lumina

Lighting Our Way with Minimal Impact

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For millennia, fire was humanity‘s sole means of illuminating the night, but this changed with the invention of electric lighting in the 19th century. Since then, artificial light at night (ALAN) has become a crucial part of our society. The advent of modern LEDs has increased usage, making artificial light more accessible and economical. Unfortunately, excessive and unconsidered use of ALAN has led to significant light pollution, harming our ecosystem as it disrupts the natural day-night cycle, an integral aspect of our biosphere‘s evolution, as night is virtually turned into day.

The widespread nature of the issue, caused by numerous light sources used for different purposes, makes it difficult to address it on a large scale with a single approach. Therefore, this thesis and project ‚Lumina‘ focuses on pedestrian pathways, isolated from roads. These pathways often use unoptimized and static lighting solutions and are frequently surrounded by areas of high biodiversity.

In this context, the research question is: How might we develop a better solution for artificial light at night for pathways, respecting the nocturnal needs of both non-human and human actors in our ecosystem?

Using design thinking, oriented around interactions between the design, the user, and the environment as a system, we can create an optimized, non-static, and customizable luminaire approach. This has led to a physical prototype, allowing for precise and tailored use of ALAN, adapted to different environments.

‚Lumina‘ features a mechanical interactive head, providing tilt, rotation, an LED slider in combination with a non-glare reflector design, to direct ALAN only where needed. With three light spectra modes, ALAN can be optimized to local needs. Additionally, motion detectors allow for intelligent and optimized use of ALAN based on pedestrian activity.

This design approach enables our society to engage in a more harmonious relationship with our nocturnal environment.

Keywords: light pollution, artificial light at night (alan), environmental design, sustainable lighting, adaptive lighting systems, glare reduction, light spectra, pathway lighting, nocturnal environment.

Table of Contents

Overview

This thesis provides a comprehensive overview of my project, Lumina.

The document is structured into four main chapters, which are as follows:

Light Pollution: An Issue on a Global Scale
Lighting Our Way with Minimal Impact
Conceptualizing My Prototypes
Reflection and Evaluation

Each chapter is divided into subchapters to guide the reader through the project.

I begin by introducing the issue of light pollution, providing context, and framing the problem. This chapter concludes with my research question and methodology.

The following chapter describes my concept, drawing inspiration from relevant projects and outlining the key features of my prototype.

The next chapter discusses the development of my prototypes, providing detailed insights into my design process.

Finally, I conclude by summarizing my findings, highlighting the insights I gained, and discussing my contributions to the field.

Definitions

Light Pollution: The excessive and misdirected use of artificial light, having unwanted or negative effects on the surroundings.

ALAN: The acronym ALAN refers to artificial light at night. It is used interchangeably throughout this thesis.

Glare: Glare refers to the situation when bright light shines directly into our eyes and causes blindness or discomfort.

Photopic Vision: The vision of the eye under well-lit conditions, primarily enabling color perception and mediated by cone cells in the retina.

Scotopic Vision: The vision of the eye under low-light conditions, mediated by rod cells in the retina, and characterized by a lack of color perception.

Mesopic Vision: The intermediate vision under lighting conditions between photopic and scotopic vision, where both rod and cone cells contribute to visual perception.

Natural Environment: The environment that surrounds us and has not been created by humans.

Kelvin: Kelvin, abbreviated "K," is a unit that refers to the color temperature of light. Natural daylight is considered to be around 5500K. Lower values appear more reddish, while higher values appear more bluish.

Amber: The term amber, in this thesis, refers to the color perceived by our eyes as between yellow and orange, specifically the emission of light at 595 nm.

1

Personal Motivation

At around the age of seven, I first encountered the field of astronomy. It was a clear night, and my father introduced me to the constellations through our roof window. This was in the early 2000s, and we used a bulky laptop running the astronomy software, RedShift 3. I still possess the original software on CD and hold many fond memories of it. I believe this experience was one of the pivotal moments in my life that ignited my interest in astronomy and technology.

Over the years, my interest for photography grew alongside. The camera became a tool for capturing what was invisible to the naked eye and I completed a Bachelor Degree in Photography and Media Art. It was later that I discovered astrophotography and became captivated by the ability to photograph distant galaxies and nebulae, revealing their incredible beauty.

However, I soon realized that observing the stars was becoming increasingly difficult from my location due to the rise of light pollution.

In 2021, I moved to Switzerland for my studies in Interaction Design and found myself living near the Alpine region. In the mountains, I rediscovered a deeper interest in night sky photography and was able to realize the deep loss we sacrifice to light pollution. I started to perform my own observations and measurements, comparing the darker skies found in the mountains to the bright glowing skies found in the urban regions.

I see my interest in the night sky as a catalyst to use my experience, knowledge and persistence for finding potential solutions to counter the environmental issue of light pollution.

2 Light Pollution: An Issue on a Global Scale

Fig. 1

2.1

Introduction

Light pollution encompasses side effects from artificial light at night, also abbreviated as ALAN. Light pollution is broadly divided into astronomical and ecological light pollution (Teikari, 2007). Astronomical light pollution is the night sky‘s brightening, primarily due to Rayleigh scattering effect (Peña-García & Sędziwy, 2020), creating a glowing dome over urban and suburban areas (Kyba et al., 2017). This impairs astronomers‘ ability to observe the sky. Ecological light pollution disrupts natural nocturnal processes in plants, animals, and humans (Teikari, 2007). Initially recognized as a significant issue by astronomers at Arizona‘s Kitt Peak National Observatory in the 1970s (Challéat et al., 2015), light pollution is a relatively new societal problem but has grown into a major concern.

Artificial light at night, essential for expanding our nighttime activities and boosting the economy, has reduced our reliance on natural day-night cycles.

Currently, about 90% of the global population has access to electricity (Statista, 2023), and the proliferation of affordable, efficient LED technology makes artificial lighting more widespread than ever. However, especially LEDs, predominantly emitting blue light (Widmer et al., 2022), significantly contribute to light pollution if used improperly. This is because blue light is more prone to Rayleigh scattering, causing increased skyglow (Peña-García & Sędziwy, 2020) while also having more profound effects on nocturnal species like invertebrates.

2.2 Why Should We Care?

Reducing light pollution is crucial, even if its impact may not be as immediately apparent as other environmental issues like air pollution, water pollution, or climate change. The complexity of light pollution and its seemingly subtle effects on the environment and ourselves necessitate the question: why should we bother addressing it?

Understanding the impact of ALAN requires recognizing first that day-night rhythms are integral to our global ecosystem‘s evolution. Various organisms have evolved specialized adaptations for nocturnal environments, such as enhanced eyesight and circadian photoreceptors in vertebrates, present for approximately 500 million years (Hölker et al., 2010). Of the total global biodiversity, a significant portion is nocturnal, with 30% of vertebrates and over 60% of invertebrates exhibiting nocturnal activities (Hölker et al., 2010). However, ALAN is adapted to human eyesight and we significantly destabilize those natural settings of day and night. For a comparison, the natural light exhibited from stars and the Milky Way can range between 0.0001 lux during an overcast moonless night to 0.05 or 0.3 lux during a full moon clear night (Wikipedia contributors, 2023). However, one single typical street lamp, in comparison, can range between 10 to 40 lux (Raap, 2018), which is up to 130 times brighter than a full moon night or up to 400,000 times brighter than an overcast moonless night.

Those circumstances can lead to significant disturbance of animals, impacting their biological rhythm, orientation, migration, the search for nutrition, and their mating behavior (Widmer et al., 2022). Plants can be affected in many ways as well, “altering their direction of growth, flowering times and the efficiency of photosynthetic processes” (Eisenbeis & Hänel, 2009). A study in the United Kingdom found that budburst occurs up to 7.5 days earlier in areas with more nighttime lighting (ffrench-Constant et al., 2016). This may not sound like an issue at first, but may lead on a global scale to problems and can alter and disrupt the interactions among various species, including plant-pollinator dynamics and herbivore-plant relationships, creating a cascading effect and potentially affecting other organisms within the ecosystem as well (ffrench-Constant et al., 2016; Bennie, et al., 2016). Other examples of disturbed animals are newborn sea turtles with disturbed orientation sense (Widmer et al., 2022). Disoriented by artificial light on often brightly lit coastlines, they don‘t find their way into the sea.

One study also highlights that various marine invertebrates exhibit synchronized behaviors with lunar or semilunar periodicities in regard to locomotion, reproduction, and molting (Naylor, 2001). ALAN near or at coastlines might impact these intricate processes.

Navigation of some birds can be affected as well by ALAN, as they use celestial objects such as the stars or the moon during the night for orientation in addition to the magnetic orientation sense (Widmer et al., 2022). Furthermore, experiments have also shown that artificial light can increase hormone levels in songbirds, impacting their reproductive process (Widmer et al., 2022).

Some obvious effects one may observe are the impact of ALAN on insects. One can distinguish between three effects:

In the scenario of the crash barrier effect, long-distance flights of insects are disturbed by artificial light, bringing them off course and eventually leading to the effects of fixation.

The fixation effect can lead insects to orbit the light till death caused by exhaustion, becoming prey to predators, or dying due to hot surfaces of the lamp.

The vacuum cleaner effect describes the process of insects being sucked out of their habitats from artificial light during the summer season, resulting in significant depletion of local populations (Eisenbeis & Hänel, 2009).

Fig. 2

Interestingly, the attraction of insects to artificial lights can vary depending on factors such as the moon cycle and weather conditions (Eisenbeis & Hänel, 2009). Light traps equipped with LED lights, on average, captured 48% more insects compared to those fitted with High-Pressure Sodium lamps (Pawson & Bader, 2014).

Those are a few examples that describe how ALAN impacts our ecosystem. Possibly, many more side effects will be discovered in the future.

Besides ecological implications, we should not forget possible societal effects on culture and our well-being. The night sky encompassed diverse values for many cultures such as "*scientific value, historical value, cultural value, recreational value, beauty, and inspirational or spiritual value*" (Gallaway, 2010). In ancient times stars played a direct and integral role in the everyday life of the common person and as Terrel Gallaway puts it in an essay, "*the heavens [were] among humanity's earliest tools [and] …for innumerable cultures, stars have been used to track the time of night and the seasons*" (Kuhn, 1957; Gallaway, 2010). Unfortunately, most of us have never witnessed a truly dark night sky as it could be found 150 years ago in central Europe or nowadays only in remote areas.

Gallaway argues that through our economy and the associated doctrines, we have lost our sense of natural beauty and are no longer aware of the importance of passive joy as it can be found in the activity of observing the night sky. The author believes it can serve as an instrument for social well-being (Gallaway, 2010).

People who once in their lives saw the pristine and sublime beauty of the night sky can probably follow these ideas.

"*...visiting a dark sky destination can be an emotional experience.*" (Kang, 2022).

"*One of the reasons people value the night sky is because it gives you a sense of transcendence and connectedness to the universe, and inspires contemplation about the meaning of life and the massive scale of stars and galaxies. …the night sky is kind of fundamental to being human…*" (Clark, 2020).

Fig. 3

Fig. 4

Personally, seeing and experiencing the depth of space filling my entire field of view, resolving the faint color nuances in starlight falling onto my retina and the dissolving glow of the Milky Way, is more than just an observation. I perceive it as an embodied experience.

The night sky reminds us that we are not alone in the universe, but are part of a much bigger picture. Unfortunately, we face a kind of downward spiral situation as most people live in the city and never had the opportunity to witness the night sky in its pure natural form. They, therefore, lack the knowledge of their loss (Gallaway, 2010) and possibly the motivation for change. It is very possible that this will have effects on society.

I believe the night sky is not only inspirational as mentioned by Gallaway, but holds creational potential as well, where we can act as the embodiment. I see the mere fact that I am creating this work, as proof of that.

We may ask the question if Vincent van Gogh would have painted his work Starry Night the same way in 1889 if the skies were already light-polluted?

Fig. 5

Fig. 6

2.3 Political and Societal Aspects

To better understand the field, I looked into the political aspects, as light pollution is closely related to political and societal issues.

Artificial light at night has become, since the discovery of fire, an integral part of human existence. It is a tool that has allowed us to detach from natural dependencies. Unfortunately, all tools come with sacrifices and side effects, especially if used unthoughtfully.

Addressing light pollution often faces resistance or misunderstanding, particularly when financial factors are involved (Challéat et al., 2015). It's crucial to convey that the solution isn't to eliminate artificial lighting but to use it more sustainably and intelligently.

Artificial light at night plays a crucial role in societal safety and well-being, providing visibility for locomotion and creating a sense of security in potentially dangerous areas.

While this is true, studies have revealed that the relationship between artificial light at night and safety can be complex and that more light does not necessarily mean more safety or well-being.

The optimal usage of light depends on the specific situation. For instance, in a park at night, lights should be neither too bright nor glaring directly at pedestrians. Excessive brightness or glare, creating stark contrasts between light and dark areas, can reduce visibility and safety, potentially offering criminals an advantage (iamthedarkranger, 2012).

Fig. 7

Results in a study conducted in England and Wales found very little to no impact of collisions on the streets and crimes in effect to reduced street lighting (Steinbach et al., 2015). In a study from the US, scientists have analyzed about 300,000 streetlight outages in Chicago and concluded that the affected street segments experienced only very little change in nighttime crimes. Instead, they found that crimes spill over to nearby street segments (Chalfin et al., 2022).

This shows that the relation between ALAN and safety is complex and that more light does not necessarily equate to more safety. A practical example highlighting this is that criminals also require some light for their activities. Using a flashlight in the dark makes them conspicuous. I personally experienced this when my neighbors mistook me for a burglar and called the police as I was setting up a telescope in our garden while using a flashlight.

Personally, I often find myself blinded by direct line of sight to the luminaries emitting light sources, causing temporary blindness resulting in a reduction of my night vision and comfort. It is likely that the optimal safety between the usage of ALAN lies in an intelligent usage of light. This should include evenly lit areas, overall lower light levels to trigger our mesopic or scotopic vision, preventing direct blinding and glare through shields.

In France, for example, politics have brought the issue into the foreground, by placing experts into key positions, contributing to decentralized and participative methods. This gave the opportunity to build networks involving experts and advancing the topic on a political and societal level (Challéat et al., 2015). Another example that demonstrates how politics on a legislative level have taken action can be found in Chile. The country is very advanced in the regulation of light pollution due to many Observatories. In 1998, policymakers found it necessary to formulate Supreme Decree No. 686 under the Ministry of Economy, regulating upward light emissions (Widmer et al., 2022). In 2014, the Chilean government released new regulations to respond to the rise of increased usage of LED lights, tightly controlling those light systems (Widmer et al., 2022).

Instead of law, one can also go non-enforcement paths. This is demonstrated by the International Dark-Sky Association (IDA) that came up with a system to designate so-called dark sky reserves. Those are regions of public or private land of substantial size of about 700 km², with exceptional or distinguished starry nights and a nocturnal environment, specifically protected for its scientific, natural, educational, cultural heritage, and/or public enjoyment.

To be designated as an International Dark Sky Reserve, a site must implement a strict lighting management plan to control light pollution, ensure significant outdoor lighting compliance, and facilitate regular public access and annual progress reporting (International Dark-Sky Association, 2018). The designations bronze, silver, and gold are available to be awarded depending on the specific fulfillment of guidelines (Meier, 2014).

Fig. 8

For setting up such areas, it is important to identify specific interest groups of people as a collective force that is interested in achieving designations. Those can be astronomers that want to preserve a place for their observations; environmentalists that value the nighttime environment for its ecological importance, and heritage preservationists that value the scenic and cultural assets of the night sky (Meier, 2014). Interestingly, politicians and business people that see the designations as a selling point or boost for tourism and fame of their region can also be part (Meier, 2014).

Regarding Switzerland‘s approach to light pollution, it is clear that the nation‘s political and legal framework is multifaceted. As per the compilation by DarkSky Switzerland, Swiss regulations encompass federal, cantonal, and municipal guidelines. The Swiss Federal Supreme Court utilizes the SIA 491 construction norm, recognizing the public‘s interest in maintaining night rest from 10 PM to 6 AM. The Environmental Protection Act emphasizes a precautionary principle, mandating light emissions in public spaces to be limited as much as possible, both technically and economically (Rechtsgrundlagen – DarkSky Switzerland, n.d.).

It‘s surprising and questionable that the SIA 491 construction norm, aimed at reducing light pollution, is restricted by a paywall from access (SIA, 2013). This is a common issue with other light pollution-related norms I encountered during my research. I believe such environmentally beneficial information should be freely accessible. While acknowledging the effort in developing these norms, I suggest government funding should cover the costs, making them available to all.

Mitigation of Light Pollution

My research was intended to provide me with a broader overview of the topic, but I set a slight focus on possible solutions. I came to categorize two high-level fields that try to tackle the issue through awareness raising or the integration of technical solutions and/or methods. I found less deep and detailed information on solutions to light pollution than I first thought. I was missing discussions and projects on alternative approaches, but I still came across some interesting projects and papers that address indirect and direct methods to mitigate light pollution.

