world (Figure 31). By turning the fire around, the connection between the physical and the digital world seems to work better (Figure 32). The better connection can be explained by the same direction of light in both worlds.

A more flexible setup of the light direction is tested in the model trial.
In the next step, different colors are incorporated into the scenes to gain a better understanding of how colors function to connect the digital and physical world. It also takes a look into the role of color in creating atmosphere.

For these tests, different visuals in different light colors were used.
The stage was divided using two different colors, as it can be seen in figure 33. The colors were adapted to the visuals shown by the illusion. As can be clearly seen in the images, the physical boxes on stage appear much more closely connected to the digital world when the colors match.

Figure 33: Testing: Dividing the stage with colors: Hösch, 2024

If they are not illuminated in the corresponding color, there is virtually no connection between the two worlds.

It can be concluded that it is important to create the right atmosphere in the physical world through color in order to connect it to the digital world. Within the theater play SKYG33N this situation is also visible (Figure 34). The actress seems to be in a digitally created forest, but due to the color differences between the two worlds, the physical and the digital parts of the scene are easily distinguishable.

Figure 34: Testing: Unmatched colors in the play; Example from theater play SKYG33N: Vertigo, 2023

Other factors:

During the on-site testing, other factors, which influence the visual connection of the digital world and the physical world where found. These influences where not foreseen in the planning phase of the on-site testing.

By creating different scenes, it has been shown that the luminance of the physical world and the illusion must appear similar to the human eye in order to create a good connection between the two worlds. This hypothesis will be tested in the model trials. Whether the luminance of the two worlds only has to look similar or whether their value has to be close to each other will be measured in model trials. Closely related to the luminance is also the factor of reflection. The reflection factor of the materials in the physical world influences the success of the connection between the two worlds. If the reflection factor is too high, the physical materials radiate too strong through the illusion. This greatly hinders the pepper's ghost illusions' effect.

Visuals:

New findings also emerged in the area of visuals. Moving images have a more interesting effect. This results in a better visual connection between the digital world and the physical world. Visuals, which create enclosed spaces on stage, have a convincing effect. The concept of an enclosed room to create a scene on stage can be easily understood by the audience. Whereas visuals of objects seem to float on the stage, seem harder to use.

This finding raises the question of whether it is possible to create a functioning connection between the two worlds in the form of objects in the digital world or whether the successful connection of the two worlds is only possible through the creation of spaces. Criteria for visuals can be explored further in the model trials.

2.3 Third Round - Model trials

Preparation:

The implementation of the third round of the experiment series is a model trial. The advantage here is that the smaller size of the setup means that less material is required. This reduces the costs and time required. There is also greater flexibility in the positioning of the different components of the setup. The challenge of rigging in a full-size production is not faced here. The focus of model trials is on the effect and implementation of the light. It is not the goal to find a new design solution for the rigging. In addition, every theater stage offers a different setup. The exact rigging must be planned individually for each of these theater stages.

Experiment setup:

The model in this setup is built on a scale of 1 to 10. The frame is made of wood slats instead of metal trusses. The drawings in figures 35 and 36 show the construction of the model, while figure 37 is a picture of the final product in the setup.

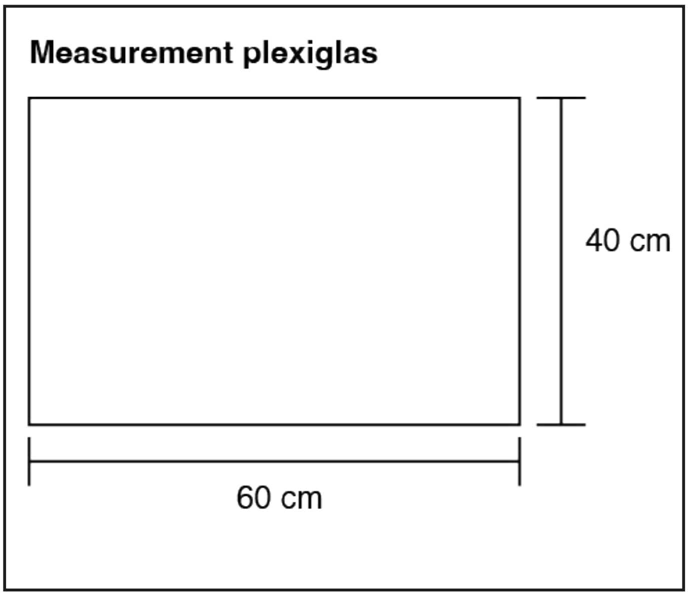


Figure 35: Drawing of model: Measurement plexiglas: Hösch,2024

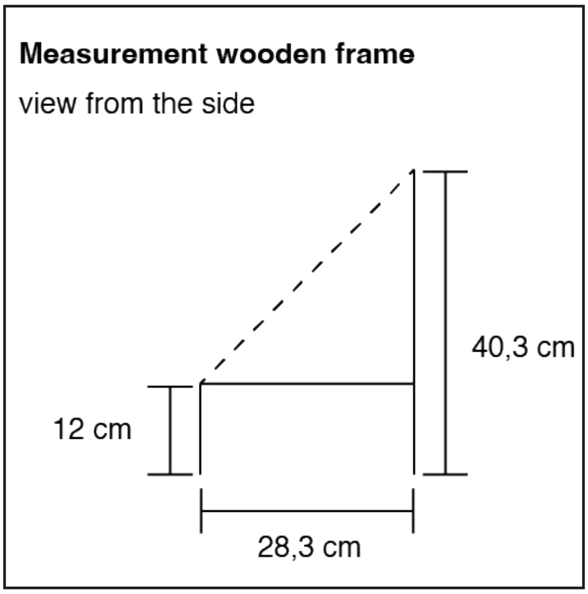


Figure 36: Drawing of model: Measurement wooden frame: Hösch, 2024

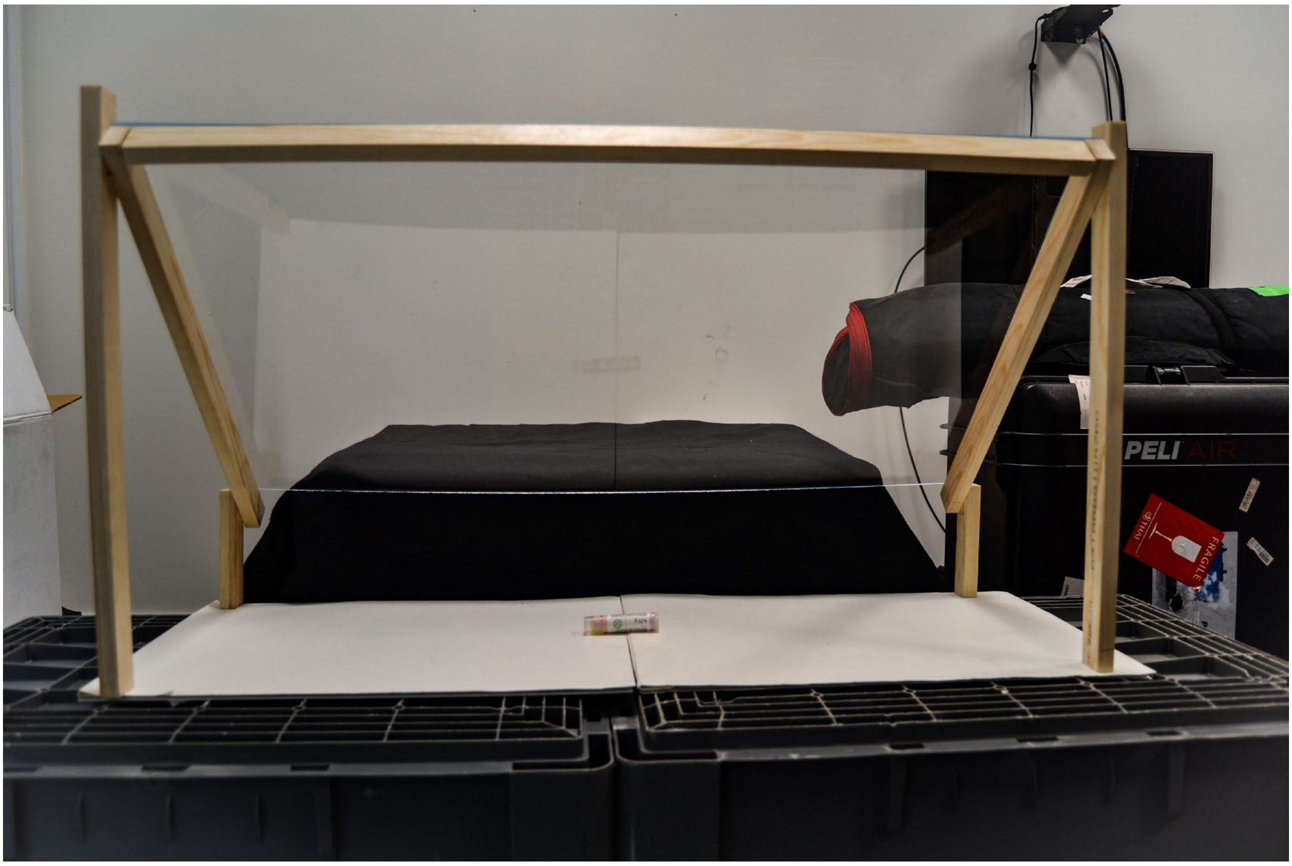


Figure 37: Picture of final model: Hösch, 2024

The screen itself is made of a 3 mm plexiglas pane instead of transparent foil. These changes in material do not affect the pepper’s ghost illusion. The placement of the projector in the model is slightly different from the full-size setup. In the original, the projector is positioned directly above the truss frame, but in the model, it is moved further back. This adjustment allows for easier implementation, as the projector can be individually mounted and positioned on a tripod. It is also based on the throw angle of the projector, which needs to be a certain distance away from the reflection surface in order to fully cover it. In figure 38, the final position of the projector can be seen.