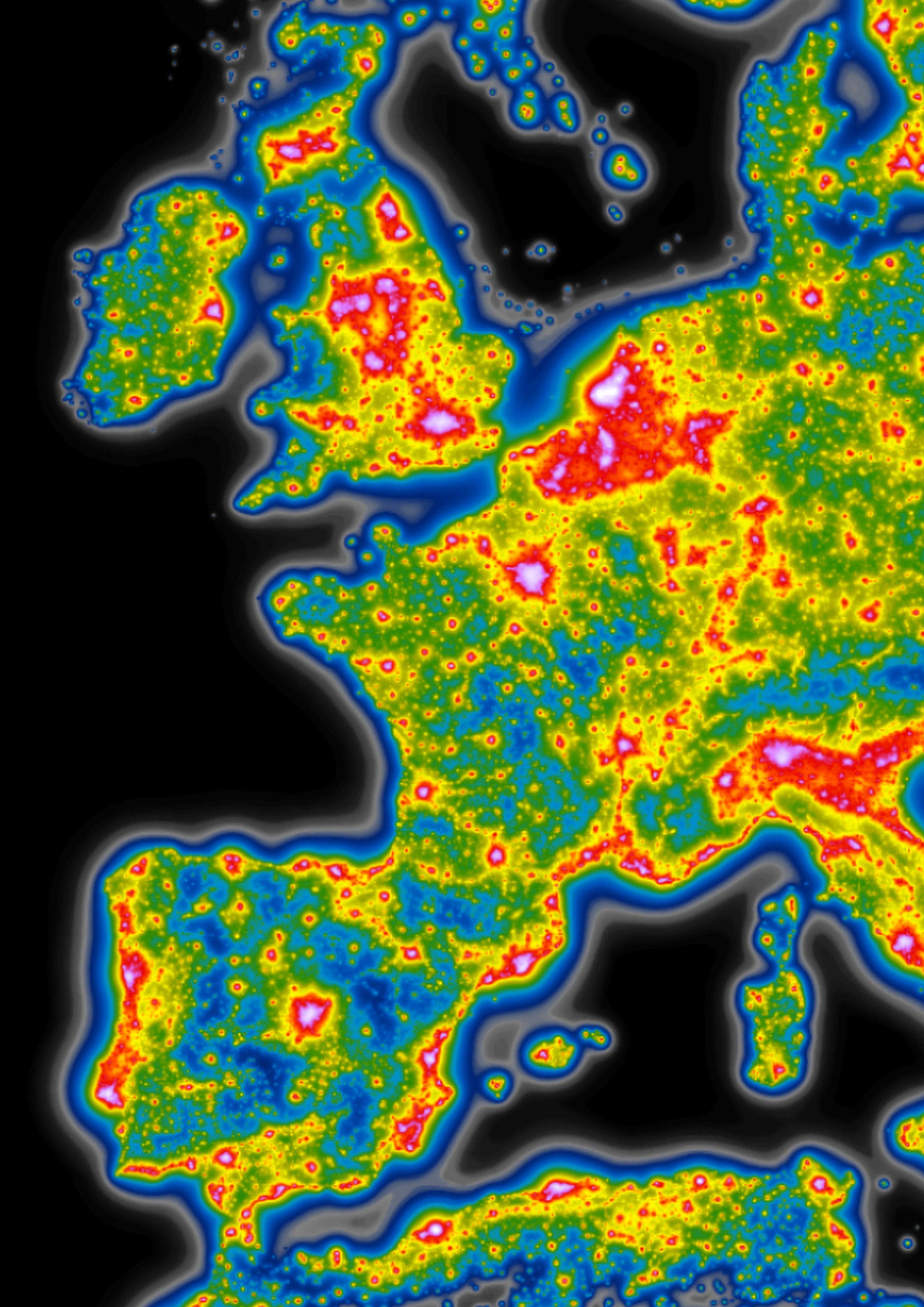
I found that the core lies in awareness raising, with many works centered around this category. These works try to bring the topic stronger into the public's mind. An exemplary effort is DarkSky Switzerland's creation of an accessible and appealing flyer, designed to educate the public and motivate action against light pollution (*Die Nacht braucht ihre Dunkelheit – DarkSky Switzerland*, n.d.).

Fig. 9

Extensive projects like Globe at Night from NASA is a citizen-science project to collect global data about light pollution while raising awareness about the impact of light pollution on our environment (Universities for Research in Astronomy (AURA), n.d.).

For visualizing the extent and spread of light pollution, lightpollutionmap.info offers an excellent global overview. Users can examine light pollution in their local region or anywhere worldwide (*Light Pollution Map*, n.d.).

By using art installations, we can make people more aware of the beauty and value of dark night skies. The Roden Crater by James Turrell in the desert of Arizona is an example (Skystone Foundation, 2023), and goes well with the argument made in the previous chapter of making the point that it is important to provide people a reference of what they lose. Turrell's land art installation brings the visitor to a remote area, providing an immersive experience between light, space, and the surroundings, creating awareness of the beauty and value encompassed in the night sky.



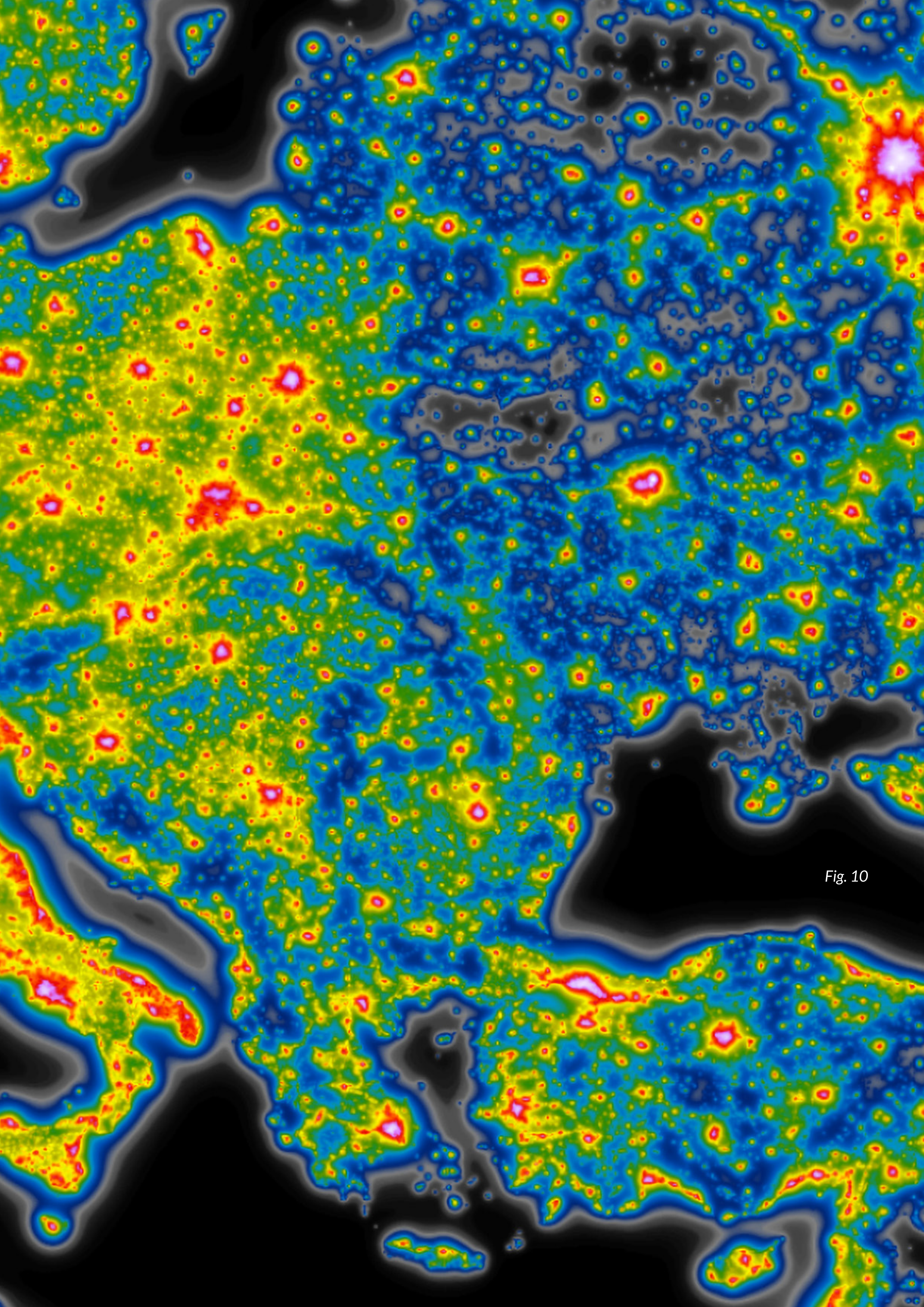


Fig. 10

I believe the experience can be one of the strongest methods to bring awareness because it can spark passion. My own fascination with the night sky was triggered by experiencing it firsthand as well. A fantastic work to provide the base for that is the Traveling Telescope project by Susan Murabana, founded in Kenya in 2014 (*ABOUT US - Travelling Telescope*, 2023).

Their team is traveling to schools and other places with a mobile telescope and planetarium, trying to spark fascination.

Fig. 11

Other projects use participative techniques to reach a greater audience and raise awareness. Examples are the annual event La Nuit Est Belle in the area of Grand Geneva, turning off public lighting for one night during the year and encouraging better lighting practices (*La Nuit Est Belle - Événement Du Grand Genève*, 2023). Similarly, although with the purpose for climate change, Earth Hour organized by WWF encourages individuals, communities, and businesses to turn off their lights for one hour during the year in the time of March (WWF, 2023).

To solve the issue, we first need to become aware of it, and we recognize through these examples that awareness can be an important first step. Nonetheless, awareness will only help to a certain point from where we will need solutions or alternatives. The project/paper „The Light Pollution Kit“ is an interesting work that extends awareness raising, creating a bridge to solutions and implementation. This is achieved by providing an interactive and engaging method kit to educate intelligent illumination engineering to students (Walker et al., 2010).

Fig. 12

From the perspective of concrete approaches to tackle the issue, the picture looks a bit scattered. Many resources and papers discuss and mandate the usage of proper lighting through shielding, reflectors, appropriate light levels, usage of specific color spectrums, and smart technologies to provide a sustainable and needs-based approach to ALAN (Walker et al., 2010; Schroer & Hölker, 2017; Peña-García & Sędziwy, 2020).

Some approaches are, for instance, applied in lighting designs like at St.-Jakob‘s church in Zurich, where stencils are used to shine light only where it is needed, and the Plan Lumiere tries to use sustainable light for historic buildings by using specific and directed illumination in combination with switch-off times after midnight (Esposito & Heizmann, 2021). On private land, one can often find the usage of motion detectors to reduce energy consumption. Although the individual components exist, they are, as far as I can evaluate through the research and my observations, barely used in a combined and effective manner that could minimize light pollution and effects on the environment. The perspective on entirely new and innovative approaches for ALAN is weak.

Franz Hölker and Sibylle Schroer provide, in a paper as an exception, some highly informative and inspiring information in this regard. They propose concrete examples of how ALAN could be implemented in new and more sustainable manners. They also encourage a fundamental rethinking of lighting practices at night by using unconventional methods such as bioluminescence or lighting systems that dynamically adapt to their environment variables, like weather conditions or biological activity from migratory activities of species (Schroer & Hölker, 2017).

Personal Observations and Assessments

My observations show that light pollution intensifies in urban regions, especially near densely populated areas. To quantify these observations, I used specialized equipment and various camera techniques for data collection. By monitoring sky brightness changes, I determined varying switch-off times for local streetlights, suggesting diverse regulations or a lack of consensus among municipalities.

Through the build of an automated gimbal for my camera, I was also able to capture the extent of light pollution from different locations as interactive night sky panoramas. This enabled me to compare different locations and precisely locate areas that emit light into the sky. It became obvious to me how insects might be affected by the effects described previously. In one particular case, the strong light from an industrial zone shone extremely bright into the night sky and was very obvious from a darker natural area nearby.

Fig. 13

In November, I visited an astronomy event organized by AGZO (Astronomische Gesellschaft Zürcher Oberland) near my village. Through exchange with the astronomers, I found that their work is more and more affected by light pollution as well. They are especially blinded by the lights mounted on a house facade close to the observatory. The lights are installed purely for aesthetic purposes and stray a lot of light into the environment. We should ask ourselves the question if it is necessary for lights to be on the entire night if their purpose is for aesthetics and not for safety.

I‘ve noted some instances where ALAN is used sustainably. In my village, certain streetlights have shields to minimize light trespass and glare for adjacent houses. Furthermore the lights switch off after 12pm.

As discussed in the previous sections, we know that methods and technologies exist today, which could reduce light pollution. Through observations I made and the knowledge I gathered in my research, I came to the conclusion that those assets could be deployed in a combined and much more effective manner while setting the direction for new innovative and more sustainable future lighting practices. A notable experimental initiative project I discovered is an experiment from 2022 by the town of Fribourg. The city experimented with dim red solar-powered LEDs installed on the ground to guide pedestrians at night. Additionally, they explored using phosphorescent glowing stone materials as alternatives to traditional ALAN (SRF, 2022).

2.5.1

Research Question & Hypothesis

Through my observations and the research conducted, I formulate my research question as follows:

How might we develop a better solution for artificial light at night for pathways, respecting the nocturnal needs of both non-human and human actors in our ecosystem?

I hypothesize that by using a diverse subset of technologies and methods, it is possible to formulate a solution for a new luminaire design that goes into a deeper relationship with its environment, by considering the needs of humans, such as providing necessary nighttime visibility, but also by considering the nocturnal dependencies of many organisms in our ecosystem. Achieving this goal will necessitate finding answers to specific questions such as:

How might we provide a method allowing for flexible and precise illumination?

How might we achieve adequate visibility with minimal light intensities?

How might we reduce the attraction rate of insects to light sources?

2.6 Envisioned Methodology

In the initial concept phase, collaborating with experts will be key. This includes light pollution specialists, such as DarkSky Switzerland, who can offer insights into local conditions. Additionally, light design experts knowledgeable about current technologies and methods are important. Collaboration with environmental experts is also crucial, as they can provide information on nocturnal species‘ needs in natural habitats.

I want to mention that my process and outcome will probably focus on areas with less safety relevance, as, for instance, addressing street lighting scenarios is beyond the scope of this BA thesis due to stringent regulations (Esposito & Heizmann, 2021). Instead, I find pedestrian pathways, natural areas, parks, or along the shoreline of lakes interesting. These places could provide potential ground for my exploration of alternative lighting approaches. Considering that even those scenarios probably underline strict approvals as well, I potentially see my work as a speculative outcome that offers a new perspective on possible lighting solutions.

After my research and consultation phase, I will start to build first prototypes by combining different technologies and approaches. It will be crucial to figure out how different people perceive my prototypes. I am interested to see how we could take advantage of human mesopic or scotopic vision which is proportionally more sensitive to lower light levels (Peña-García & Sędziwy, 2020).

3 Lighting Our Way with Minimal Impact

Fig. 14

3.1
A Lack of Optimized and New Solution

The rise of LED technology gave us many advantages, such as high efficiency, more control over the color spectrum, being able to dim the light with affordable hardware, and use them in various different scenarios. Furthermore, the technological landscape around LEDs has evolved as well. Sensors and other hardware have become more accessible and affordable. For instance, motion detector sensors that use radar instead of infrared and offer more functionality and reliability are even available today to private users for relatively low cost. Furthermore, new manufacturing technologies have become available today that were impossible or very expensive in the past.

These things are not necessarily directly related to light pollution, but they could potentially contribute to a significant reduction of the issue when combined in an intelligent manner, merging all of their strengths and allowing us to have more control over ALAN. It is good to see that some of these technologies are already being implemented in the urban landscape. For example, a growing number of street lights start again to use LEDs with warmer color temperature, and there are even some locations in Switzerland that have started to implement motion detection. Nevertheless, most of the time, I still see the same old and inefficient polluting lighting fixtures that waste energy, disrupt ecosystems, and obscure the beauty of the night sky.

In November 2023, I took part in the annual DarkSky International Conference, a global gathering dedicated to addressing the issue of light pollution. I participated in a workshop that was tailored around the topic of sustainable outdoor lighting practices. I found it generally interesting, and I learned some new aspects. Nevertheless, I was a bit disappointed, because I expected the discussion of new, innovative, and bold approaches that would go beyond the common knowledge one can find in literature or on the internet.

I noticed a similar trend during my research. Here I came across literature and other resources that discussed the issue of light pollution in detail.

Most were about discussing how the issue is caused, what the effects are, and how politics or societal aspects play a role, or it was simply about raising awareness in the public domain. A smaller fraction was about discussing potential solutions, and often, those discussions only touched the known basics. I wished that there was more research on new innovative approaches that try to think outside the box.

I believe we have nowadays in our advanced technological landscape the privilege and responsibility to reimagine artificial light at night by using all of the available technologies that can contribute to the reduction of light pollution. We should try to find a balance between our needs and the best for our natural environment.

Before I go into a detailed description of my concept, I will show how specific projects and my own observations inspired my direction.

Factors of Influence: Projects

It was early in my research phase when I first discovered an intriguing project through a short segment in an SRF contribution video on light pollution (SRF, 2022). This project stood out to me as it diverged from the common practices aimed at reducing light pollution. The segment showcased how the town of Fribourg in Switzerland began in 2022, testing the use of glowing phosphorescent paving stones and small solar-powered LEDs inserted into the pavement as alternative forms of artificial light at night. Unfortunately, at that time, I was unable to find more detailed information about the project. However, later in February 2024, I had the opportunity to interview Jérôme Mayer, who is the scientific assistant in the city's ecological transition sector and who was part of the project. This interview allowed me to gain deeper insight into the technical aspects, objectives, and preliminary outcomes of their project.

The city's goal is to transition its lighting strategy to a more sustainable approach on a large scale over the next 10 to 15 years. They are employing various techniques and technologies to reduce light pollution and its impact. For the existing infrastructure, they have introduced a so-called „Smart City Box", which enables the lighting systems to be programmatically adjusted in terms of light intensity and shut-off times. Mayer informed me that the town has reduced the brightness of some lights by up to 70% during specific hours. Astonishingly, up to 10% of streetlights have been turned off completely, with no operational time remaining. Moreover, they are transitioning to warmer light colors. For commercial and central areas, a color temperature of 3000K (Kelvin) is employed, while historic areas use 2700K to provide a cozy and historical ambiance reminiscent of firelight. For high biodiversity areas, such as along the river and where the impact on the natural environment is a significant concern, an even warmer and softer color temperature of 2200K is utilized (J. Mayer, personal communication, February 14, 2024).

Fig. 15

I am encouraged to see that more regions are beginning to adopt new lighting strategies to mitigate the impact of ALAN. I believe this will lead to a more pleasant nighttime experience overall, particularly since I find warmer light to be more comfortable and aesthetically appealing. However, the most fascinating aspect, in my opinion, is the incorporation of tiny solar-powered LEDs into the pavement in the form of cobblestones. I admire this innovative approach, including the use of phosphorescent paving stones. It represents a very different approach to utilizing ALAN. In the case of the LEDs, the emitted light is orange-red, and the light levels are low. For the phosphorescent material, the color tends to be more turquoise or blue, which is generally not recommended. However, the light levels are in this case very low compared to standard lighting. It‘s important to note that the primary goal here is not to illuminate the ground but rather to guide pedestrians through the darkness, ensuring they stay on the path.

Jérôme Mayer also shared insights into the feedback received from the public, which I found to be very intriguing. I was not permitted to disclose the full details of their user survey, but I can share that the general response was positive, with about three-quarters of the feedback being favorable towards the new lighting methods. Some respondents even mentioned that the new lighting approach has brought back appreciation for the nocturnal and natural beauty around the lake and were comparing the lights to candles in the night. The remainder of the feedback was a mix of neutral and negative reactions (J. Mayer, personal communication, February 14, 2024).

Fig. 16

Furthermore, Mayer mentioned that, despite initial concerns, there has been no increase in safety issues in areas with reduced or no lighting. The local police have not reported any problems attributable to the decreased lighting levels (J. Mayer, personal communication, February 14, 2024).

I view their initiative as a pioneering step that has informed my approach: They have demonstrated that it is possible to adopt innovative approaches by exploring new form factors and technologies and utilizing low light intensities by primarily using the lights as navigational aids rather than for area illumination. Of course, this approach is not universally applicable. There will be scenarios where clear visibility of one‘s surroundings or pathway is necessary, whether for safety reasons or simply to provide a sense of security. Furthermore, their approach poses several disadvantages in certain situations, such as snow or bad weather, as the light solely relies on solar power. Additionally, their lights are not really interactive or adaptive, regarding changes in the environment.

3.3 Factors of Influence: Observations

Light pollution is a highly complex and multifaceted issue that stems from the entire usage of artificial light at night. A view from space down onto Earth makes the widespread nature of the issue visible.

Fig. 17

The diverse appearance of luminaires, from technology to form factor, makes it difficult to tackle the issue with a single approach; it is virtually impossible to find a perfect solution. From an environmental perspective, it would imply that we would simply switch off or remove all the lights at night, which is not feasible in all cases. What we can do instead is improve the existing situation and provide new systems for future scenarios.

Because of the complexity of the issue, I have decided to focus my BA thesis and practical work on a specific scenario where I see potential for a new approach and an improvement of the situation that could potentially contribute in a positive way to the larger picture over time.

Over the past few months, I have made observations of my surroundings to identify situations that could be interesting for my thesis. I observed how different types of luminaires are utilized for various purposes across different locations. For instance, we find the classic streetlights in huge numbers all along main and residential roads. They come in various form factors and often exhibit different color temperatures. However, the general consensus is that the light emitter is installed on a high pole with an arc shape that positions the light and reflector above the street. This common design of streetlights might be well-suited for road situations where safety is important, as the height of the light allows a large area to be illuminated. Unfortunately, this type of luminaire also exhibits poor characteristics that contribute to light pollution, or they simply lack the modifications that could lead to improvements. The reflectors often act solely to redirect upward light downward, which is desired, but the downward-reflected light is then dispersed into surrounding areas, which may include meadows, forests, or the nearby gardens of people, areas that can contain high biodiversity. At times, I have also noticed reflections from nearby materials scattering the light in all directions, including into the sky. Moreover, many lights still use neutral white or cool light, whereas it is recommended to use warmer colors such as 3000K to 2200K, or even orange and red light (J. Mayer, personal communication, February 14, 2024). Furthermore, many lights remain on the entire night, even if they are not used, as they lack motion detectors.

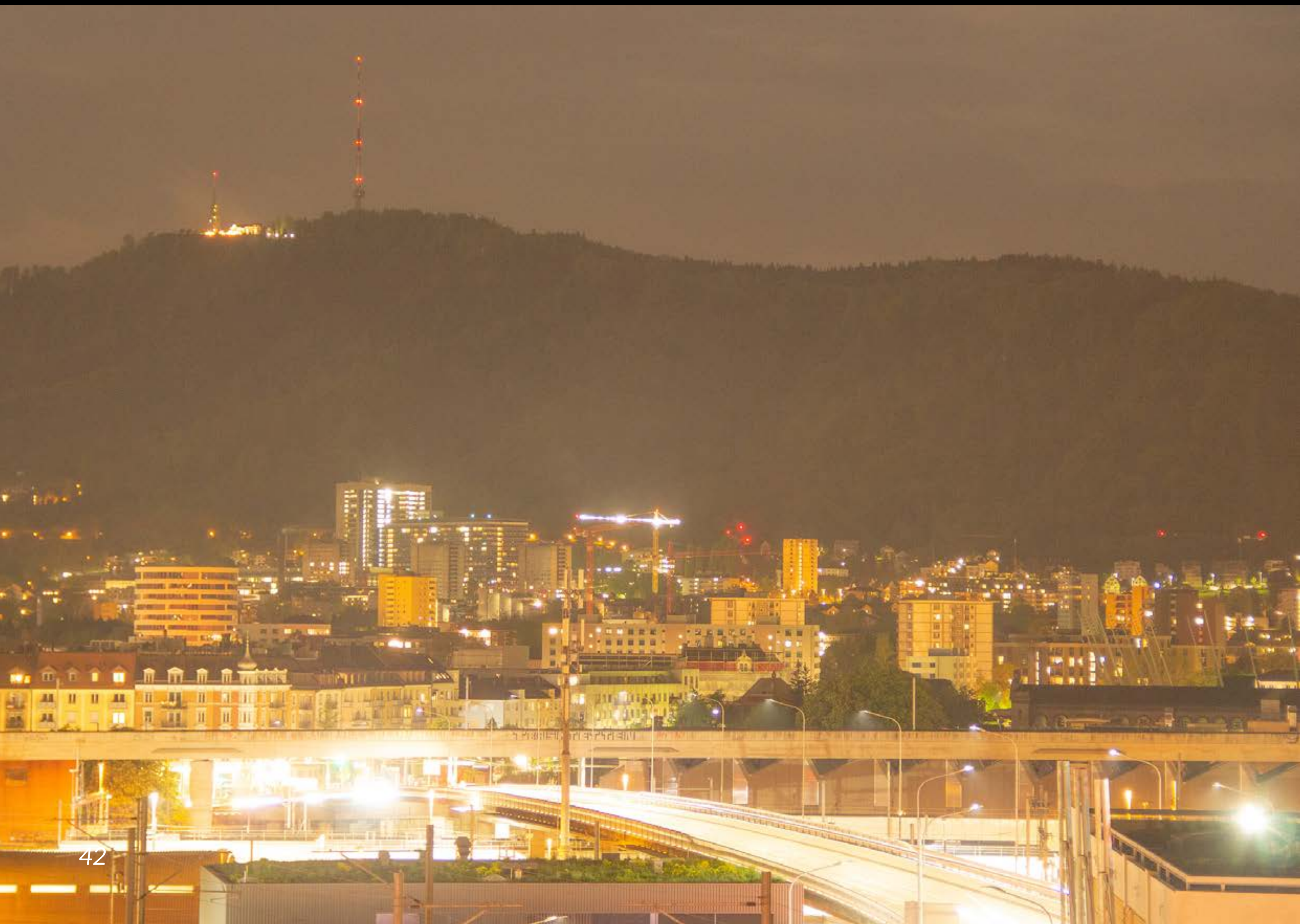
The most significant issue I have observed in almost all cases is glare or direct blinding. This occurs when the eye has a direct line of sight to the light emitter. Unfortunately, this is somewhat unavoidable with typical streetlights or other high-mounted lights, where the light is installed above human eye height. The issue is that at some point, one will inevitably cross the direct path of the light rays emitted from the luminaire. This can cause an immediate reduction in night vision and causes afterimages.

It is interesting to note here that we often underestimate the capability of human night vision. Remarkably, our retinas can detect a single photon, but to avoid visual noise, neural filters only process a signal if 5 to 9 photons arrive within 100 milliseconds (Gibbs, 1996). Many people seem unaware of our abilities, likely because we‘re constantly bathed in bright lights. Through my experiences with astronomical observations and astrophotography, I‘ve often experienced how our vision adapts to the dark after just a few minutes of adjustment, but can easily be disturbed within fractions of a second when looking into bright light such as glare.

If we could completely avoid glare and blinding, our eyes could better adapt to darker environments, thus reducing the need for stronger nighttime illumination, achieving more with less. I consider this aspect as very important, and it will play a crucial role in my concept.

If we take a nightly walk through Zurich or any other town, it will quickly reveal numerous light sources that significantly contribute to light pollution and glare. The sources are varied, encompassing billboards, aesthetic illumination of historic buildings, lights from commercial buildings and offices, private use of artificial light, traffic lights, and lights for high-safety areas such as railway stations or other important areas, to name just the main categories. Within these categories, both the technology and form factor vary as well, making the search for a universal approach to reduce light pollution particularly challenging, if not impossible. Additionally, luminaires that are related to safety are very hard to tackle due to strict norms.

Fig. 18

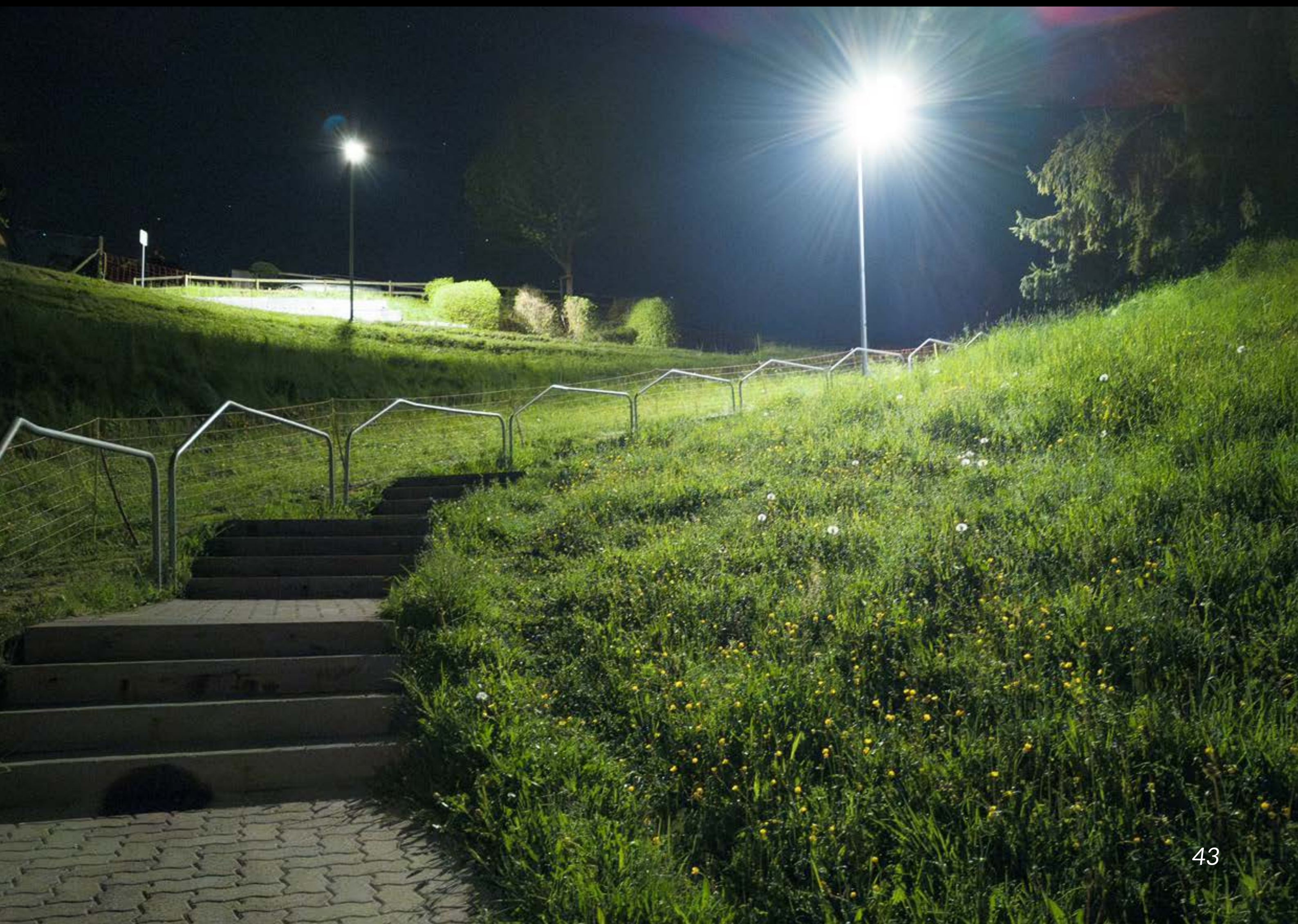


However, during my observations, I found it particularly interesting how common streetlights or other high-mounted lights, not optimized to reduce light pollution, are used to illuminate pathways for pedestrians, even if those are far removed from high-traffic streets. I identify the following areas: lake shorelines, parks, jogging routes, pathways connecting residential areas, and in residential zones themselves where car traffic is generally not permitted or is rare.

Due to the reasons mentioned above, I will focus my concept on scenarios of pathway lighting illumination that include those areas. These locations present an excellent angle for my BA work and pose an opportunity to reduce light pollution for several reasons:

The luminaires used are often not optimized; the scenario is approachable as the main intent is to illuminate a path; furthermore, safety and norms are less of a concern and the total number of those areas is likely to be quite high throughout urban regions. All of this offers a promising and versatile scope for the focus of my BA concept and the resulting practical prototype.

Fig. 19



Concept Description

At the beginning of this chapter, I have briefly touched upon the potential of leveraging modern technologies in synergy to enhance our current situation. I view specific areas such as shorelines, parks, jogging paths, or other pedestrian pathways as prime opportunities for introducing innovative and improved approaches to ALAN within the scope of my BA thesis. Therefore, I propose a customizable and modular outdoor lighting solution, designed from the ground up to minimize light pollution and its effects on the environment. This approach promises enhancements and presents an alternative approach for Artificial Light At Night compared to the static and fixed luminaire designs that exist. The customization aspect broadens its applicability across various settings in these areas by allowing lighting to be tailored to specific area needs. Moreover, the modular design facilitates the incorporation of technologies, such as sensors, optimized reflectors, and LEDs, which provides control mechanisms over how the light is used, aiming to make proper use of ALAN easier for the user.

Modules and Componets

To achieve my goal, it is necessary to identify the parameters that need to be covered by the design approach. This includes control over the height of the light, adjustment of the light beam in x and y, the shape of the beam, and control over light intensity and color temperature or spectra. Furthermore, the design could include possibilities for incorporating different sensors and features. One module can offer space for various sensors, such as motion detector sensors or other environmental sensors like photodiodes, to trigger and control the light in different circumstances. Open-source electronics, such as the Arduino platform, provide interesting hardware that extends the freedom of customization and makes it easy to add new functionalities to the luminaire.

Through this design approach and by using symmetric geometries such as cylinders and spheres, we allow for the adjustment of the light‘s height and direction while providing space for additional components. I envision three main module categories within the design, each allocated to different purposes.

The bottom and first module would serve as a base, securing the luminaire in its location on the ground. It would also host the incoming cables to power the light and offer space for possible electronics. Additionally, it could include the capability to house a rechargeable battery for off-grid operation in combination with a solar cell. This module will also feature a small red indication LED, optionally to be used as a navigational aid in a series installation. This idea is inspired by Fribourgs lighting concept. The LED can indicate and outline the pathway direction ahead, until the main lights of the luminaries will switch on as motion sensors detect the presence of the pedestrian.

The second module acts as a spacer module, allowing for the adjustment of the light’s height.

I consider the height aspect in my concept as important because it is directly related to glare, which I previously discussed. If the light source is at or above eye level, glare becomes unavoidable. Therefore, my approach is a low-profile solution where the light and reflector should be installed between 60 and 100 cm in height. I assume that restricting the light beam only to the pathway area in combination with a low height of the light emitter could be beneficial for the environment, particularly for insects. The light would not be visible from nearby areas, such as high biodiversity areas, and the light rays would travel through less air space, potentially affecting fewer insects flying in the air. However, finding a compromise for the height is crucial because lowering the light‘s placement makes it more challenging to distribute it over a larger area.

Shadows will also become more pronounced with a lower angle, and the characteristics of the ground, such as evenness and flatness, will play a critical role in determining the best placement. Therefore, I see the spacer module as an important part for adapting the luminaire to specific locations.

The third module focuses on the lighting element itself, incorporating a reflector system designed to direct the light beam precisely where it‘s needed. It‘s crucial for the beam to have a sharp cutoff line to ensure it extends only to the border of the street or pathway and no further, unlike regular lights that illuminate surrounding areas. This approach guarantees that high biodiversity regions, such as meadows, remain unaffected by artificial light.

To develop a reflector design that meets the specific requirements of my project, I have explored various car headlight designs for inspiration. Many car headlight designs are engineered to produce sharp cutoff lines to minimize glare and prevent blinding. Furthermore, an adjustable LED sliding mechanism will provide additional enhanced control over the width and shape of the light beam.

All those components for the reflector, including the reflector itself, are installed in the third module which I call “head.” The head is basically a sphere, interlocked on a rotating platform below. This allows the entire reflector to be rotated by 360° and tilted by about 40°, providing control over the direction, throw distance, cutoff, and shape of the light beam.