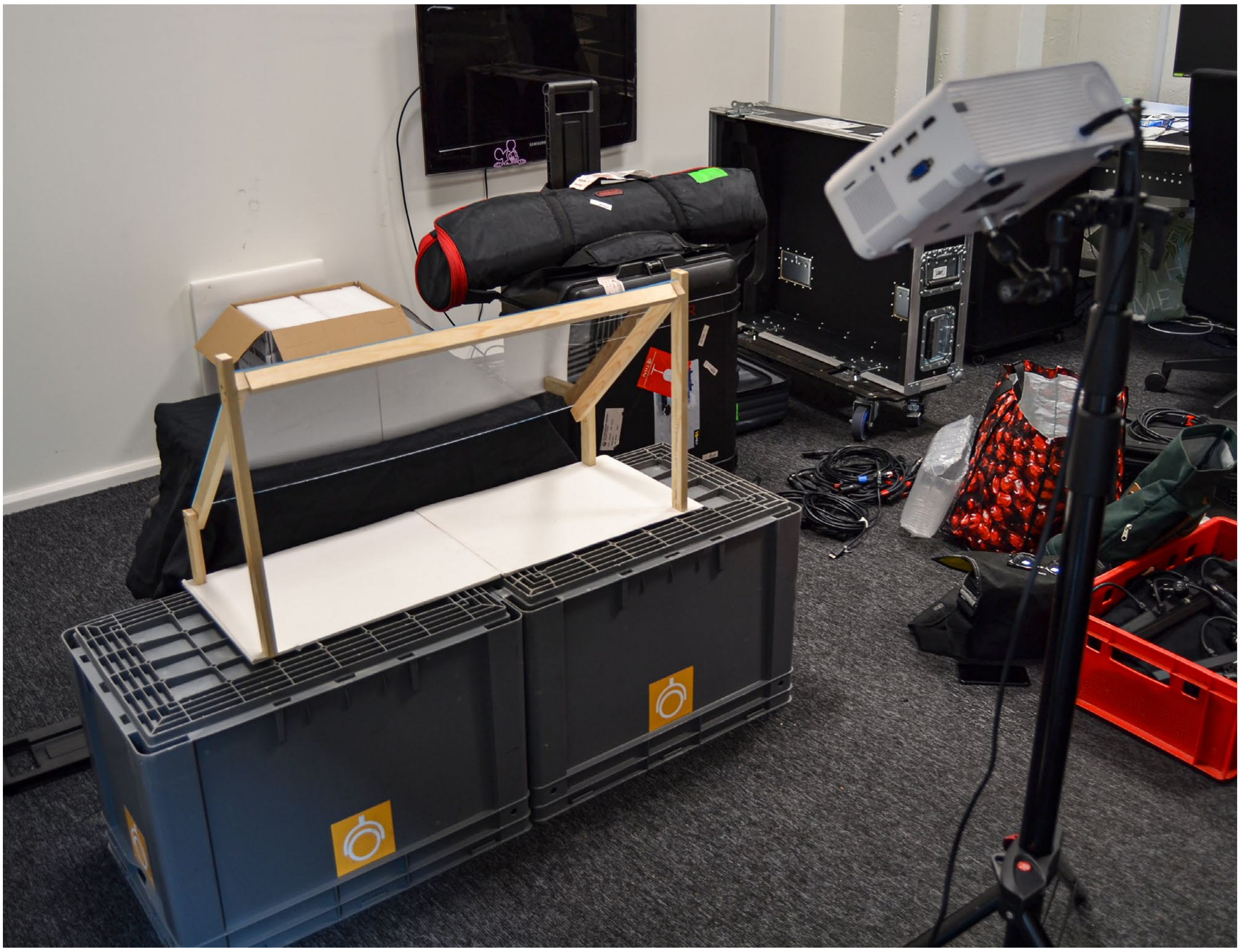


Figure 38: Setup with model and projector: Hösch, 2024

The 45-degree angle of the projector is maintained in this model.
As in the original setup, the stage is raised in relation to the reflective surface on the floor. Due to this elevation, the illusion does not start directly at the front of the stage edge but is shifted backwards by the distance of the elevation. This allows actors to move around the stage comfortably without getting too close to the screen. It is also possible to illuminate the actor without hitting the screen with the light.

Two fixtures and a projector are used for the physical light in this experiment. The fixtures are LED bars designed and built by Vertigo Aps. Both consist of one row LED strips. The difference between the two LED bars lies in the lens or diffuser. One is characterized by a gray diffuser, which slightly dims and softly diffuses the light. The other LED bar is equipped with a 20-degree lens, which emits a harder, more directional light. These two fixtures offer enough flexibility to test the different hypotheses. All light sources and projectors are controlled via Madmapper. The program offers the advantage of controlling the entire setup on one computer. Because of this setup, the same material can be played across all light sources if necessary.
The model person used in the experiment does not correspond to the scale. The effect of the light and the illusion can still be tested without any alternation in the results.

Like the observations and the on-site testing, the model trials are evaluated by the author and not by a test group. The focus of the series of experiments is on further development between the three rounds. It is therefore important that these be evaluated by one person. Of course, this means that there is a bias, which is why a particularly critical evaluation is important. The advantage of this type of evaluation is that it can focus on the important parts. This means that the perfect coverage of the construction does not play a role in the model trial. This makes the building process of the model easier. The knowledge of an illusion also means that it tends to be evaluated more harshly (Gregory, 1996).

The sequence of the model trails follows that of the first two rounds of the experiment. The different hypotheses are specifically tested. For better comparability, the same visuals as in the on-site testing are used in some scenes. The different steps of the model trail are:

Shadows:

- New idea to create shadows:
    - Use inverted picture with a second projector from the side to create a shadow
    - Create shadows through the digital world

Directions:

- Try new positions of light without hitting the screen:
    - In front, underneath the stage
    - More sideways
    - Create a full round light circle around the screen

Color:

- Use different colors to play with them
    - Try to match them perfectly
    - Try to not match them at all: Could that be used creatively?

Illuminace:

- Measure the different parts to see if there is a pattern in the ratio

Luminance:

- Measure the different parts to see if there is a pattern

Reflectance:

- Collect new findings

Results of model trials:

Shadows:

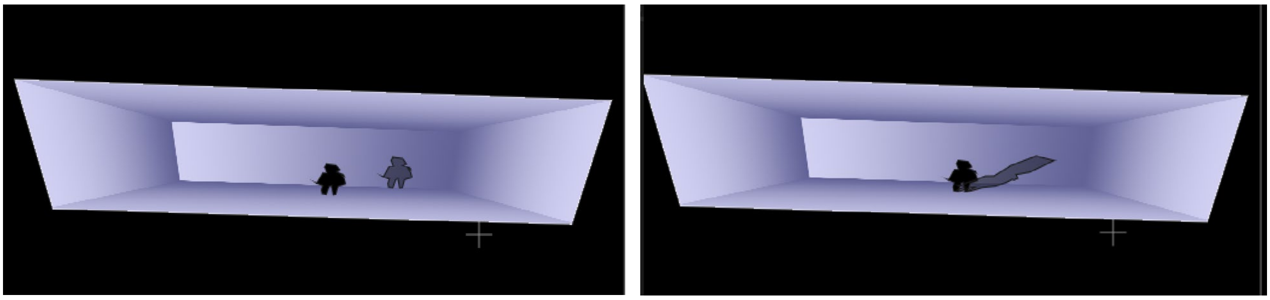
Creating shadows by using an inverted picture projected by a projector from the side:

When using the projector from the side, it becomes apparent that the projection surface appears to be too small for a clear image of the person. This means that no clear image can be created and the desired effect cannot be achieved. One explanation for this result could be the small size of the model. When taking the viewing ankle and the projection angle into account, it can be assumed that the desired effect cannot be achieved in a full-size implementation either. It is possible to precisely influence the direction of light using the projector.

Based on the results, a different idea for the realization of shadows was developed. The shadows were projected onto the stage using the illusion. By adapting the direction and intensity of the shadows to the scene, realistic-looking shadows were created in the digital world.
In various steps, the shadow in the digital world was adapted to the situation in AR.

Figure 39 shows how the shadows are built digitally in the madmapper file:

Process of creating shadows; screenshot from madmapper file



Final used digital shadow; screenshot from madmapper file

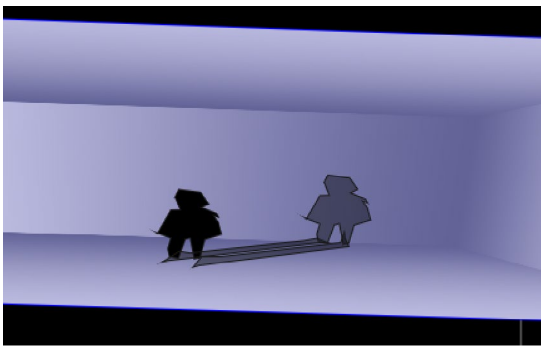


Figure 39: Creating shadows digitally: Hösch, 2024

In order to achieve the desired connection between the digital and physical world, particular attention must be paid to the direction and intensity of the light and the corresponding shadow. Like in figure 40.