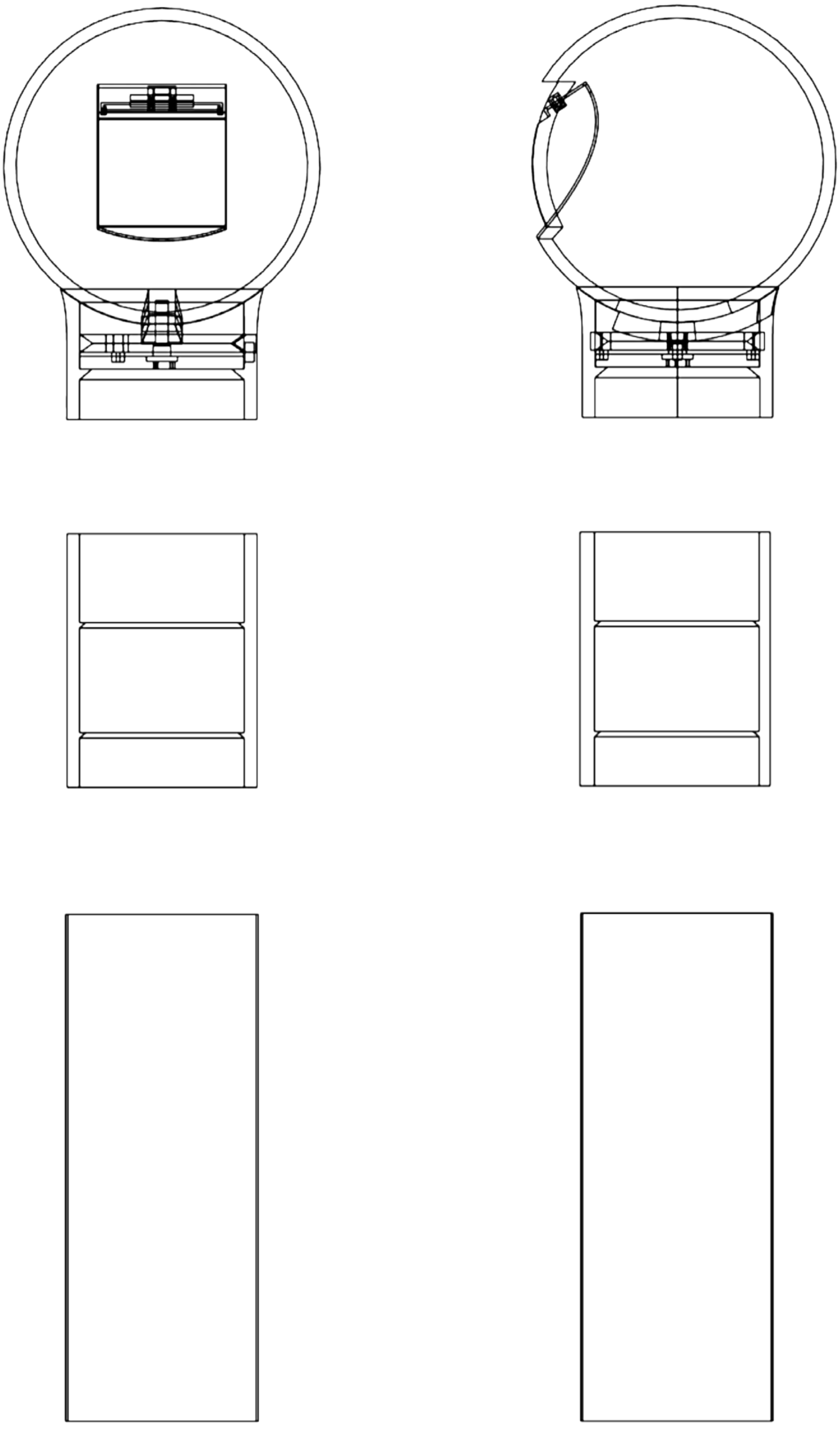


Fig. 20

3.4.2 Agency to Environmental Factors

The head will feature two motion detector sensors, one on the left and one on the right side of the sphere. These sensors could be seen as an analogy to the ears, as they are monitoring at head in opposite directions. This will allow the luminaire to be active when pedestrians come by and automatically switch off when not needed, thus saving electricity and preserving the nocturnal environment.

It is here, where an open-source hardware platform, such as Arduino, will come in very handy. In my prototype, I will use an ESP32 as they also offer wireless communication over WiFi and Bluetooth. This could allow a series of luminaires to interconnect and exchange data. An Arduino-compatible platform could allow for the programming of interesting and useful behaviors that would automatically interact with the environment. For example, as already implemented in other systems, the light could “wander” with the pedestrian, always encompassing them in a following light trail. It could be decided whether the lights would dim down afterward to a minimum level or switch off completely. Open-source hardware would allow easy programming of even more detailed behaviors. During my research, I came across a paper that discussed how insects might change behavior depending on factors such as the moon cycle and weather conditions (Eisenbeis & Hänel, 2009). The luminaire could react accordingly to those external factors by adjusting its light intensity and color spectrum. Either the head could offer enough space to incorporate the necessary hardware, such as ambient light or humidity sensors for weather and moon condition sensing in remote areas, or the luminaires could interconnect with an external remote real-time database to provide the necessary information.

My final prototype will offer the hardware and functionality to potentially address the above-mentioned criteria. But in a further iteration, this concept could be spun even further. Environmental data could be incorporated and managed by using sophisticated algorithms or AI, to adapt the lighting of large urban areas even further to external factors such as bird activity or nighttime bird migration. Furthermore, the light could mimic a temporal color temperature shift, inspired by the shifting color temperatures that we can experience in the morning or evening hours. For example, in early evening hours, the light could be close to neutral white, while slowly shifting to warmer color temperatures during the night and affecting less the circadian rhythm of humans, featuring dynamic light aesthetics.

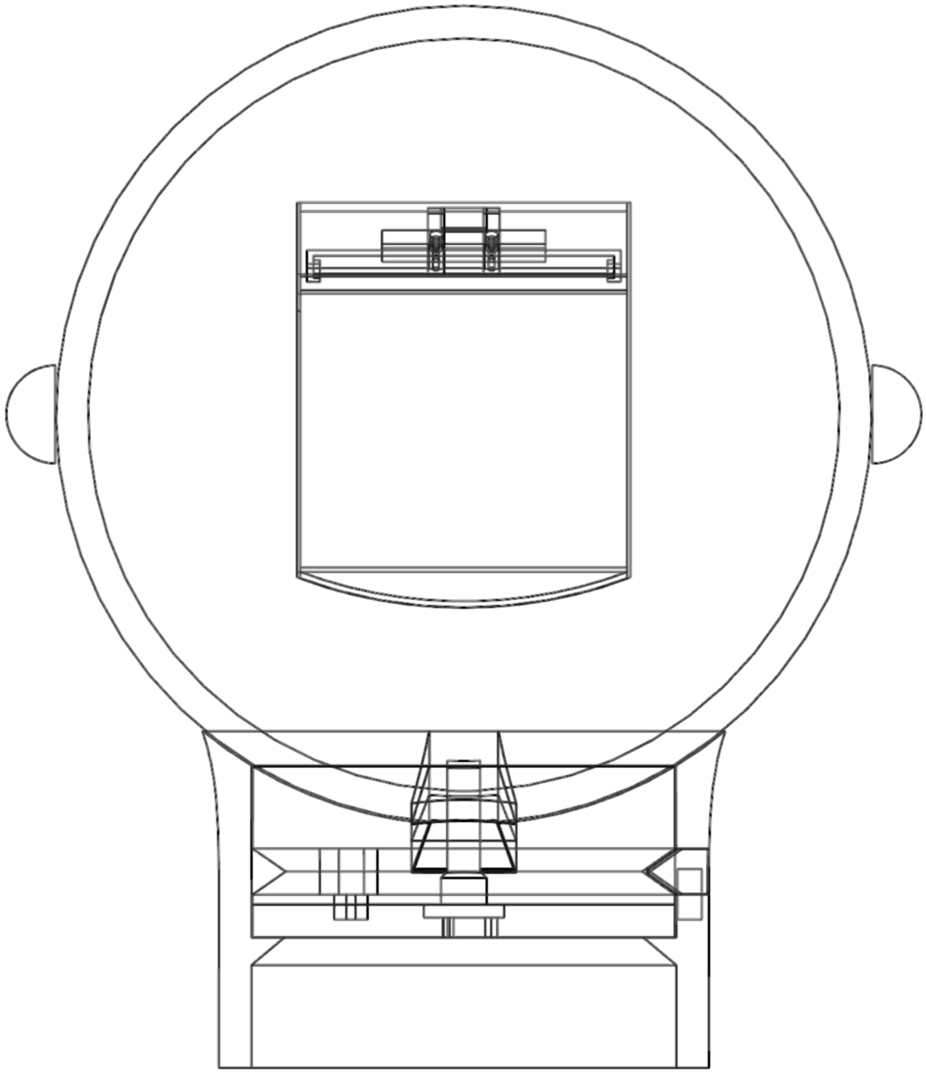


Fig. 21

3.4.3 Light Spectra

One very important aspect of my final prototype is color temperature and specific light spectra. I see light spectra as an additional aspect of the customization part of my approach. It will allow the user to better fit the light into different environments that pose varied needs. Therefore I have decided and defined three modes:

Eco Mode: The Eco Mode focuses on high biodiversity areas or dark sky reserves, where protecting the night has the highest priority. In this mode, pure amber LEDs are activated and produce a narrow light spectrum around the wavelength range of 595 nm. The light produced is monochromatic and close to the red part of the spectrum; it resembles light emitted by sodium vapor lamps. This spectrum is less harmful to many nocturnal animals, especially insects, as the light contains no blue. Furthermore, due to its longer wavelength, Rayleigh scattering, causing sky glow, is drastically reduced. The narrowness of the spectrum would also allow for easy filtering out, e.g., during astronomical observations.

Low Intensity Mode: The Low Intensity Mode should be considered as an experimental mode that uses pure green LEDs, emitting light at around 525 nm. By using this color range, we can leverage the highest sensitivity of the human eye, as scotopic and photopic vision have peak sensitivity in this wavelength. This potentially allows us to use very low light intensities compared to other colors, especially orange or red. This mode is strongly dependent on a good reflector and shielding design to avoid glare. By completely avoiding blinding, glare, and direct eye contact with the light emitter as provided with my reflector, we can achieve high visibility with very low light intensities. This results in lower electricity consumption while potentially also affecting the nocturnal environment less, compared to white light.

Urban Mode: The Urban Mode allows the user to freely define a color temperature between 6000 and 1800 Kelvin. The mode uses two different LEDs, producing pure white, up to highly warm white, resembling that emitted from a candle flame. The potential for this mode ranges from urban to rural areas. For places where a higher alertness is required, such as close to railway stations, pure white (6000K) could be used. A color temperature of 6000K already contains a significant amount of blue components; therefore, this color temperature should only be used if necessary. However, due to the effectiveness of the reflector and the head mechanism, the pure white is acceptable for certain situations in this case. For other areas, especially where the blue light components should be reduced, the luminaire could gradually be set to warmer color temperatures, down to 1800K. The Urban Mode mode could easily be used for the aforementioned dynamic light aesthetics, where the luminaire could shift overnight in color temperature.

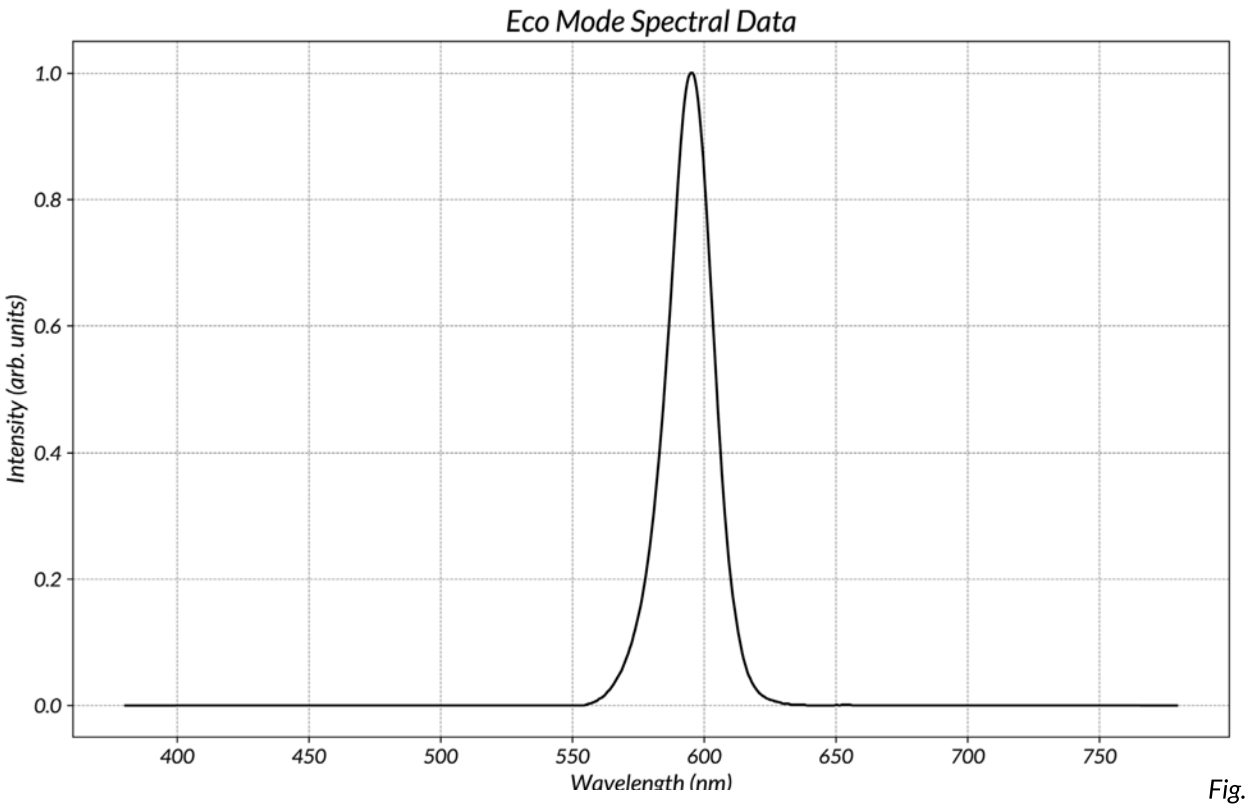


Fig. 22

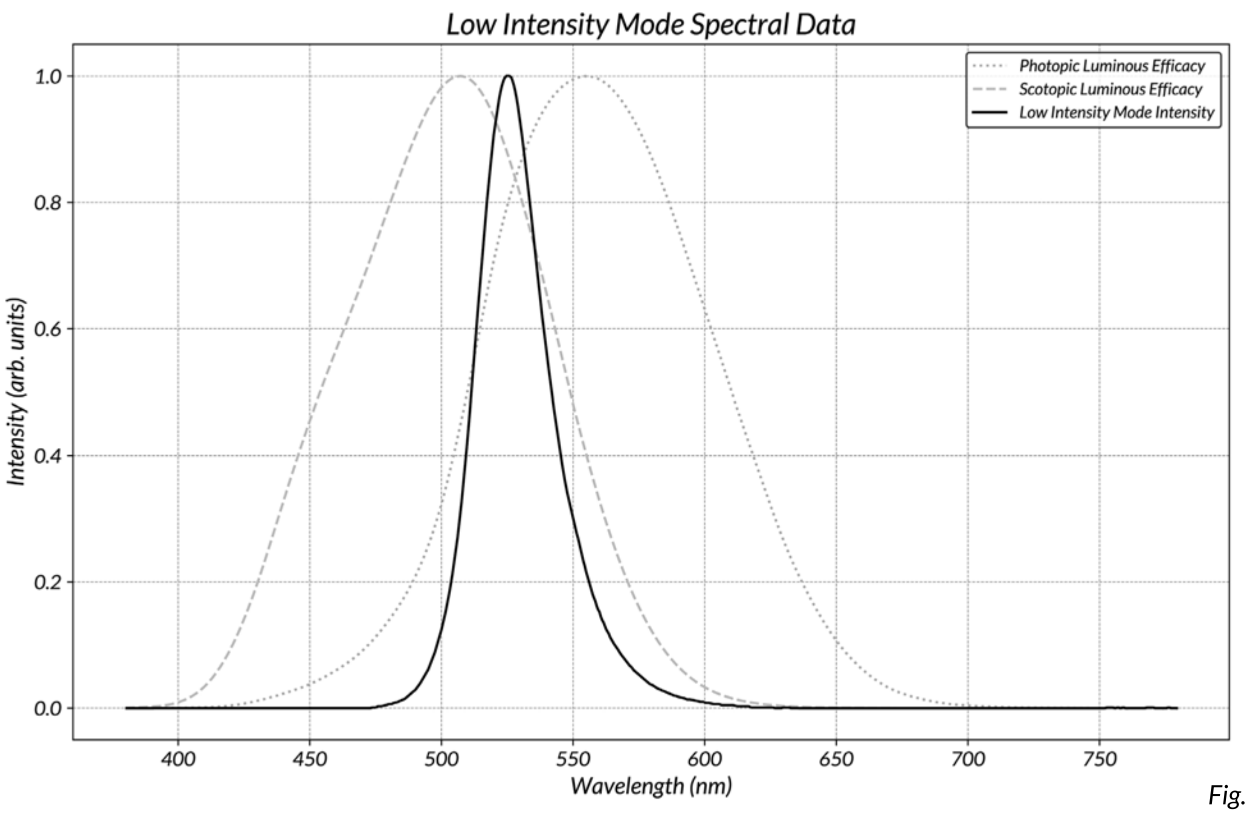


Fig. 23

Fig. 24

Urban Mode Color temperatures 6000 to 1800 Kelvin

These three modes will be implemented into the final prototype. However, if the project would be developed further, it could be worth investigating even deeper into the use of color spectra. As LED technology has made significant advancements, it is nowadays easier and cheaper to source diverse technology in this field. During my research, I found that the entire visible light spectrum can nowadays almost be covered by individual LEDs producing specific color ranges. This means that we could literally produce white light, not only by using white or RGB LEDs, but by using much more defined values of light. Therefore, I would suggest research into an experimental full-spectrum LED that uses individual LEDs to reproduce any spectrum needed. This would provide ultimate control over the light and one could tailor it very precisely to local needs. If, for instance, an endangered nocturnal species would require special care, one could tailor the lighting specifically to it. As the real-life applicability of such a lighting system is still speculative and could be expensive, I am also suggesting a simplified alternative. This light would use “RYGCB” (red, yellow, green, cyan, blue) LEDs to achieve white light. This composition of LEDs would still allow much more freedom than a standard white or RGB light source.

Comparison to Other Designs and Projects

I compare my strategy of providing a new design for artificial light at night to the concept of ‚fighting fire with fire.' By offering a sustainable lighting design that uses artificial light more effectively and intelligently, we can reduce light pollution and eliminate the need for poorly designed lighting fixtures.

Compared to other projects and designs, I see my approach as a variant or iteration of current lighting solutions, leveraging technological aspects to minimize the environmental impact of artificial light at night. During my observation phase, I frequently encountered smaller lights similar in height to my design. However, these outdoor luminaires were static, offering no interaction, customization, or responsiveness to their environment. The most significant drawbacks I found were poorly designed reflectors and light colors, which resulted in excessive light spillover and glare, including the use of cool color temperatures.

In comparison to the lights used by Fribourg, as described earlier, my concept is intermediate between theirs and common lighting concepts. It also brings in environmental consciousness by making the light customizable and reactive to the environment.

Fribourg presents a minimalist approach to artificial light at night with innovative uses such as tiny solar-powered LEDs and phosphorescent paving stones, which serve as navigational aids by outlining paths at night. This approach minimizes light pollution, however, such solutions may not be universally applicable. In certain scenarios, area illumination is necessary due to safety concerns, such as on uneven or rocky paths, to provide a sense of safety or simply for enhanced visibility and aesthetics. Additionally, the compact size of these ground-embedded lights presents challenges in conditions like maintenance, leaf cover or snow, potentially covering solar cells and disrupting battery charging, especially since these lights lack external electricity options.

Fig. 25

During my research, I came across a compelling project titled "Performing Light: The Impact of Public Lighting in Informal Settlements in Cape Town". This initiative, led by ETH researchers Stephanie Briers and Yael Borofsky, may not directly address light pollution. However, it broadened my perspective on how my work could extend its impact beyond my immediate locality. The project introduced wall-mounted solar-powered lights in informal settlements around Cape Town as an alternative to traditional high-mast lighting, which often leaves the spaces between settlements in darkness. This intervention made these areas more accessible and safer at night (Briers & Borofsky, n.d.; GreenCape, 2022).

Fig. 26

I was particularly inspired by the collaborative effort of the community to bring this project to life. It made me envision how my design could similarly benefit developing urban areas by providing a sustainable and environmentally friendly lighting solution, as opposed to the prevalent use of unshielded floodlights. However, I recognize that adapting my current concept to such contexts would require consideration of challenges such as vandalism and high manufacturing costs in its current form.

On the other hand, I can definitely envision my approach being applied in more developed countries and nations that are increasingly shifting towards future cities and exploring how we might integrate more harmoniously with nature. In this regard, I engaged in a discussion with Dr. Julio Paulos, the associate director and researcher at the Future Cities Laboratory at ETH. His team focuses on merging sustainable urban planning with cutting-edge technologies to forge cities that are more resilient and efficient for the future.

I was somewhat surprised to learn that they have not yet conducted specific research or projects on how ALAN can be utilized in future cities in a more sustainable manner. However, this revelation also highlighted the potential for my project to make a significant impact in the future. I could very well envision a future research team dedicated solely to discovering new, innovative, and sustainable lighting methods for future smart cities.

4 Conceptualizing My Prototypes

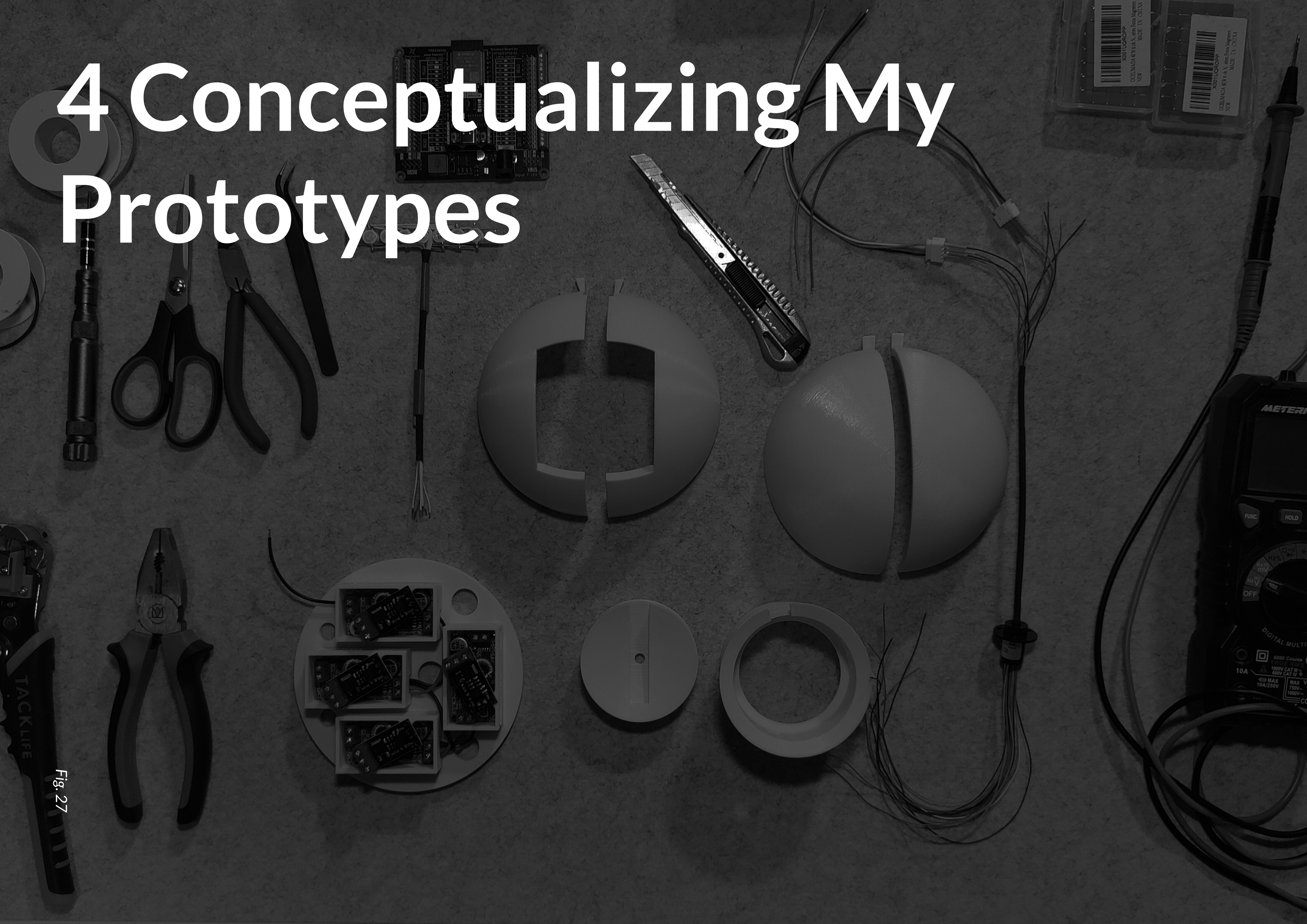


Fig. 27

The Foundation: Insights from the Concept Seminar

From January 8th to January 19th, we engaged in the concept seminar as preparation for the BA thesis. This seminar aimed to set us on a course for the weeks and months ahead. It was an intense two weeks, during which I enjoyed generating numerous ideas, ranging from feasible ones that could be implemented to far-fetched concepts that seemed more at home in the realm of science fiction.

By the end, I had developed two main conceptual directions, which I showcased during the final presentation of the concept seminar through a short video.

The first concept revolved around smart modules integrated with a token system. The notion was to incorporate these electronic components into the existing lighting infrastructure, thereby making the lights ‚smart.' This meant the lights could be programmed to exhibit specific behaviors to minimize light pollution. This system could be operated using a token or an app in conjunction, allowing communication with the infrastructure. An interesting aspect of this could have been the personalization of ALAN. Individuals could have the ability to set their personal minimum requirements for ALAN, for example, for street lighting.

However, I soon realized that pursuing this direction might lead to a dead end for my practical work. This was because similar systems already exist and are being implemented (e.g., Smart City Box in Fribourg). Additionally, the diverse technological requirements of lighting systems would have posed significant challenges for me. Furthermore, I began to question the added value and effectiveness of personalizing ALAN through a token.

My second conceptual direction focused on a modular outdoor luminaire designed to mitigate light pollution. This design included individual modules that could be customized for specific local needs, while addressing key factors to reduce light pollution. Initially, I saw this approach as a viable solution for developing countries, where communities are increasingly transitioning from no light to poorly designed LED lighting as they become more affordable.

The envisioned design included several features: a filter system to modify the light color, exchangeable motion detectors adaptable to various scenarios, an efficient reflector design to minimize glare, and the integration of solar cells to broaden the application possibilities.

Within a week following the concept seminar, I concluded that this concept was the optimal path forward. I felt confident and interested in pursuing this direction further.

4.2 Initiation: Technology Encounter and First Experiments

After the conceptual seminar and establishing the direction, I felt an urge to dive quickly into practical work. Compared to many other projects I undertook during my studies in interaction design, my BA would significantly rely on physical fabrication and experimentation. Therefore, I decided to swiftly gain an overview of the technologies available that I could potentially use for initial experiments. I arranged a discussion with Markus Pericin, who, alongside Florian Bachmann, oversees the management of the Farb-Licht-Zentrum at ZHdK.

I met with Markus and discussed my project with him. It was enlightening to hear his perspective, as it introduced new aspects I hadn‘t considered before. My focus had always been intensely set on reducing light pollution, but his viewpoint also considered how one could make the utilized light aesthetically appealing. It might seem contradictory at first to aim for aesthetic beauty while reducing light pollution, especially since many lighting solutions that use Artificial Light At Night for aesthetic purposes contribute significantly to light pollution and negatively affect the ecosystem around.

However, I believe that lighting designed to minimize light pollution can also be aesthetically pleasing. For instance, one could employ warmer colors or create intriguing light patterns projected onto the ground. Provided the light contains little blue and is used only where necessary—ensuring no light strays into the sky or into unintended areas—I see no reason why playing with light for aesthetic purposes should be discouraged.

Markus introduced me to the various LED technologies available. I found myself particularly drawn to LEDs capable of producing narrow spectrums. He shared insights on true amber LEDs, which can now be manufactured to emit narrow, monochromatic light similar to that of sodium-vapor lamps. Such light, commonly used in street lighting in the past, is less harmful to the environment due to its proximity to the red spectrum and its narrow distribution.

I also explored different methods for directing or reflecting light. Beyond standard reflectors, we discussed grid-like structures designed to modify light beams. Markus also explained how Plan Lumière employs stencils to project patterns of light onto buildings and the potential of using projectors for projection mapping.

The idea of illuminating the ground with lines or dots via a projector, as opposed to the broad area lighting typical of conventional fixtures, intrigued me.

Following our conversation, I returned home with a stage light featuring an interactive mechanism that uses a lens to focus or diffuse the light. Additionally, I acquired a Lee filter set containing numerous sheets with spectral data curves. However, the most significant piece was an Aputure MC Pro video light, equipped with full RGB capabilities and adjustable color temperature.

For my initial experiments with the borrowed equipment, I aimed to answer the following questions, among others:

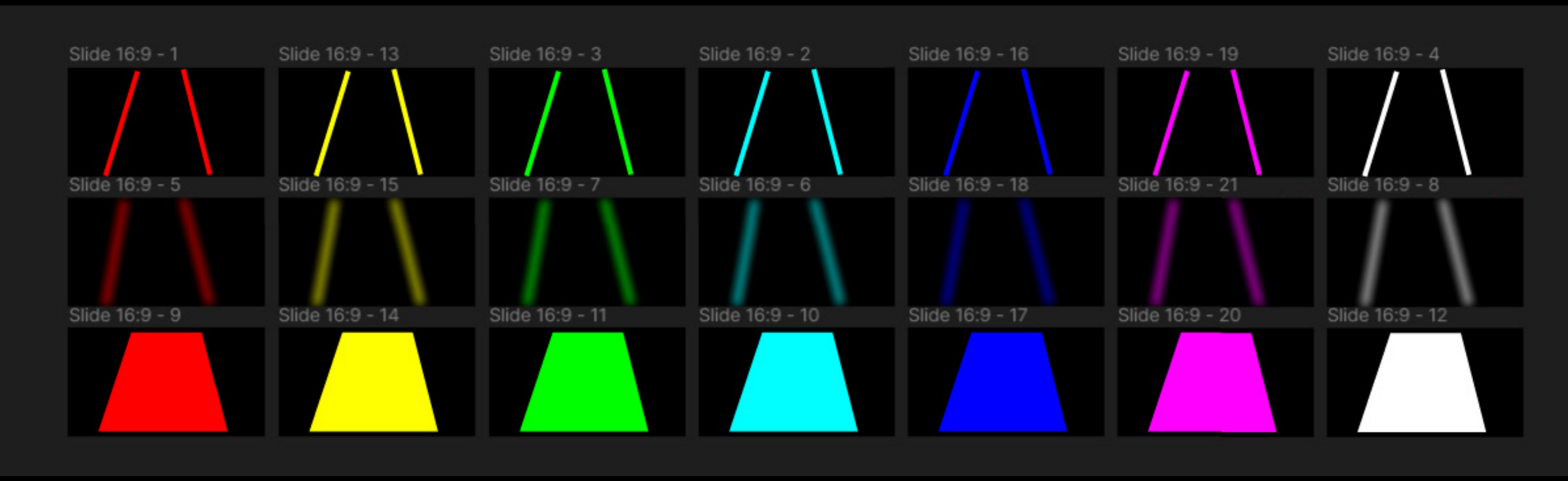
How would the height of a light source affect visibility?

How would color temperature influence visibility?

What kinds of projection shapes and colors could serve as alternative methods for nighttime illumination of streets and areas?

For the projector-related questions, I selected a small, battery-powered Akiyo projector and created some projection shapes and color surfaces using Figma.

Fig. 28



I chose a location near my home but outside the village to ensure no other lights would interfere with my experiments. This spot featured a small street with a variety of surfaces suitable for testing.

Fig. 29

Some of the main discoveries from that night included observations that very low-placed lights could cast stark shadows, yet elevating the light source slightly, to about 40 cm or higher, significantly mitigated this issue. Interestingly, the height of the light source seemed to have minimal impact on visibility distance.

Fig. 30

Moreover, I observed that a warmer color temperature, specifically 3700K, was exceptionally effective for illuminating areas with grass, enhancing visibility even at lower light levels. This could be attributed to the grass's brownish hue, likely reflecting light better within this color range. Conversely, I noted an improvement in visibility when increasing the color temperature from 2000 K to 3000K, finding warmer colors more pleasant than cooler ones. Cooler light temperatures conveyed a sense of sterility and felt somewhat eerie in that setting.

Fig. 31

Experimenting with a projector provided me insights for considering its application for Artificial Light At Night. A significant challenge encountered was the projector's focus plane; when projecting a line or any shape onto the ground, the focus was sharp only at a specific distance, with areas in front or behind appearing blurry. Additionally, the projection's brightness diminished with distance, and the projection expanded in size the further it was cast. Although adjusting the shape of the objects to counteract this issue was possible, it compromised the projected image's quality.

Fig. 32

I encountered an intriguing phenomenon with blue light that was new to me in this intensity. When I projected a blue shape onto the ground and the light intensity of the color was very low, the blue light appeared more blue-grayish, almost as if the color had been desaturated. I speculate this effect may be due to the increased activity of the rods in our retinas at night, which are highly sensitive to light intensity but not to color. Interestingly, I observed a heightened sensitivity in my peripheral vision to blue light. However, what puzzled me was that I did not experience the same effect with green or red projections. The image below offers a representation of how I perceived the situation.

Fig. 33

Additionally, I conducted a visibility test by projecting shapes onto the street to determine which color subjectively offered the best visibility. Below, I have ranked the colors from best to worst visibility based on this test:

1. White
2. Green
3. Cyan
4. Yellow
5. Red
6. Magenta
7. Blue

Fig. 34

To document my experiment, I brought along a Canon EOS M and a fast lens. It was particularly fascinating to observe how the camera responded to different colors and intensities compared to my own eyesight. For instance, as already mentioned earlier, blue appeared pale to my eyes but was captured as saturated intense blue by the camera. To ensure the accurate representation of the camera's recordings, I shot only in RAW format and set the white balance to 5500K. Digital cameras have a great ability to capture color in low light conditions with appropriate exposure times, compared to human eyesight, which relies on monochrome scotopic vision in low light conditions. The RGGB Bayer matrix on the sensor captures red, green, or blue photons, regardless of how low the photon flux is. Furthermore, the quantum efficiency throughout the spectrum can be different and higher compared to the sensitivity distribution of our eyes.§

The images displayed here were edited in Adobe Camera Raw to closely match my subjective experience. It's crucial to view these images as approximations rather than exact representations of the scene I experienced.

Among all the insights gained that night, one in particular stood out to me: the profound influence of glare and direct blinding on night vision. I positioned a flashlight to illuminate a street downward. Walking towards the flashlight, I was blinded and immediately lost my dark adaptation.

In everyday nighttime settings, we are constantly subjected to various lights that produce glare, and we have become used to this, often without realizing its impact. However, during my test in a dark area outside the village, where no other lights were present, the effect of glare was unmistakably clear.

I concluded that developing a design that minimizes glare as much as possible would be crucial for my concept and further procedure.

Fig. 35

Prototype Development

The following sub-chapters aim to provide the reader with a clear and comprehensive understanding of how my practical work evolved over the months. In retrospect, I can identify roughly three main phases that I went through. These phases were primarily defined by the level of experimentation, the knowledge I gained, and the extent to which the physical prototypes were refined. I will conclude each phase with my findings, which guided me to the next iteration and influenced the decisions I made. The conclusion of phase 3, regarding the final prototype, will be discussed in the final conclusion of my thesis.

Fig. 36

Phase One

In my studies in interaction design, I learned that defining the start and end of a prototype can be challenging because the process is continuous from beginning to end. Therefore, I consider the experiments and findings I described earlier as an initial part of the first prototype. These findings, particularly the issue of glare I mentioned, led me to develop the first iteration of a modular outdoor luminaire designed to minimize glare. This prototype was to include the capability to adjust light at various angles on a horizontal plane and feature exchangeable shielding modules. Adjusting the height of the light was crucial for me, allowing it to align with the angle of the shielding I later developed. Furthermore, I planned to incorporate some first sensors to make the light interactive to its environment.

I decided to create individual, symmetrical, and stackable cylinders to house the functionalities and parts such as the electronics, shielding, and sensors. For an easily manipulable prototyping material that would provide volume, I chose polystyrene. This material is simple to cut with a hot wire machine and is also affordable.

On February 13th, I began cutting the material in the low-level workshop at ZHdK, and over the following days, I prepared the individual parts, including some initial 3D prints. For certain features, like the housing chambers for the LEDs I intended to integrate, I had to plan carefully and employ some tricks with the hot wire machine.