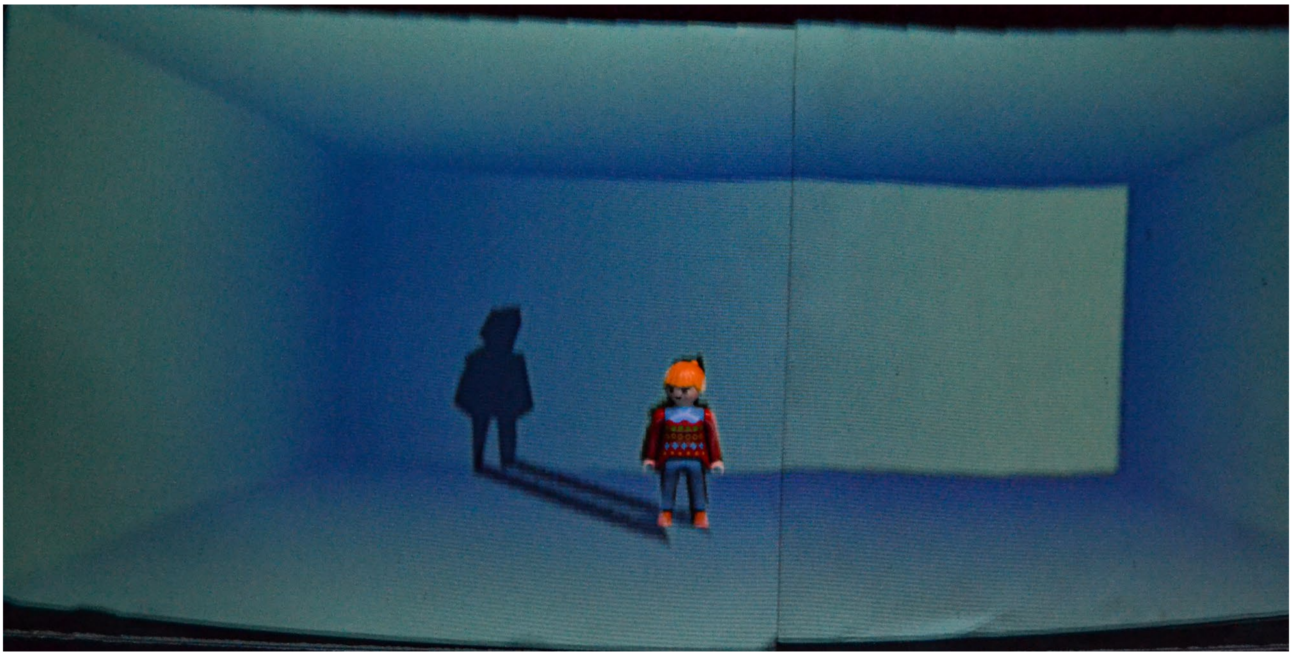


Figure 40: Digital shadow used in a scene: Hösch, 2024

If the light source is supposed to be made visible by the digital world, the setup is slightly different. In the example in Figure 41, the fish is the apparent light source of the scene. As there is no end to the room in the scene, no visible shadows are required in this case.

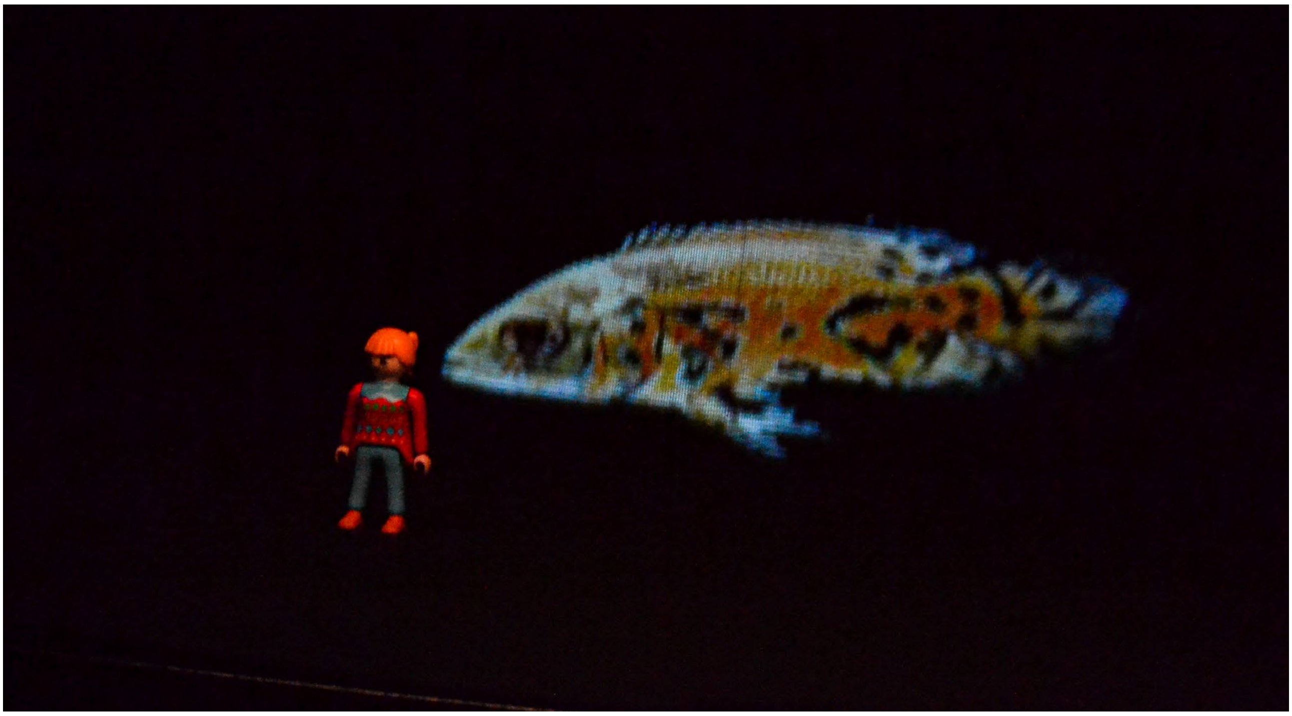


Figure 41: Scene without the need for a shadow: Hösch, 2024

The direction of the light used is also important here. More on this in the next section on page 56.

Direction:

During the on-site tests, it was already established that the alignment of the light direction of the digital and physical worlds is of enormous importance for the successful interaction of the two. Therefore, different positions were tested in the model test with the aim of being able to illuminate the stage from all four sides. Figure 42 shows a picture of fixtures positioned above and at the side of the screen.

Figure 42: Positioning of light fixtures above and on the side of the screen: Hösch, 2024

As can be seen in image 43, the lighting from below has the desired effect.

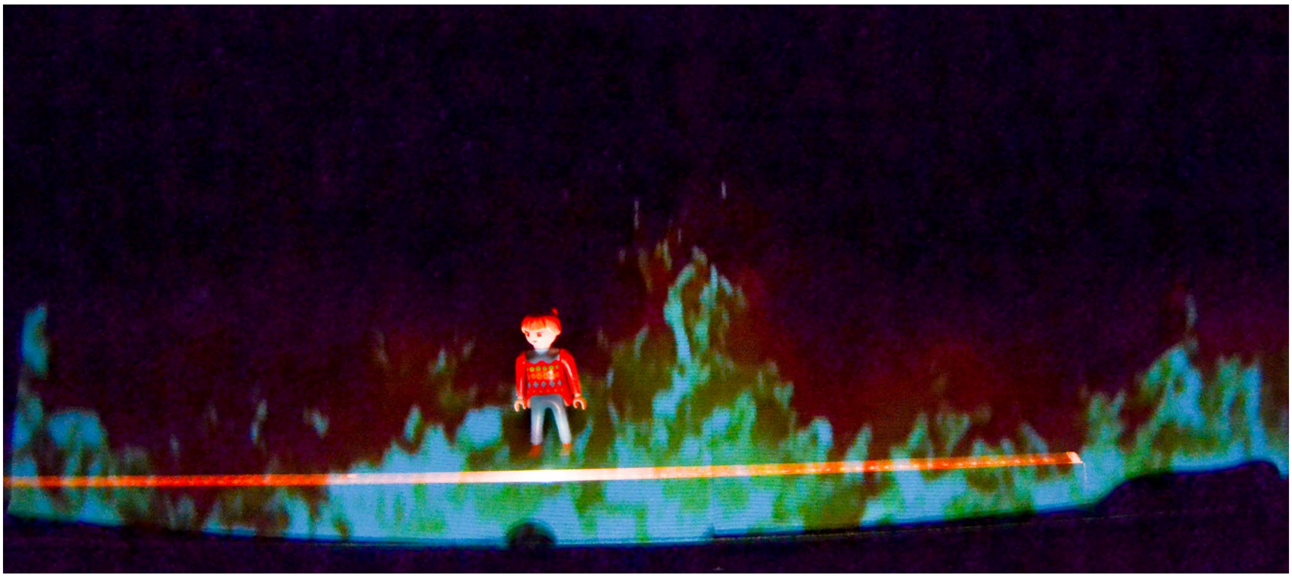


Figure 43: Scene with lighting from below: Hösch, 2024

The physical and digital worlds are visually well connected. The fact that the same visuals are played out by the pepper's ghost illusion and the LED bar has an influence on this. As a result, the light in the physical world and the visual in the digital world.
Logically, light from below does not create the most beautiful "beauty" atmosphere since it is casting hard shadows onto the persons' face on stage. The interplay between the digital and physical world is the main focus here.
The best effect on the scene was achieved by using the LED bar with the lens. The lens creates a similar look and feel of light as it occurs in the visuals.
A practical implementation of this setup is possible if, particularly, flat fixtures are used. These fixtures are not conspicuous due to their proximity to the floor. As the upper stage is raised, the visuals of the illusion start further back on the stage. This results in an unused area at the front end of the stage. In this space, flat lighting fixtures could be installed. In addition, the fixtures would have to be equipped with barndoors and have a suitable beam angle to illuminate the actors on stage without hitting the screen.

As the attempt to create shadows by using a projector has shown, projectors have the great advantage that the emitted light can be directed very precisely. This prevents the screen from being illuminated and unintentionally made visible.
Furthermore, smaller visuals can also be projected onto the actors if this is appropriate for the scene. An example from the theater play SKYG33N is in Figure 44.

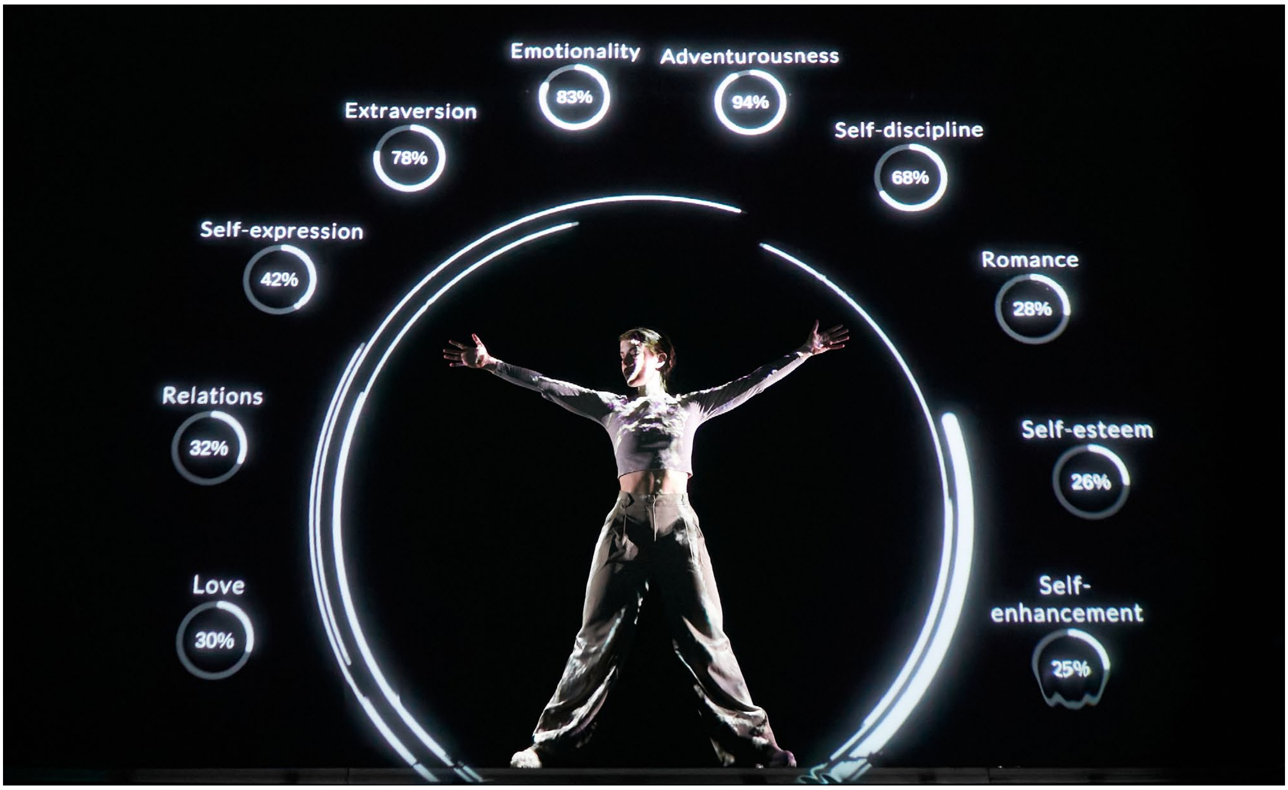


Figure 44: Projection on the actress during the play SKYG33N: Vertigo Aps, 2023

In addition, the influence of the character of the light became clear during the investigations about direction. For example, the direction of the light is more clearly visible when using the 20-degree lens than when using the gray diffuser.

Color:

To understand the exact effect of color, two scenes are illuminated with different colors. The first visual is a purple three-dimensional room (Figure 45):

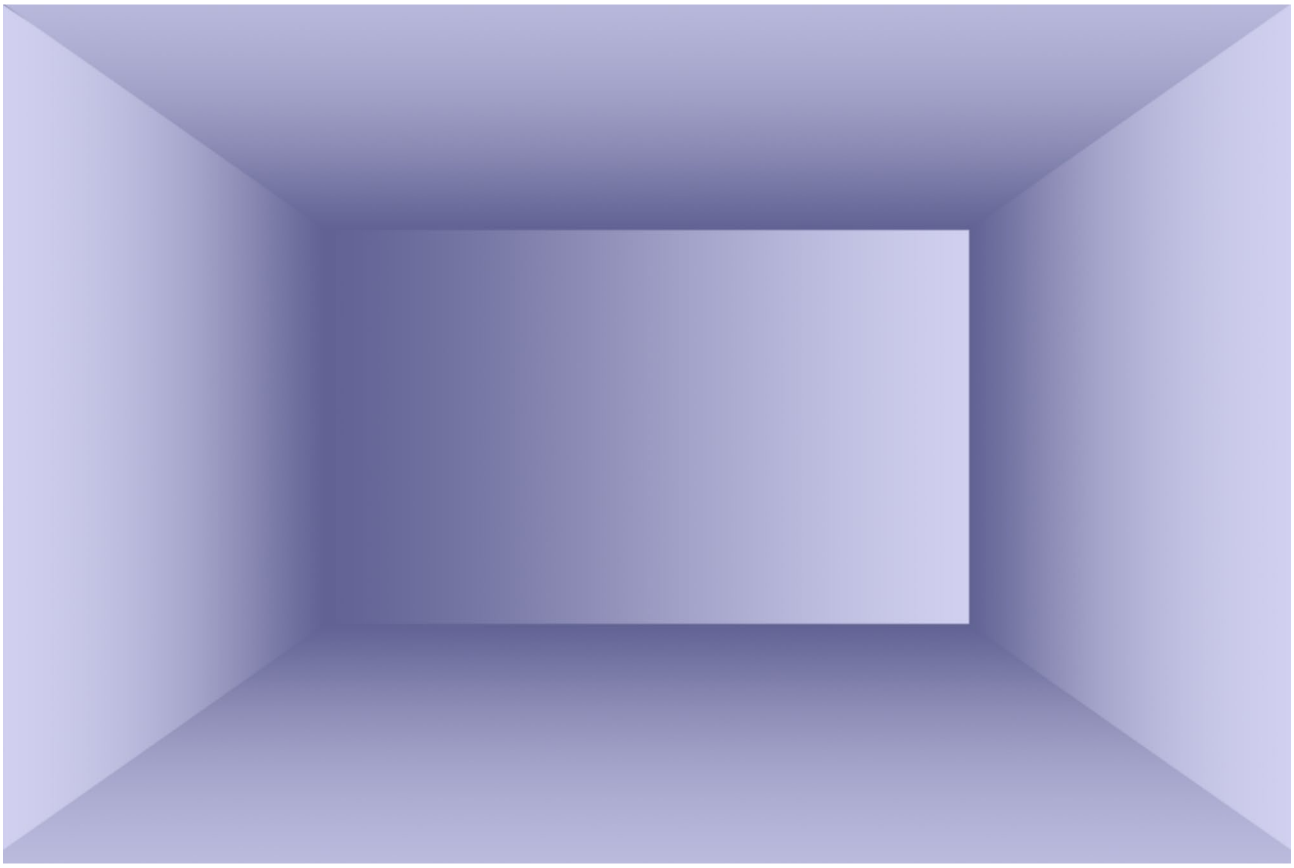


Figure 45: Original picture of the purple room used for the model trials: Benzoix, 2021

The following is a brief summary of the light settings used and the results obtained. Not all scenes are supported by image material, as the small changes caused by the light were only visible to the human eye and not through the camera lens.

Description of the scene:	Assessment
Purple room and diffused 100% light from the top using the same purple room by computer.	Blends in relatively good but quite bright.
Purple room and diffused 100% light from top using the same visuals on the led and side light sold white, dimm to 64%.	Needs some barndoors to keep from the screen and casts a shadow on the stage floor. The shadow is not visible to the audience. The light from the side gives the whole scene more texture.
Purple room and diffused 100% light from the top using the same visuals but on the LED.	The person on stage is well visible but slightly glary. The glare makes it difficult to see the person.
Purple room and diffused 100% light from the top using solid color white.	The lighting generally fits well and the person is better visible. But it seems like the person is flowing in the air instead of standing on the floor in the room.
Purple room and diffused 100% light from the top using solid purple, but this time the color was adjusted to look the same in real life.	The two worlds melt well together. But the physical world is slightly less visible. It shows here that it is more important that the color looks the same in real life for the human eye than if it is the same color on the computer. To make the workflow easier, lights with a good CRI might be useful.

As a second visual, a realistic fish was used. For some scenes, the idea was to make the fish seem like a light source for the whole scene. For others, it was supposed to be part of the scene.

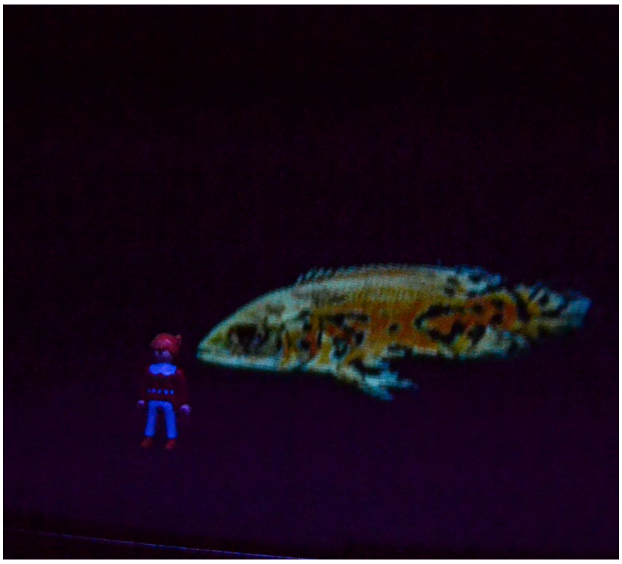


Figure 46: Fish and blue light; model trials: Hösch, 2024

Figure 47: Fish and yellow side light; model trials: Hösch, 2024

Description of the scene:	Assessment
Fish and blue diffuse light from top 100% but dark color (Figure 46)	The blue light makes it seem like the scenery is under water. The physical and the digital world are well connected visually.
Fish and yellow/orange direct from side 100%, which the color matched by eye (Figure 47)	The fish starts to seem like the light source. The exact position of the light on stage should be matched better to get a better result.
Fish with yellow light like the fish, color matched by eye. Light diffuse 100%, from top which the	It doesn't seem to make much sense in an artistic way. The scene is lit up, but there is no meaning behind it.

Measurements of Illuminance and Luminance:

The aim of the luminance and illuminance measurements was to find out whether a certain pattern is recognizable in scenes where the physical and the digital world are well connected with each other.

The absolute measurement result is not as important here as the relationship between the values.

The results of the measurements are shown in the following figures: Figure 48 shows the measurements of scenes that had a great visual connection between the digital and the physical world. In figure 49, the measurements of scenes with a bad visual connection between the two worlds are stated.