Fig. 37

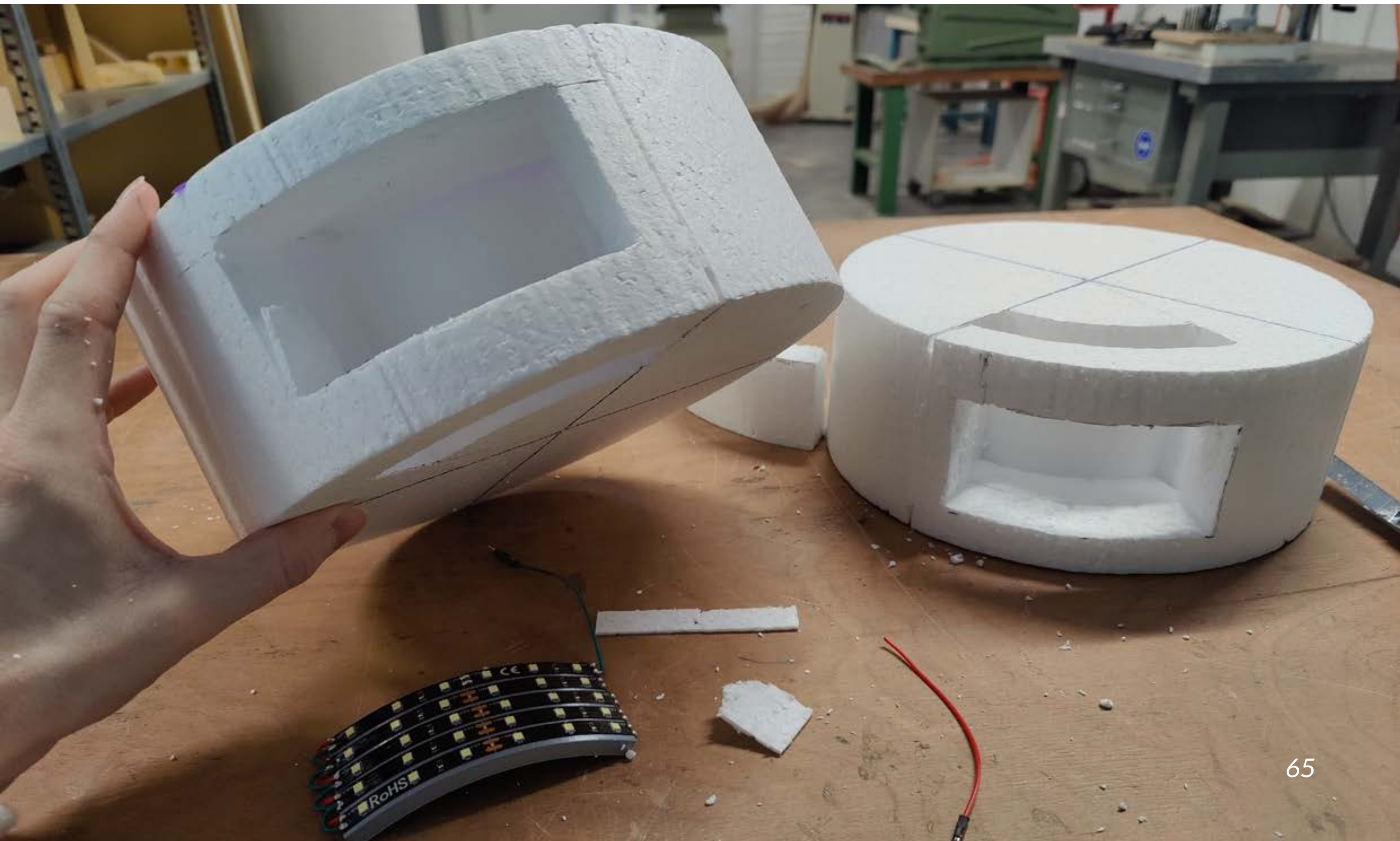
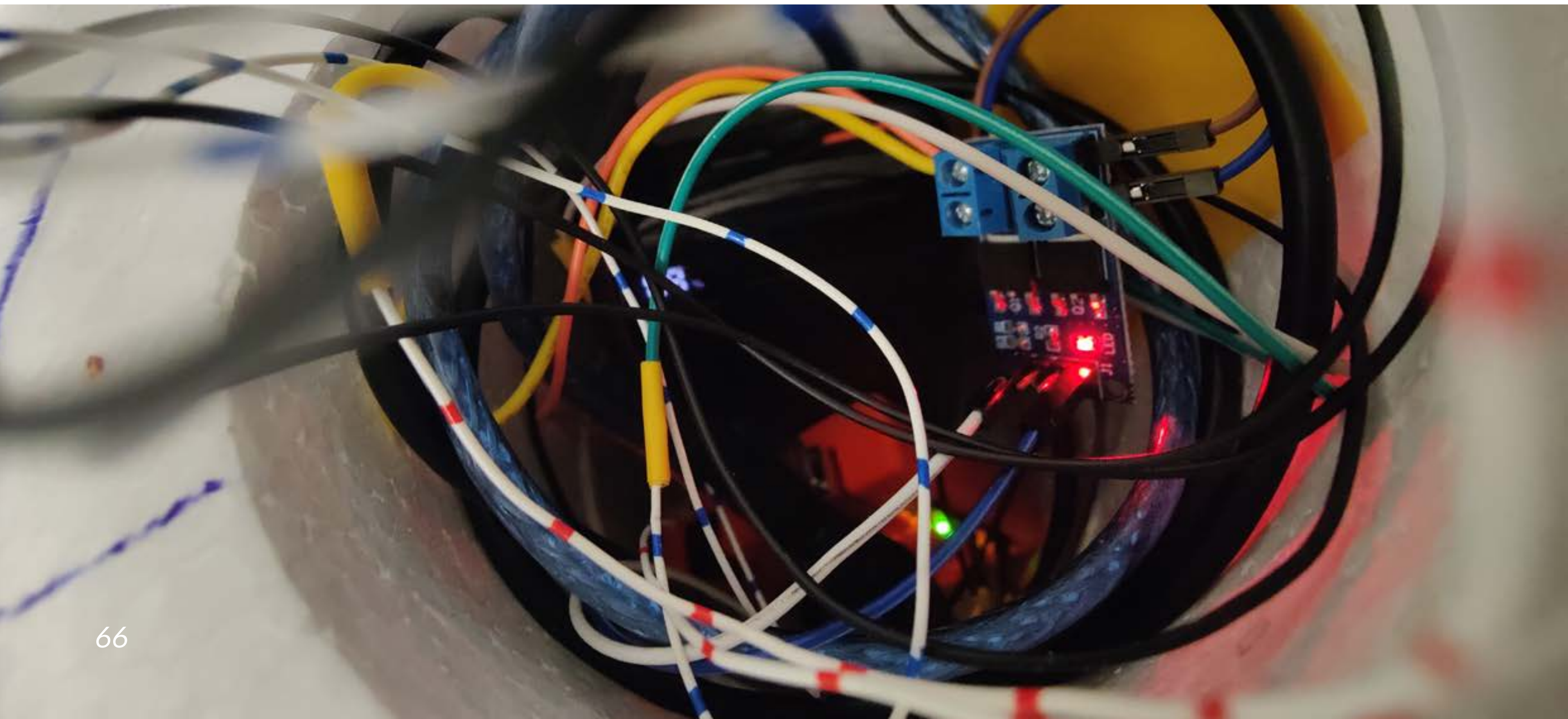


Fig. 38

Then it was time to prepare the other parts. This included designing a shielding system, assembling the LEDs, and integrating the hardware and software for the motion detector sensors. I designed a shield in CAD that utilized fins. These fins were placed closely together and angled to direct light downwards, theoretically allowing light to illuminate only the intended ground area. Behind the shielding, a curved plate would house the LEDs. Both parts, the shielding and the plate, were 3D printed. For the shielding, I chose black PLA to make the reflector as dark as possible. During the final steps, I connected all the hardware and assembled the entire prototype. Several issues arose during and after assembly, such as the jumper wires often becoming loose from the breadboard. However, after some trial and error, I managed to get everything to work.

Fig. 39



One evening, I stayed longer at Toni and waited for darkness to conduct a realistic test on the terrace. I selected a dark spot in the garden area with no surrounding lights. Without light, I could barely see the path. I tested the ease of rotating the modules to direct the light, the effectiveness of the shielding, and the performance of the motion detection.

Fig. 40

Fig. 41

Fig. 42

4.3.2 Evaluation and Learnings from Phase One

With my first prototype, I demonstrated my concept in an early stage. Overall, I see it as a solid success. It provided a foundation for my subsequent work over the coming months and set the direction in many ways. I felt that I had identified solid working areas, from prototyping with different materials to 3D printing, CAD, electronics and sensors.

Nevertheless, I encountered initial issues that I would need to address in future iterations. One such issue was the efficiency of the shielding. They performed close to my expectations regarding how they directed light downwards but fell short in terms of efficiency. The translucent properties of the polystyrene made it evident that there was significant light loss inside the modules.

The LED strips I used emitted light at shallow angles. This meant that light rays not perfectly passing through the gaps between the fins were lost inside the luminaire. Additionally, I realized that the black PLA I used for the shielding became somewhat reflective, creating a bit of glare and scattering light upwards into the sky. This observation underscored the importance of iterating on a new approach for the shielding. Even though most of the light was directed downward, I was unable to precisely control the shape and cutoff of the light beam. The only adjustable aspect was the direction on the horizontal plane, achievable through the rotation of the cylindrical modules containing the LEDs and sensors.

Fig. 43

The stacking of the modules was successful, but the internal electronics and cables running up to the LEDs and motion detectors made it difficult to assemble and disassemble the units without losing internal connections. I was pleased that the motion detectors worked well. The prototype included a top cylinder that housed two motion detectors, placed at an angle from each other to cover a wider field of view. I realized that both the sensitivity and the timing of the switching could be improved, but this would not be a big issue. The great advantage of using Arduino hardware and its peripherals is the considerable degree of freedom and flexibility they offer for rapid prototyping.

I aimed to address all these mentioned criticisms for my next iteration and phase. Also, for this first prototype, I did not focus too much on the light spectrum, prioritizing more apparent issues such as the modules. However, the light spectrum and color temperature would become an important detail for the next milestone.

4.3.3

Phase Two

On February 22nd, we had our first progress session, which provided valuable feedback about the initial experiments and prototypes. This session also marked my transition into the next stage, where I planned to delve deeper into the details and optimizations of my prototype and concept.

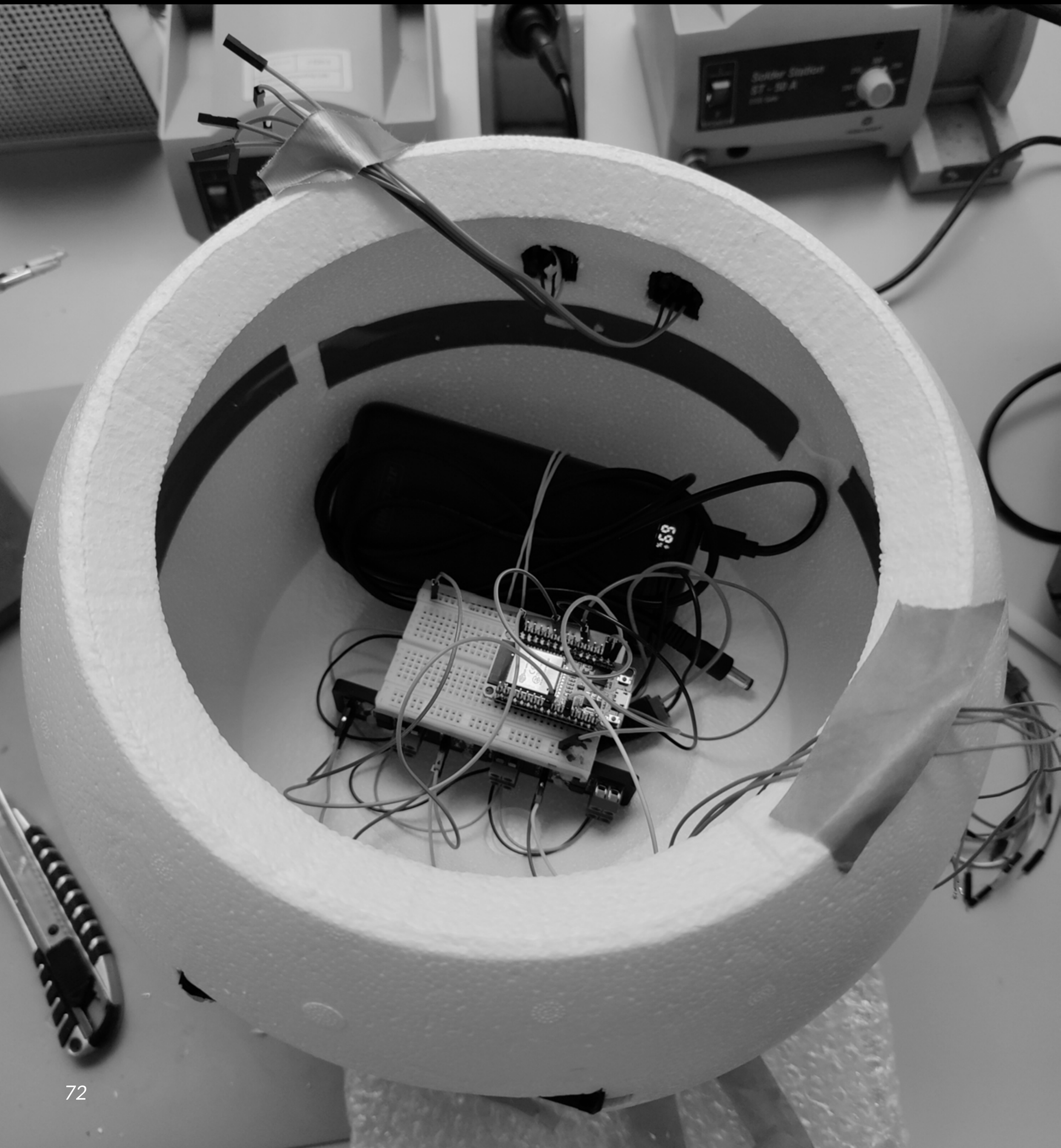
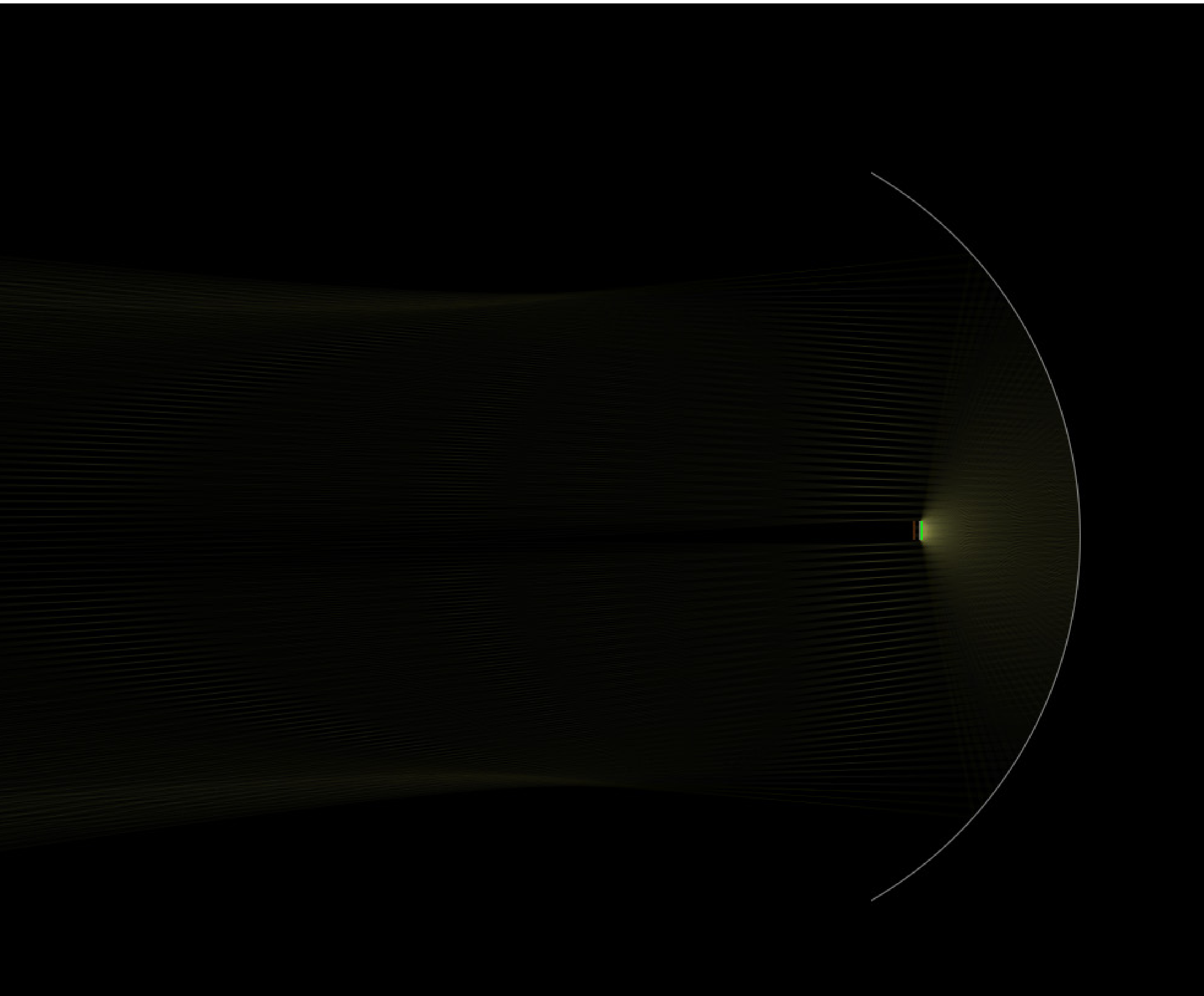


Fig. 44

The Reflector

My top priority was to further develop the shielding/reflector system, as the first iteration was inefficient and not adjustable. To maximize my time, I decided to start by experimenting with a ray tracing simulator. Through online research, I found an easy-to-use, web-based ray tracing simulator called Ray Optics Simulation (Tu, n.d.). Compared to other available software, it is very basic and limited but extremely easy to use and does not require one to be an optical engineer to get started. I saw it as an opportunity to experiment with different reflective shapes. I had to keep in mind that the simulation only displayed a 2D plane, but it should provide a general idea of whether a reflector design could work in reality or not.