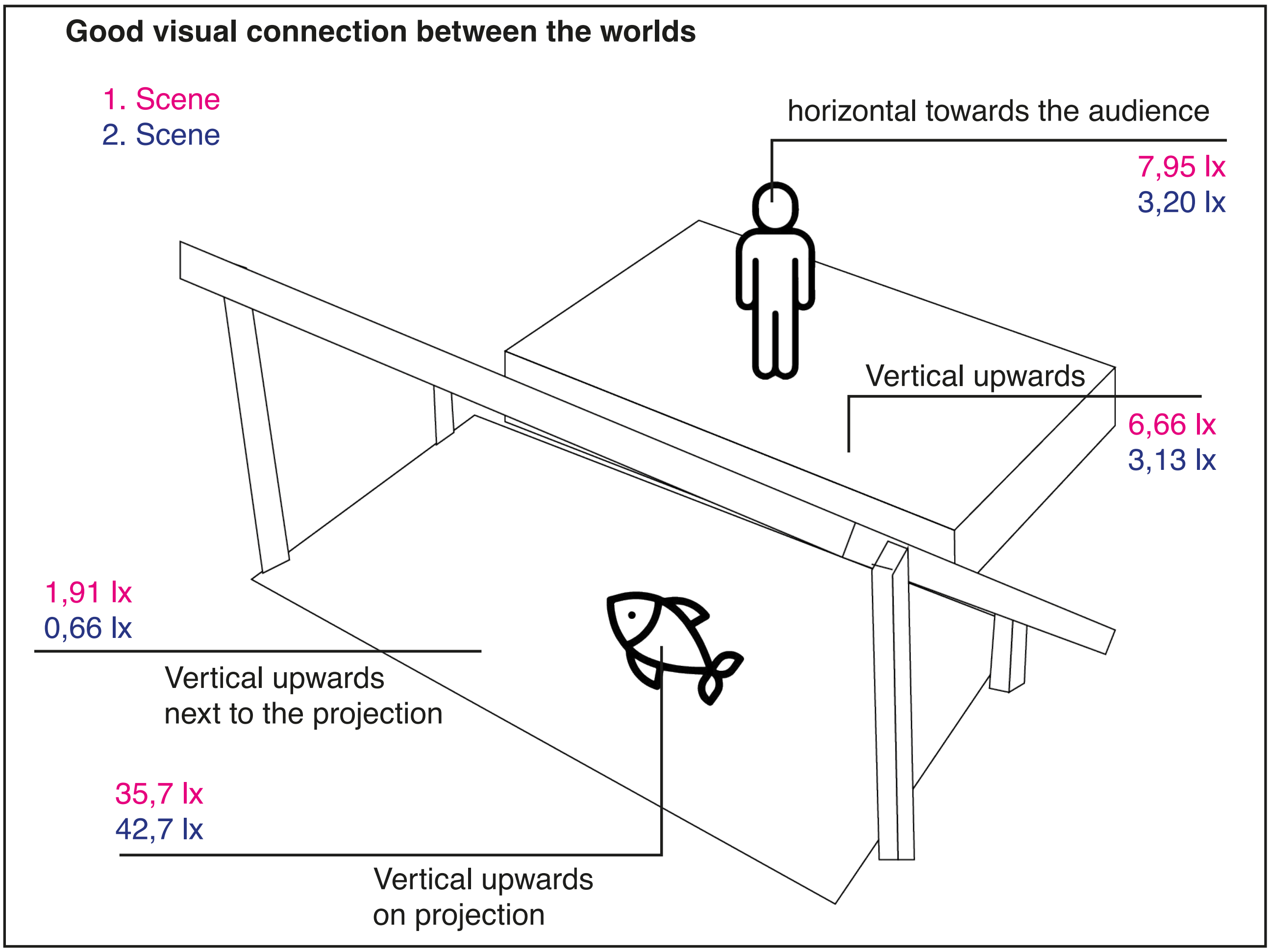


Figure 48: Illuminance measurements of good visually connected scenes: Hösch, 2024

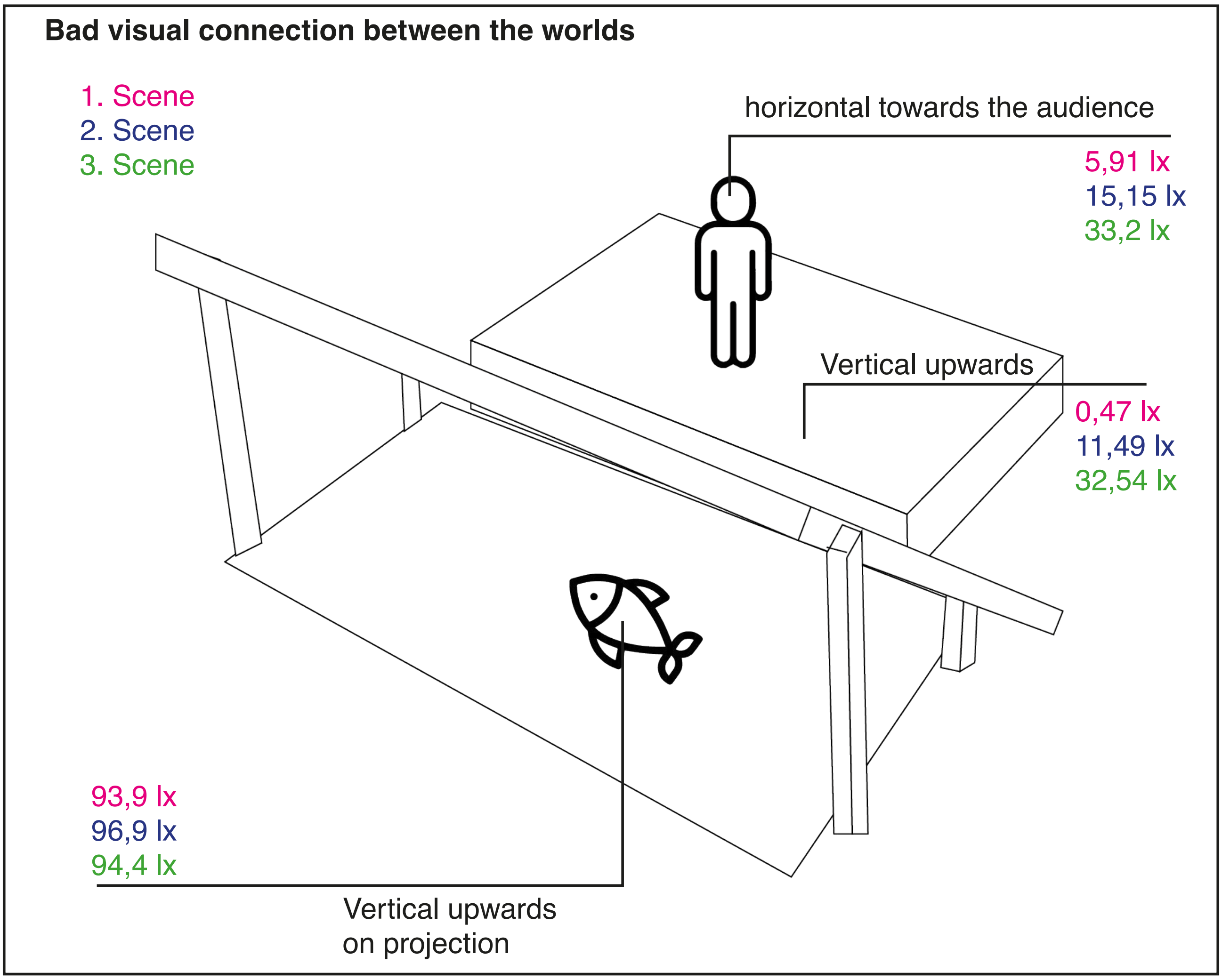


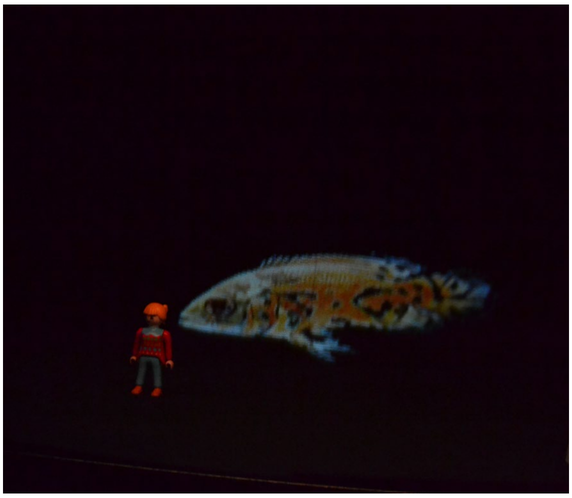
Figure 49: Illuminance measurements of bad visually connected scenes: Hösch, 2024

The illuminance was measured in different scenes at the same locations. Figure 50 shows the scenes that visually resulted in a successful interplay between the digital and physical worlds. Figure 51 shows the scenes in which the two worlds appeared separate from each other.

Good visual connection between the worlds

Please notice: The photographic documentation may differ from the real perception

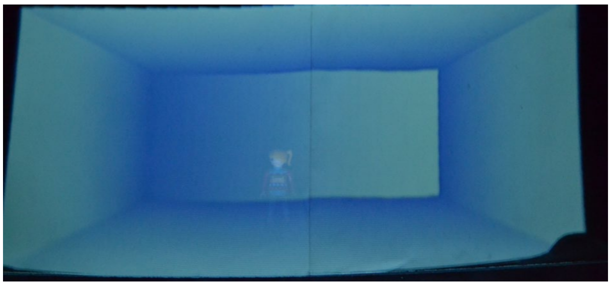
1. Scene: Fish and blue diffused light 100% from top



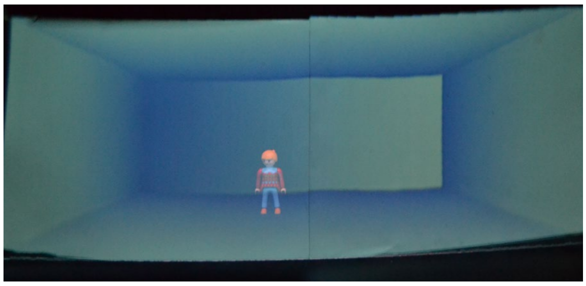
2. Scene: Fish and yellow light through lens 100% from the side

Figure 50: Pictures of good visually connected scenes: Hösch, 2024

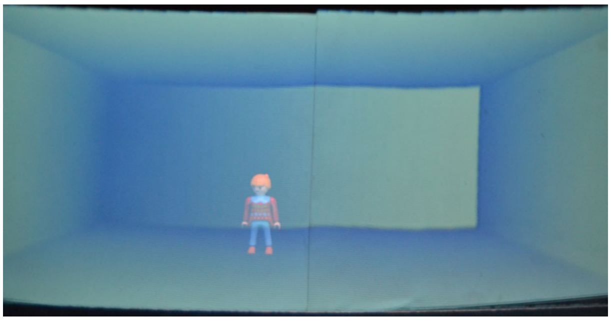
Bad visual connection between the worlds
Please notice: The photographic documentation may differ from the real perception



1. Scene: Purple room and no light on stage



2. Scene: Purple room and diffused 100% light from top using same visuals



3. Scene: Purple room and diffused 100% light from top using solid color white

Figure 51: Pictures of bad visually connected scenes: Hösch, 2024

In all the measurements, the extreme difference in illumination between the reflective surface and the stage is particularly striking at first glance. This finding shows how important a powerful projector is in order to create the pepper's ghost illusion.

In figure 51, it becomes clear what makes a person visible on stage. In the first scene, the stage is only illuminated by spill light, and the person is almost unrecognizable. In the second scene, the person is not particularly strongly illuminated with a measured 15.15 lx in the horizontal plane (Figure 49). But the person still appears too bright to be easily recognized. Interestingly, the person in the third scene is even more illuminated at 33.2 lx in the horizontal plane and is clearly visible to the human eye. But the quality of this scene is poor. As already described in the "color" section on page 67, the person appears to be floating in the scene. This does not create the desired connection between the physical and digital worlds.

In figure 51, a different visual was used for the scenes. In that scene, no visual is projected directly in front of the person on screen. As a result, the person on stage is visible in all scenes.
As a result, the area of the person in the illusion was masked out. If something should be clearly visible on the stage, there should not be any visual in front of it on the screen. Part of the physical world on stage can be hidden by placing a particularly bright visual in front of them in the digital world.

In figure 48, it is shown that if the illuminance levels are closer in relation to each other, it can be assumed that the physical and digital worlds interact better. The ratio of the illuminance levels of the two worlds can therefore be used as an orientation. But in the model trials, there was not enough quantitative data collected about the illuminance to support this statement completely.

The hypothesis that the ratio of luminance in the physical and digital world has an influence on the interaction of these two was tested by creating two HDR images.
It is important to note that the luminance itself was not measured, as the exact value has no valuable information for testing the hypothesis. Not every theater stage is the same; therefore, fixed luminance values from the model trials would not be translatable to the theater stages. Therefore, only the relationship between the areas is analyzed, not the values themselves.

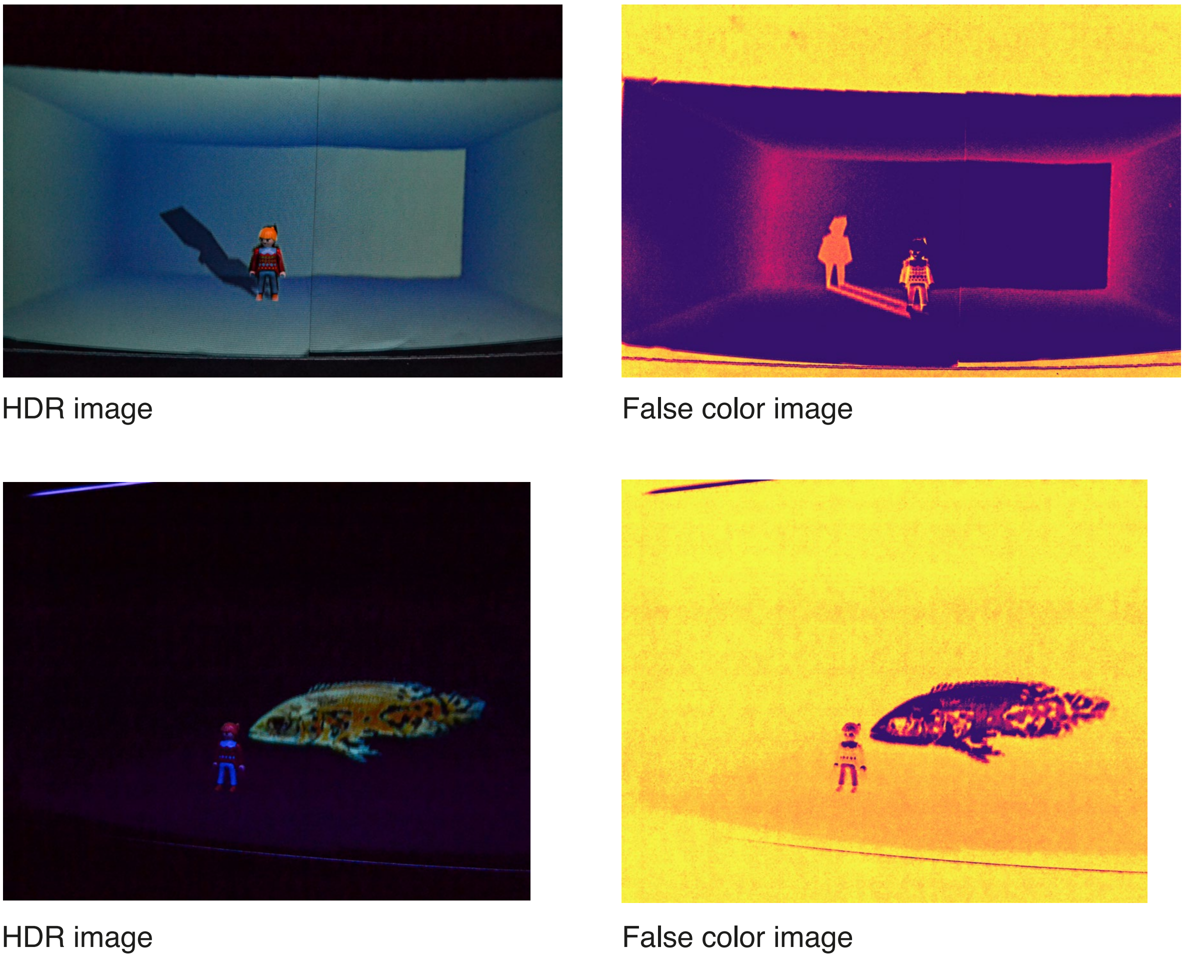


Figure 52: HDR Images and false color images for visually good connected scenes: Hösch, 2024

In figure 52, the HDR images and corresponding false-color maps are shown. It is noticeable that the differences in luminance are not particularly large. The outlines are clearly visible. It can be concluded that the difference in luminance must be so great that the digital world does not blend in with the physical world. At the same time, the difference in luminance must be kept so small that the physical and digital worlds appear visually connected.

Reflectance:

Over the course of three rounds of experiments, a number of observations were made on the reflection of different materials. Therefore, no separate analysis of different materials was carried out. The findings are briefly summarized below. Materials like the gray plastic of the boxes used in on-site testing have specular reflectance. The plastic of the model figure used in the model trials has a similar reflection factor. Since the model figure is that small, the reflection factor has no major influence. On larger surfaces, such as the gray boxes in the on-site testing, the higher reflection factor can quickly lead to the light on the stage being reflected too much. As a result, not all visuals of the pepper's ghost illusion can be recognized, as can be seen in figure 53.

Figure 53: Example for an invisible digital world due to too high reflection in the physical world; from on – side testing: Hösch, 2024

The experiments have shown that material with special reflections should therefore be avoided on stage. Materials with diffuse reflection work particularly well. A good example is the stage in the model trials. It is covered with black molton (Figure 54).

Figure 54: Stage covered in molton in model trials: Hösch, 2024

Due to its low reflection, almost no light is reflected back. This means that the entire space around the person on the stage can be used very well with pepper's ghost illusion.
In summary, the experiments have shown that materials with a low, diffuse reflection are better suited for a project with a pepper's ghost illusion, as this makes it easier to control which components of the structure are visible to the viewer.

3. RESULTS

To summarize the collected results from the three rounds of experiments, they are organized into the three areas of humanities, social science and natural science of lighting design. A hypothesis was formulated for each of these areas, at the beginning of the series of experiments.

Humanities:

Hypothesis: Different light scenarios can create an all-embracing experience for the user based on cultural backgrounds.

Results: The pepper's ghost illusion offers the possibility to create anything visually presentable on stage. The literature research gave great insights into the topic of humanities in optical illusions. The challenge in this situation is to create scenes that exist in the everyday human imagination. These types of situations ensure that the performance appears credible. However, because the audience is in a theater, this imagination can be far greater, as there is an expectation of the imaginative.

In this area, the light in the physical world has the task of supporting the realism of the illusion and disguising the technical implementation of the illusion in order to support its credibility.

Similarly, when implementing an AR environment with a pepper's ghost illusion, special attention must be paid to the visual interplay of colors in the physical world and digital world. Carefully selected colors can make the connection between the two worlds more convincing, which improves the overall experience for the viewer.

Social Science:

Hypothesis: Different light scenarios can create certain atmospheres, which are important for the different situations or scenes based on biological backgrounds.

Results: The experiments have shown that the physical light must appear as natural as possible to better connect the digital and physical world. Particularly good results are achieved when the direction of the light and the resulting shadows follow the same direction. The character of the light, whether rather hard and focused or softly diffused, should be based on what is known from real life. The aim when implementing the physical light for AR situa tions should be the best possible imitation of natural light.

Natural Science:

Hypothesis: Lighting in the holographic visuals and the physical world around them need to have a certain relation to one another to achieve the effect.

Results: It was discovered that there are no set settings for luminance or illumination needed to successfully connect the digital and real worlds using a pepper's ghost illusion. Two important components can be identified in this area. The goal, in order to connect the digital and physical world, should be to create a similar value in luminance. Too little difference will make the physical world disappear and too much difference will not create a visual connection between the two. Furthermore, there are no minimum lux levels for these situations. The human eye can adapt well to different conditions, while the viewer's attetion is drawn to the brighter parts of a setup. This should be used to direct the viewer's attention.

PART 4: FINAL DESIGN FINDINGS

As mentioned in the introduction, the design goal is to develop a framework for creating an AR environment through a pepper's ghost illusion. The findings are summarized in figure 55. This graphic can serve as a guide when implementing comparable projects in an AR environment, even if not using a pepper's ghost illusion.

These final design findings are intended to answer the final problem statement:
How can conventional physical lighting design tools be utilized to develop a specialized tool case tailored for optimizing augmented reality applications?