Fig. 45



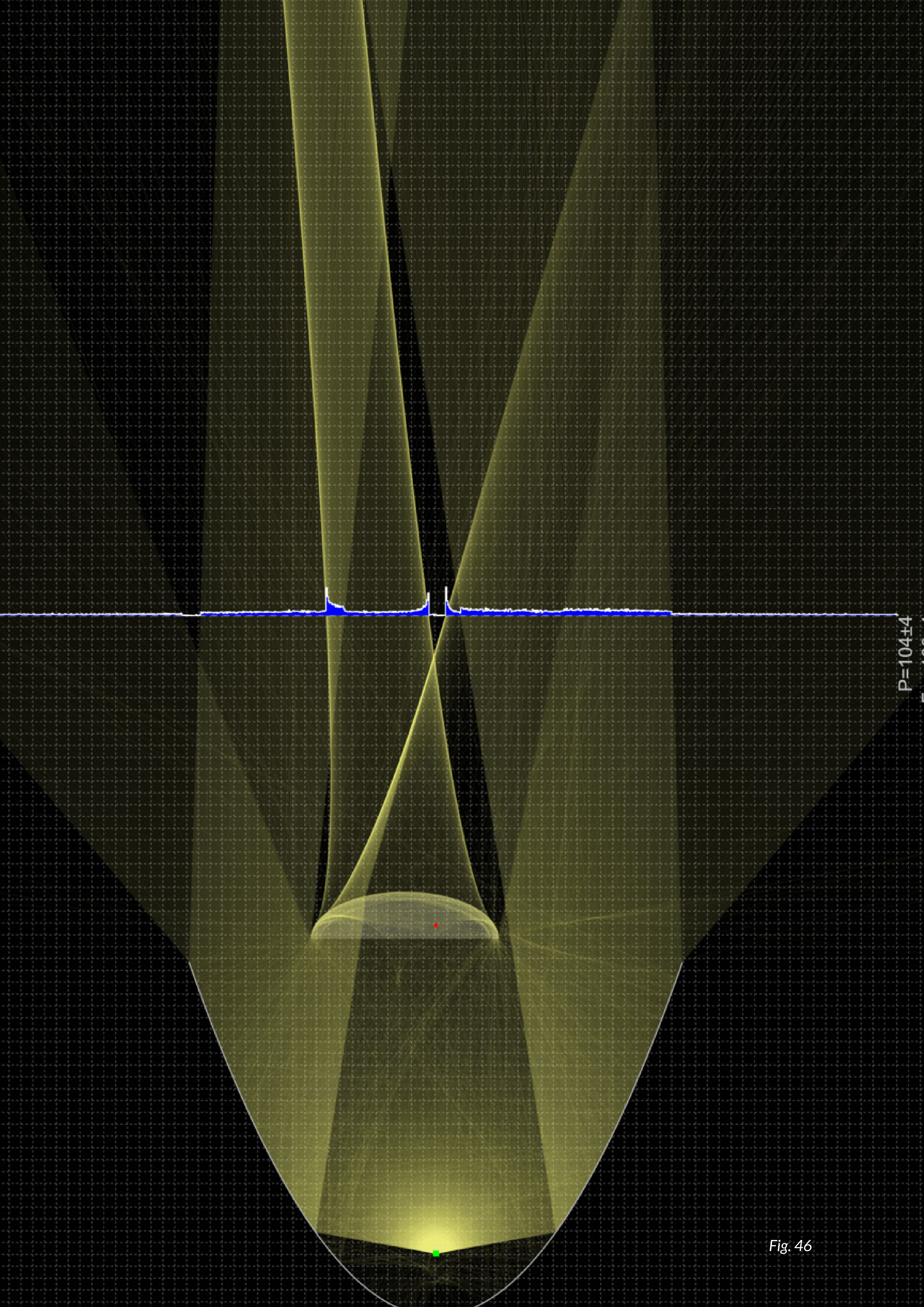


Fig. 46

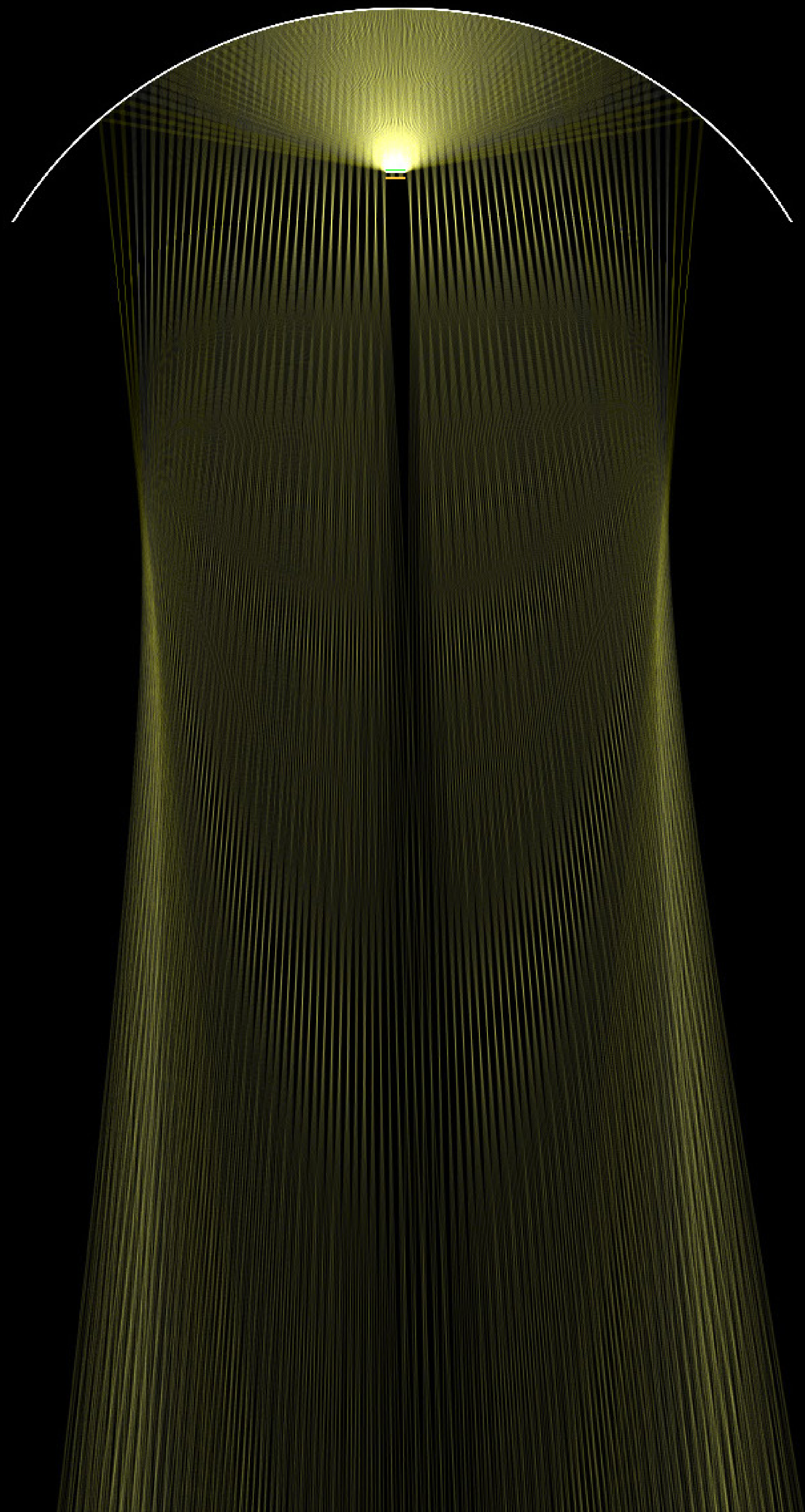


Fig. 47

My objective was to construct a design that concealed the light emitter from the viewer to prevent glare while allowing for precise light direction. Through experimentation, I arrived at a parabolic reflector. In this design, the light source was positioned directly in front of the mirror, shining inward. I recreated this exact shape in CAD software, 3D printed it, and lined the interior with a highly reflective, flexible sheet. After testing, I was pleasantly surprised by how well it performed and how closely the results matched the simulation.

Fig. 48

This success motivated me to continue with new iterations. Although the reflector effectively directed light forward, there was an issue: the light beam had a dark line in the center, a consequence of the lights themselves obstructing the reflection.

Further exploration into reflector designs led me to an informative YouTube video about the optical systems in car headlights (Diode Dynamics, 2023). There, I discovered an inspiring design known as a half "bowl reflector," which appeared promising. However, initial experiments with this exact design did not yield the success I had hoped for, as I couldn't direct the light precisely downwards onto the ground. I experimented with the parabolic shape and found the following equation that describes the shape of the mirror: $y = x^{0.4}$. This shape effectively reflected light downwards, concealed the light emitter, and did not produce a shadow in the light beam like the previous parabolic design.

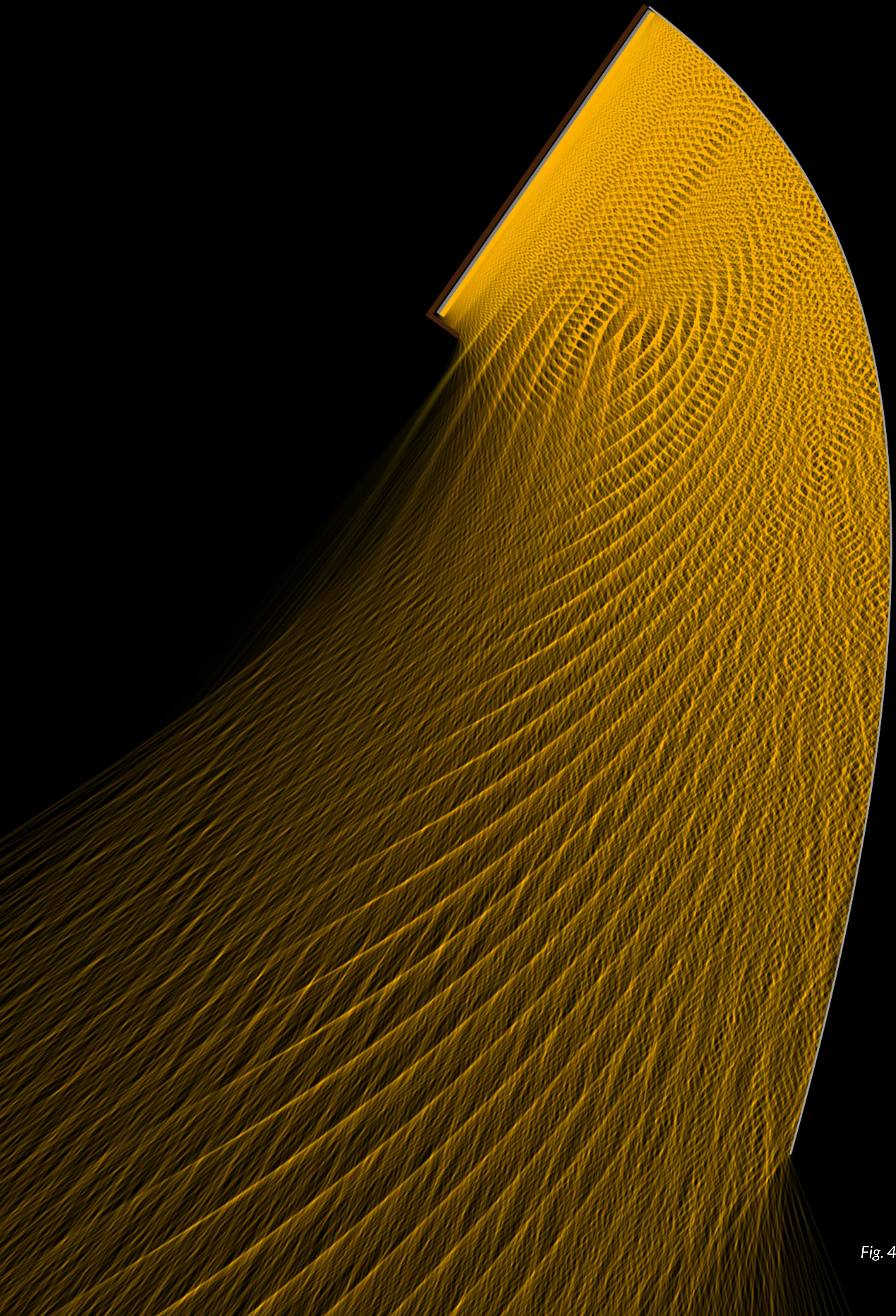


Fig. 49

I 3D printed the reflector shape with a mount that could also act as a slider, positioning the LED strip in the correct location. I explored whether the LEDs could be moved along the Z-axis to manipulate the light beam, which turned out to be true. I could further utilize the tilt of the entire reflector on an X-axis to gain even more control over the light beam. Moreover, I was able to create very sharp cutoff lines of the light, which was fantastic and precisely what I aimed to achieve. This could potentially allow for very precise illumination of pathways without spilling light into the surrounding area.

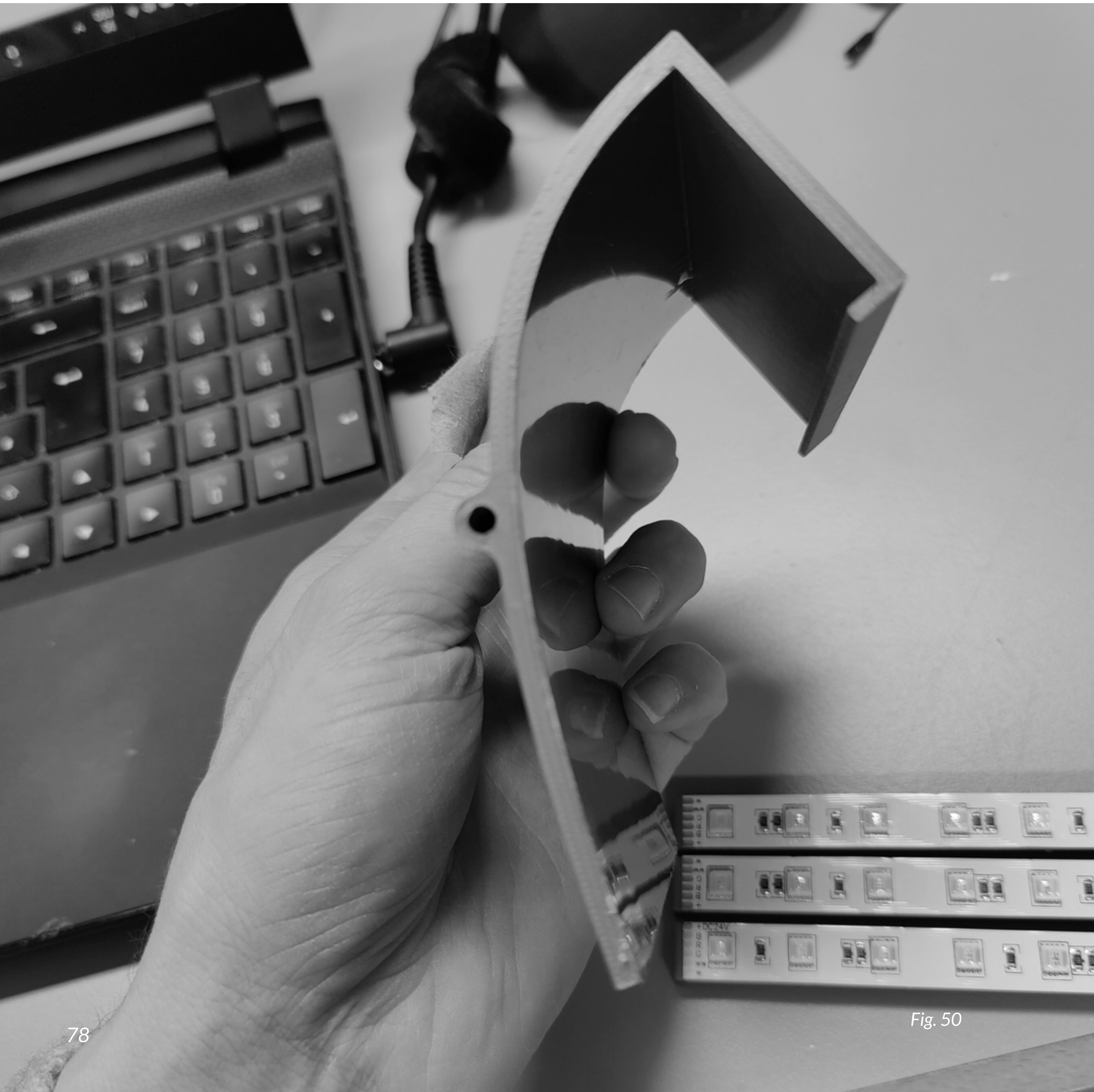


Fig. 50

Functional Form and Features

In parallel with my experimentation on the reflector, I began to contemplate how the design could be enhanced from a functional form perspective. My first prototype utilized simple cylindrical shapes, which, at the time, were sufficient for allowing rotation on a horizontal plane. However, with the introduction of the new reflector design, the ability to rotate components on a vertical plane also became crucial.

Given that modularity remained a key aspect of the design, I sought inspiration from nature to find solutions that could offer both flexibility and modularity. I was inspired by the modular structures of diatoms and how some phytoplankton naturally stack on top of each other, which reminded me of my initial prototype.

What I found most applicable for my prototype was the bulgy and flexible form of caterpillars. A similar form could provide the necessary flexibility, especially for vertical rotation. By the end of February, I had conceptualized a new functional form for my prototype. I used CAD software throughout the process to have visual feedback, which helped me to better plan and refine the concept over the following days.

I developed a structure that would utilize stacked spheres instead of cylinders. These spheres would need to be precisely cut at the top and bottom to allow them to be stacked without losing stability while still providing the necessary rotation and tilt freedom. By the first quarter of March, I had solidified a clear idea of how to proceed. At this point, selecting a suitable material that could house the electronics and reflector, including the LEDs, became important.

I chose polystyrene again because it is well-suited for rapid prototyping, and it didn‘t make sense at this stage to opt for higher-quality materials or methods like 3D printing.