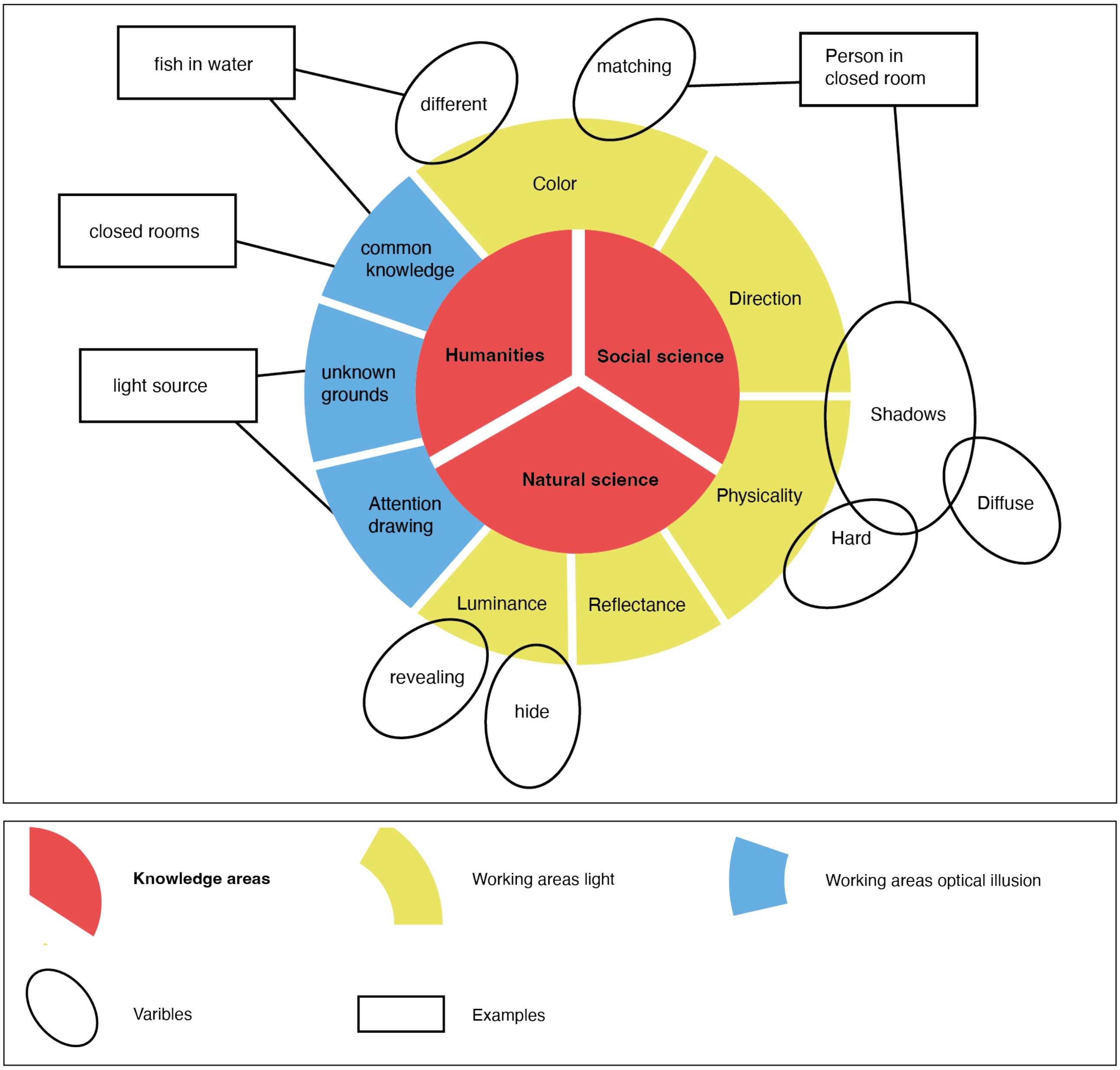


Figure 55: Visualization of newly developed design framework: Hösch, 2024

The framework for physical light in AR environments (Figure 55) is based on the assumption that lighting design operates in the three knowledge areas of humanities, social science and natural science. For these three areas, literature research and the experiments were used to define eight working areas that particularly influence the visual connection between the digital and physical world in an AR environment. The working areas are further divided into the two areas of light and optical illusions. This subdivision was not planned at the beginning of the research. The research showed how important it is to include the implementation of the optical illusion used. The main aim of this framework is to work with physical light, but a basic understanding of the technology used to create the digital world is necessary.
The different work areas are characterized by the fact that the different variables are defined in them.

In the “Color” work area, the color tones can be adjusted or deliberately designed differently. If the color tone is closely matched, the two worlds appear very closely connected. The scene of the purple room (Figure 56) is an example.

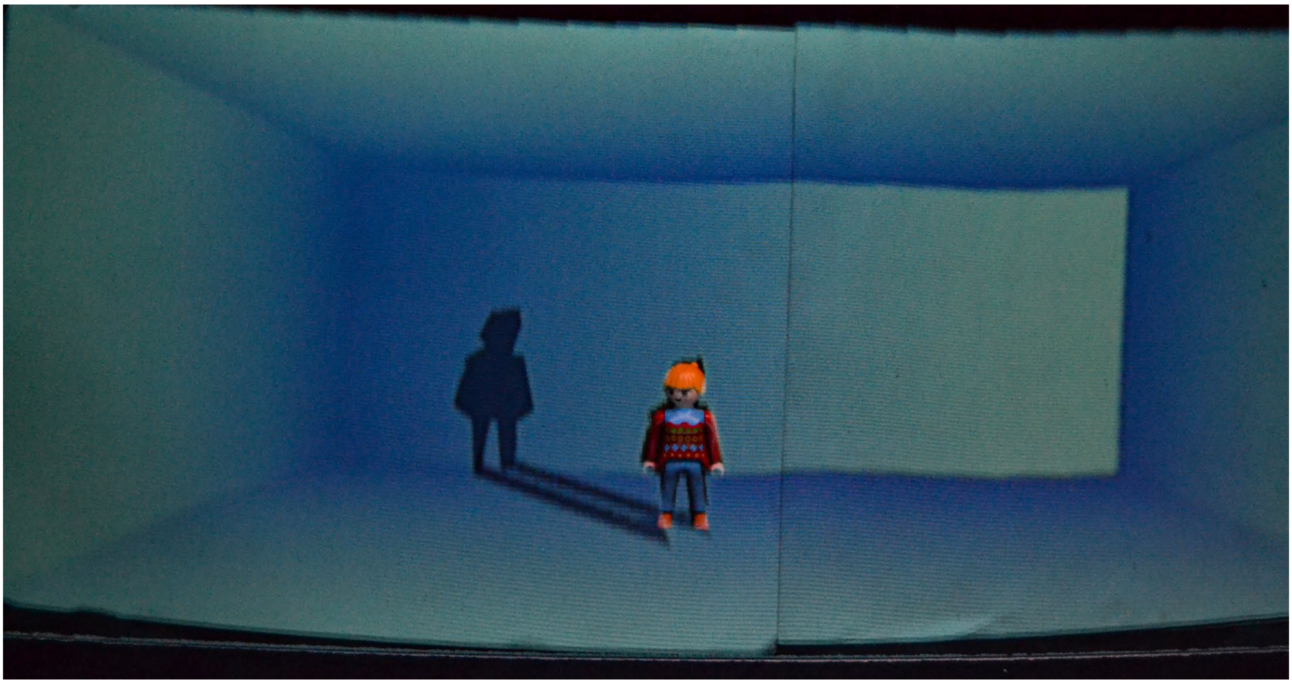


Figure 56: Example for the successful use of colored light in a scene; same color in the digital and physical world: Hösch, 2024

If a different color tone is deliberately chosen, this can create a different scene. For example, the fish in the water (Figure 57)

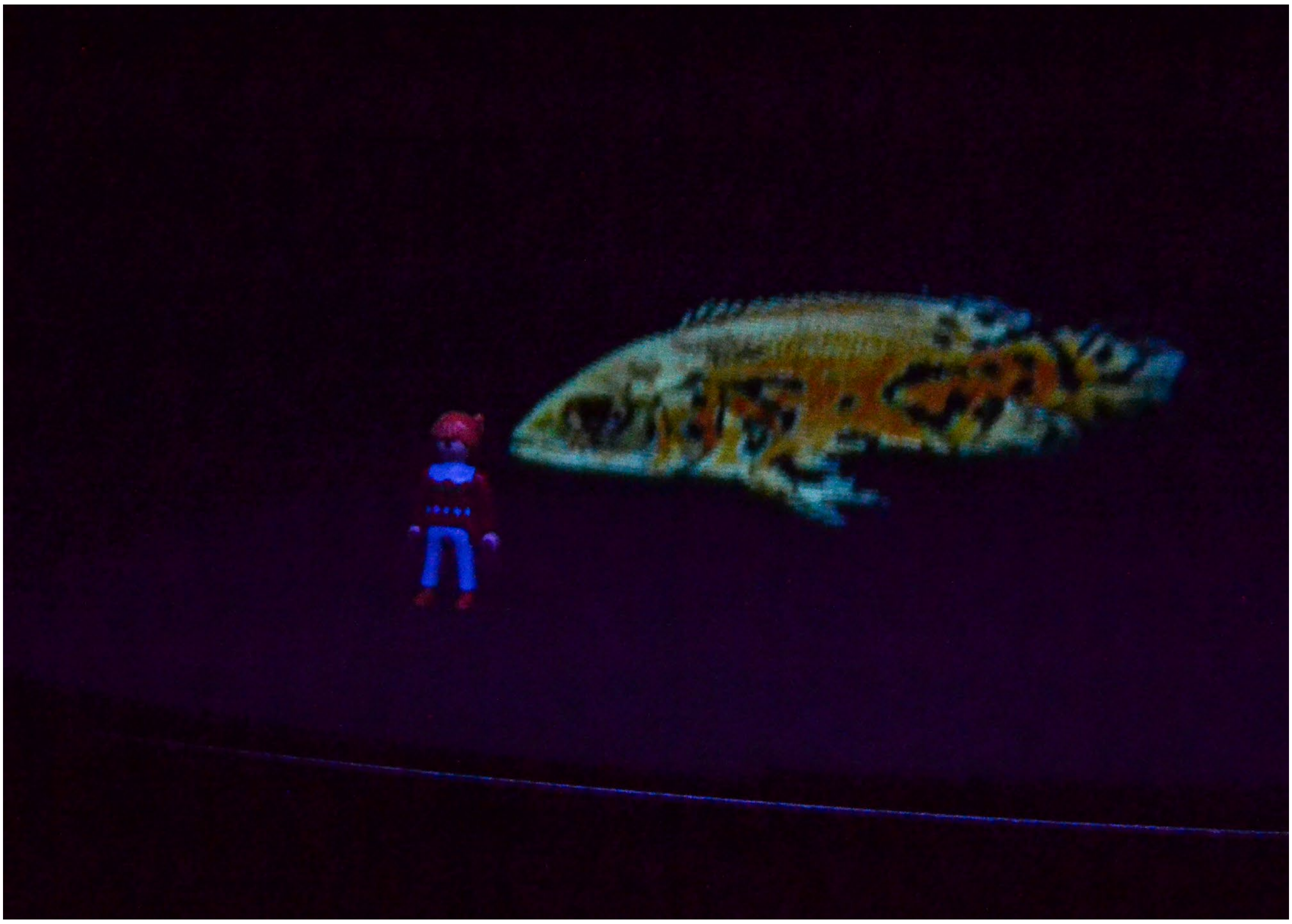


Figure 57: Example for the successful use of colored light in a scene; different colors in the digital and physical world: Hösch, 2024

The light direction is defined in the "direction" work area. The experiments have shown that matching the direction of light in the digital and physical world is particularly crucial in order to create a visual connection. The challenge in this area lies in its practical implementation. The parts that need to be considered are the rigging of the fixtures and their alignment with the different parts of the pepper's ghost illusion. Due to the setup of pepper's ghost illusion, the screen stretched in front of the stage can't be illuminated by any light other than the reflection; otherwise, the optical illusion would not work.
If a different practical implementation is used for an AR environment, the special features must be considered separately.

The work area "Physicality" shows that the normal physical properties of light must be emphasized in order to create a credible AR environment. An example of this is the digital creation of the shadow of the person on stage in the model trial (See figure 39, page 63).

The “Reflectance” work area should be seen as a reminder to consciously choose the materials used with regard to their reflection. The experiments have shown that materials with low, diffuse reflection are easier to handle during implementation. They do not throw scattered light into areas that are deliberately kept dark. There is also less chance of the viewer being unintentionally distracted.

In the “Luminance” work area, the relationship between luminance and illumination between the digital and physical worlds is defined. For a successful visual connection between the digital and physical worlds, a balanced ratio of luminance between the two worlds should be targeted. If the physical world is too bright compared to the digital world, it looks as if the two components are floating on top of each other. If the physical world is too dark in relation to the digital world, it is not visible. Both extremes can be used artistically, if desired.

The three following work areas, “Attention drawing”, “unknown grounds” and “common knowledge” are focusing on people’s perception.
A person’s attention can be directed particularly well using different levels of illuminance. The “attention drawing” area describes how to use this tool. This allows different areas of the stage to be highlighted or hidden.

The “unknown grounds” section aims to keep knowledge about the practical implementation of the pepper’s ghost illusion away from the viewer. The viewer’s lack of knowledge supports a better overall experience for the audience. As a result, its effect can be further intensified.
An example of this is the visual representation of fantasy figures, such as in the play SKYG33N (Figure 58).

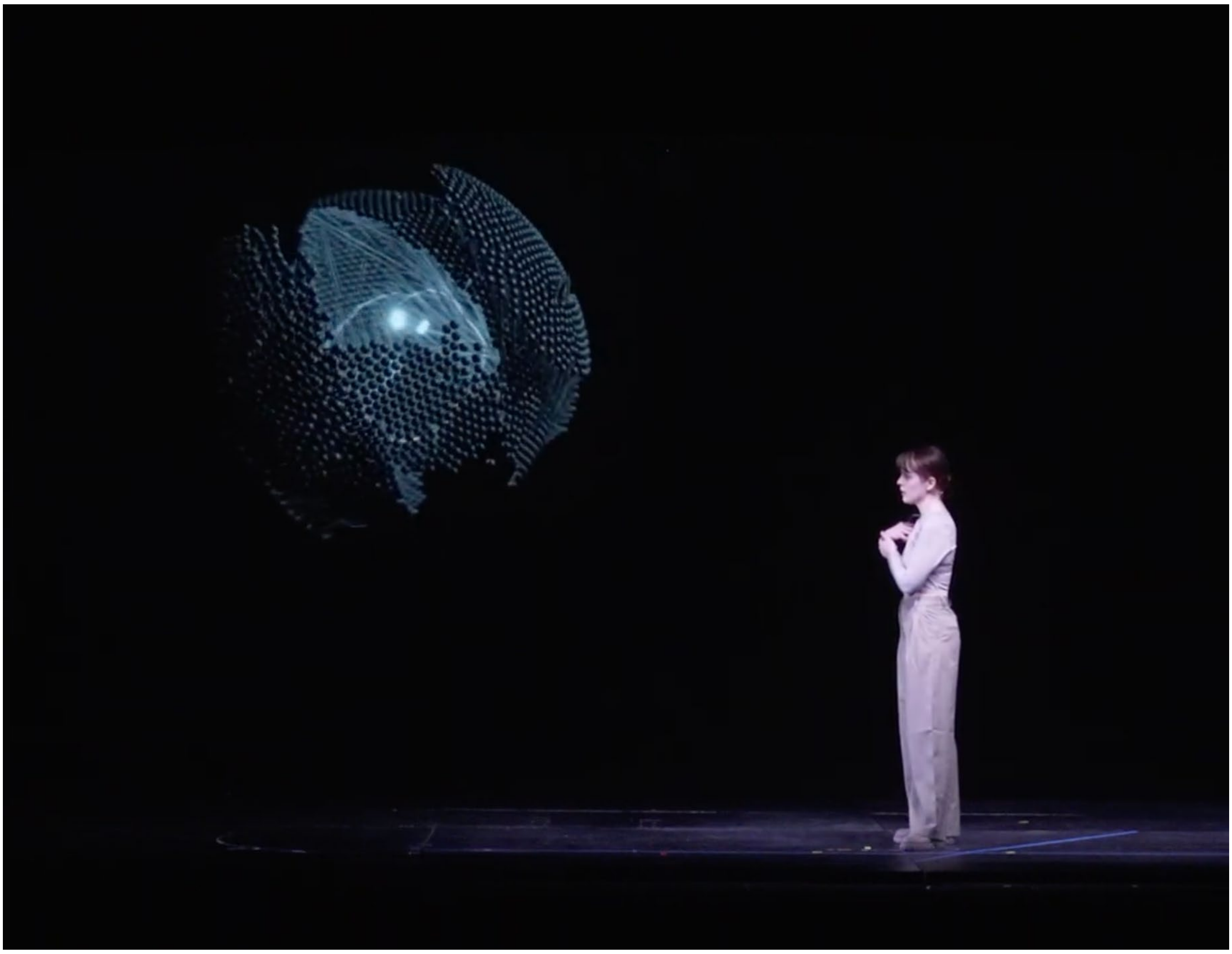


Figure 58: Example for “unknown grounds”; neural network as a light source in the theater play SKYG33N: Vertigo Aps, 2023

The “common knowledge” work area is based on the assumption that all viewers of the AR environment have a similar level of knowledge. When implementing an AR, this should be used as a basis in order to achieve fundamental credibility.
The fish in the water (Figure 46, page 69) from the model trial is a good visual example. Despite the fact that the colors of the digital and physical world do not match, the scene looks convincing for a theater stage, as the blue diffuse light gives the impression of being under water.

If these eight working areas are taken into account for the different desired scenes and their variables are adjusted accordingly, a successful visual connection between the digital and physical world can be created in an AR environment.

CONCLUSION

The following section summarizes the results of the research and experiments. It also takes a critical look at this work as a whole. An outlook on possible further steps to improve the current status is also given.

The combination of literature research and a series of experiments has shown how complex the work with physical light in AR is. The aim of lighting design in this area is to achieve a specific function, with the visibility and visual connection of the digital and physical world being the first priority. A fundamental understanding of human perception is particularly important for the realization of this task. If the AR is created through an optical illusion, as in this case, the implementation of this illusion must be understood in order to optimally support the physical light. On this basis, lighting design variables such as illuminance, luminance, color and temperature, height, density and direction, and distribution can then be implemented. At this point, a link can be made to more general or architectural lighting design. These six variables correspond to the six principles of lighting design by Hernvé Descottes (2011). Lighting design for connecting the digital and physical world in an AR environment is about understanding the creation of this environment precisely, analyzing human perception in detail, and using the tools of lighting design in a targeted manner. Through the series of experiments in this work, these influences were tested in different states. The three rounds – observation, on-site testing and model trial – were designed to build on each others' findings. The findings could be carried forward between the rounds, allowing the tested hypotheses and guiding questions to develop dynamically. By building the experiments on the theater play SKYG33N, the experiments were based on an already implemented project. This way, it was insured that the general practice of using a pepper's ghost illusion in an AR environment is successful. This provided an excellent opportunity for this work to focus on improving the practices' strengths. Since the experiments were designed simultaneously with their implementation, a great deal of flexibility was given. Therefore, the experiments were targeted exactly at the process.

In the future an interesting task would be to run a similar round of experiments again, while evaluating the results through a bigger group of people. This practice could give a broader view on the given results and therefore help to eradicate any weaknesses in the current design finding. Since the two first rounds of the experiments were conducted on the set of SKYG33N a further possible is to improve the current setup with the design findings of this work and then conduct the experiments again with a test group. By already implementing the new design findings into a next turn of experiments, the new design findings would be tested while the overall setup of the theater play can be improved. Within these future experiments, it would be possible to collect more quantitative data, in order to strengthen the findings in this work. A step to collect more quantitative data would be a great addition to the current work, since the amount of collected quantitative data is rather small.

Next to improving the given experiments, the implementation of a new project, using the newly developed framework would be an interesting further path. A newly designed AR environment could enable test the framework and give new insights into the practice. However, this test series would have to be implemented as part of a planned theater production due to the financial and personnel costs of such a project.

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