Fig. 51

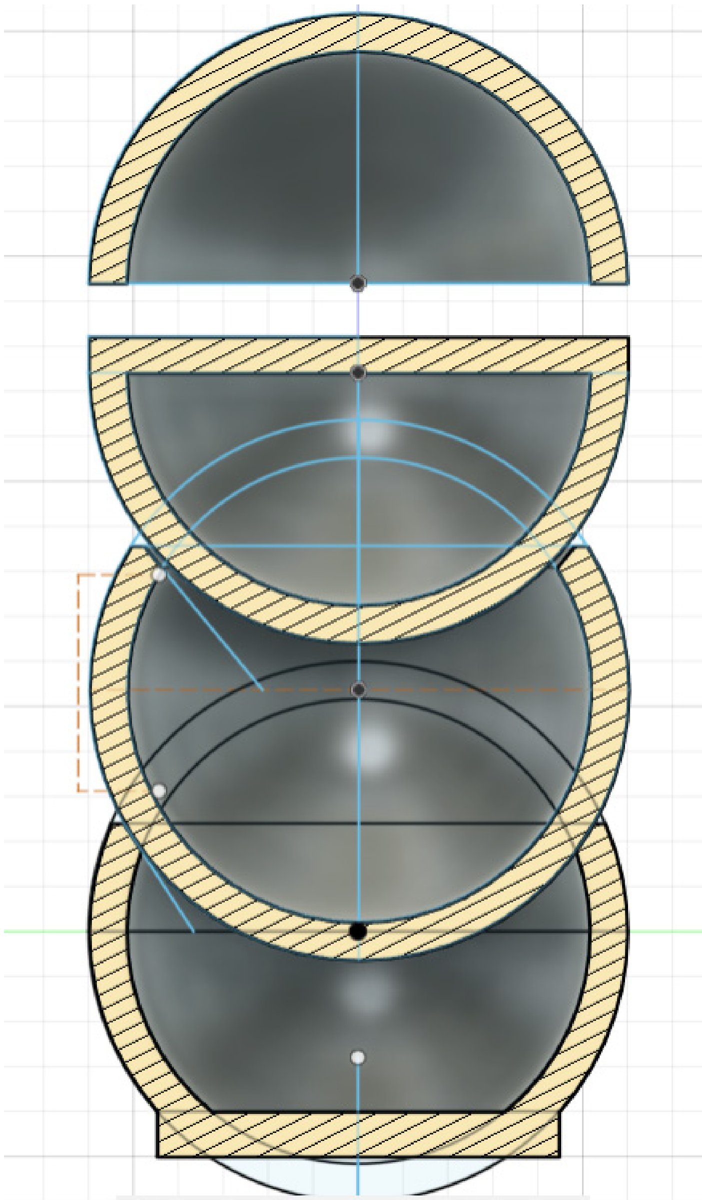


Fig. 52

As with the first prototype, I began processing the material by using the hot wire machine. Precise and clean cuts were much more critical this time, and I needed to consider different methods Tto achieve the desired results. It also became crucial to plan exactly how I would implement the electronics to interact with the light. I chose to use an ESP32 with two motion detector sensors, two potentiometers, and a touch sensor. As the code for the microcontroller started to become quite complex, I worked with ChatGPT to generate the code. To fit the hardware, I had to cut several holes to fit the electronics. I needed to redesign the reflector in some aspects, allowing it to interact with the slider and to fit within the prototype's outer shell.

The assembly of the electronics, cables, and other elements proved to be the most tedious part of the process. This time, I focused on improving the wiring and used hot glue to ensure that connections did not come apart.

Fig. 53

Given that my initial concept included the possibility of integrating a solar cell, I constructed a mockup. This cell was designed to be placed on top of the prototype, which featured a flat top ideally suited for such an addition. This placement not only allowed for tilting but also potential alignment with the sun's position. Additionally, the prototype featured a touch sensor at its top, allowing for temporary light requests. By touching the sensor, the light entered high-power output mode, providing maximum visibility for a limited time before returning to low power mode. This functionality could be important in situations where someone using the pathway would need increased visibility or would feel unsafe. Another feature was to hold a phone close to the prototype, which opened a website on the phone, informing people about the luminaire, its function, and the issue of light pollution. The integrated ESP32, featuring Bluetooth and WiFi capabilities, could enable interconnectedness among individual luminaires, allowing them to communicate signals to increase light intensity in the nearby area.

Compared to my first prototype, it became essential to consider how the luminaire would utilize color and light spectrum. To address this, I combined warm white and red LEDs. The back of the prototype featured two potentiometers: one controlling overall light intensity and another adjusting the light ratio between the white and red LED. This allowed me to shift the color from white to red, mimicking a color temperature change.

Fig. 54

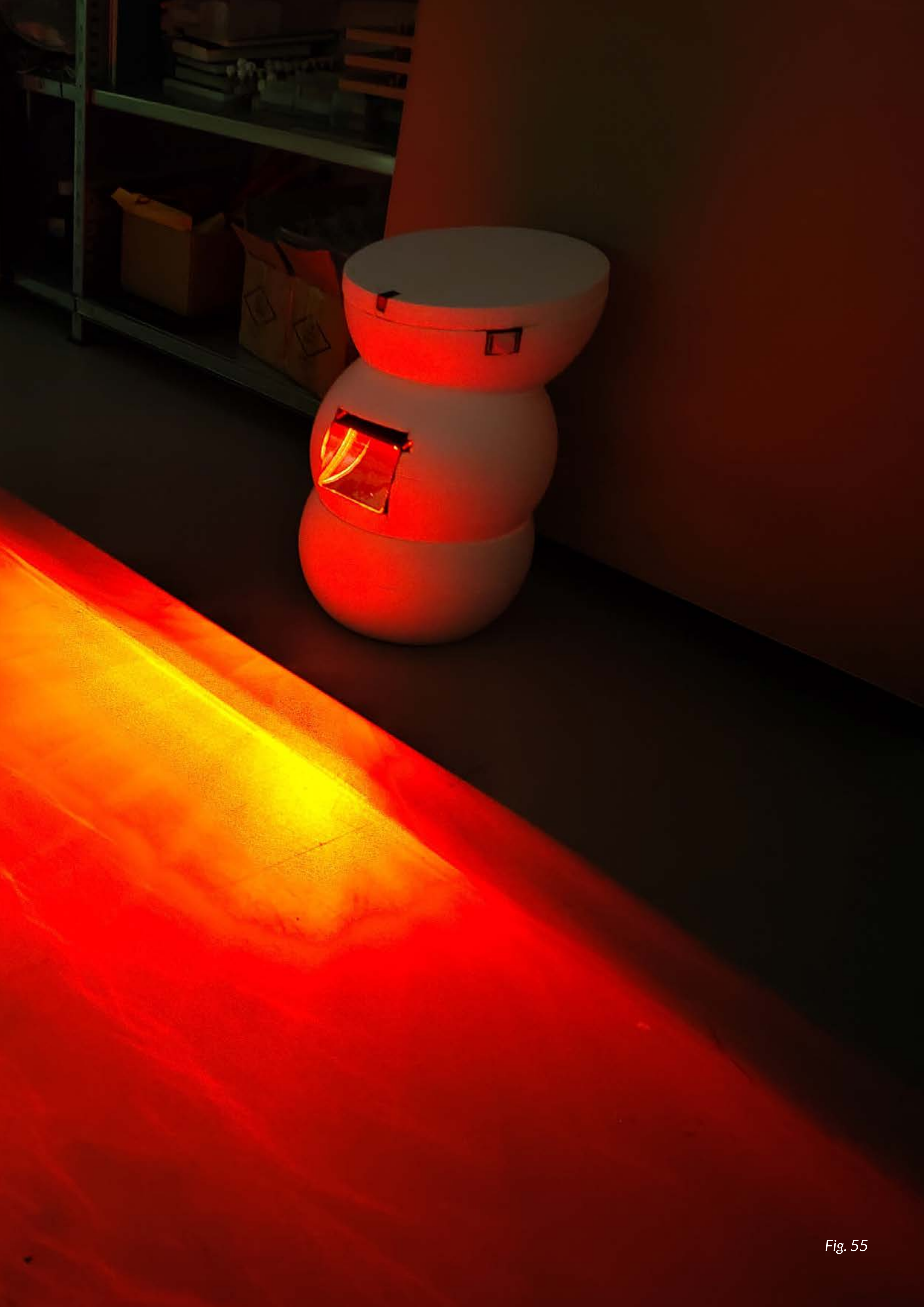


Fig. 55

4.3.6 First User Tests

During mid-March, I felt confident with some aspects of my concept to proceed with first user tests. I was pleased with the performance of the reflector but wanted to test it with people. Additionally, I was curious about how color would influence visibility as well. To approach this topic, I set up three hypotheses regarding glare and the use of color, which are listed below:

Hypothesis 1: *A design that produces no glare and blinding is perceived more pleasantly.*

Fig. 56

Hypothesis 2: Green light provides the best visibility compared to blue or red light.

Fig. 57

Hypothesis 3: *Warm colors, such as yellow or red, are perceived as more pleasant than cooler colors.*

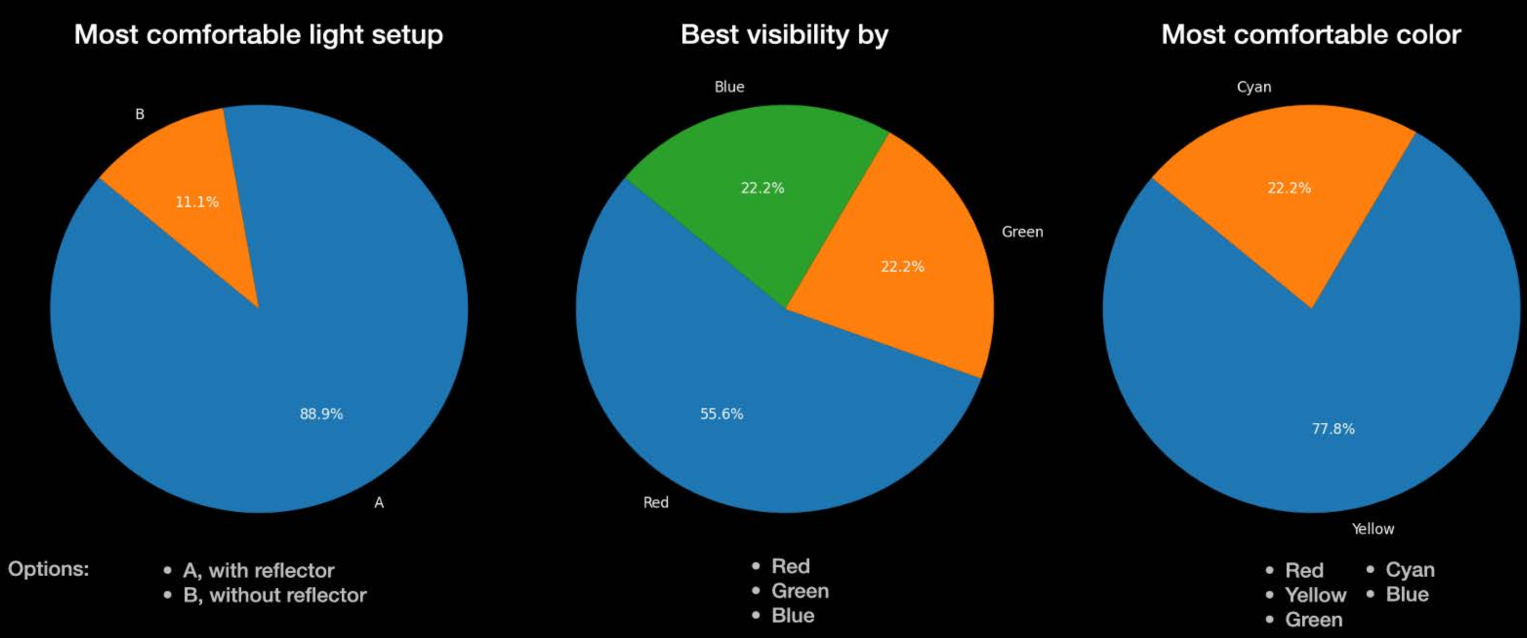
For testing, I built a setup with my reflector design mounted onto a rod. I used a wireless LED controller connected to an RGBWWCW (red-green-blue-white) LED strip to control the colors and brightness values from my phone.

Regarding the first hypothesis, I used an unshielded video LED light to compare against the light with a reflector. To ensure comparable results, a lux meter was used to verify that all colors and light sources produced the same lux value at the ground level. As a location, I chose a dark spot on the Toni Terrace in the garden area, which featured a natural pathway for my setup. I used a Google form for the questions I had created so that I could easily share them with a QR code for people to fill out on their phones.

As for my target group, I aimed for random people around the area and in the building. This turned out to be quite difficult, as most had gone home or were not willing to participate. However, in the end, I managed to collect data from a total of 9 people. I wished I could have gathered more participants, but it was not possible that evening. I was still happy and fascinated about the data, as it was unexpected in some regards.

Below are the charts from the results:

Fig. 58



Interpretation:

Hypothesis 1: The data indicates a very strong tendency that a shielded light is perceived more pleasantly as blinding is avoided. This leads most likely, in return, to better overall visibility as the eye can better adapt to the dark environment.

Hypothesis 2: The data shows variety and a tendency towards red light. This result is somewhat unexpected, as it is known that human vision is most sensitive in the green part of the spectrum. The deviation could potentially be attributed to ground variations or insufficient amount of data.

Personally, I perceived blue light as the color providing the best visibility.

Hypothesis 3: The data shows a strong tendency towards warmer colors to be perceived more pleasantly, in this case, yellow.

Evaluation and Learnings from Phase Two

Overall, I consider Phase Two a great success. It built upon the improvements made in most aspects that became important through the first prototype. This includes the interaction with the overall design, finding a functional form, adjusting color temperature, and particularly, developing an efficient and customizable reflector that enables precise use of light. I view this prototype and the entire process as a creative and productive exploration into the possible functions that could become crucial for my final stage. While not all aspects will be integrated into the final prototype, it provides a wide range of options to choose from. Prioritization may be necessary in the last phase to focus on the most significant factors affecting light pollution.

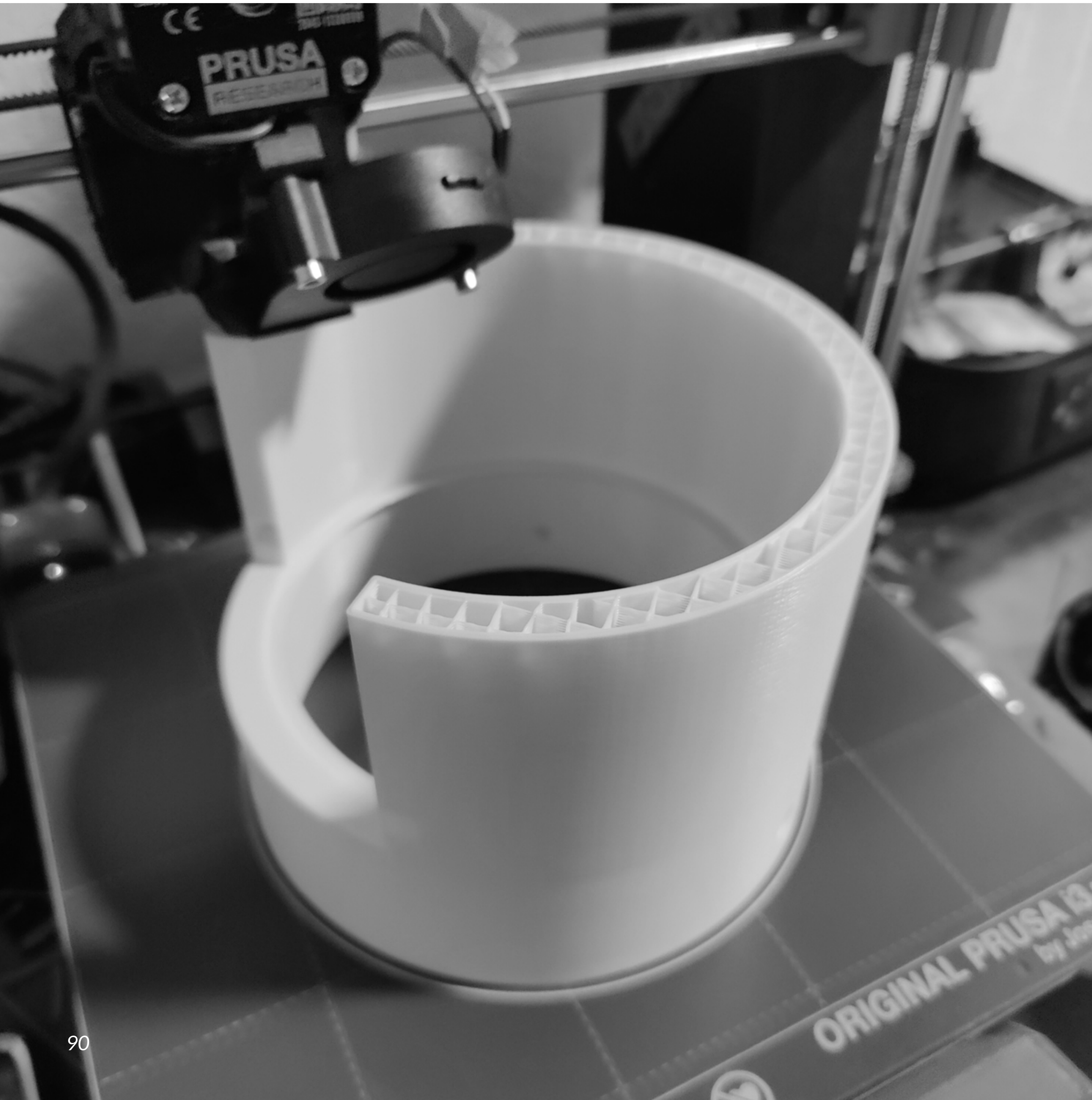
By the end of Phase Two, I realized that I needed to shift my focus from making major changes to refining existing solutions. For instance, my decision to enable a rotation tilt mechanism made the prototype bulky and low in height. During testing, I discovered that the ideal height falls between 60 and 100 cm. This required refinement on the functional form aspect, as the current design using stacked spheres was not suitable for achieving this height.

During this time, my personal interest in light color and spectra deepened. Through online research, I found that LED manufacturers offer a wide range of different spectra. My second prototype already utilized white and red LEDs to mimic an adjustable color temperature. This was a good start, but I wanted to explore further how other colors could be leveraged for reducing light pollution and potentially improving visibility.

Phase Three

I identify phase three as the last part of my process. It encompasses everything that happened after finishing the second prototype. This phase was not only about refining and developing the final prototype but also very much about finding a representative way to showcase my work for the upcoming exhibition. Additionally, I conducted tests with insects to assess the impact of the light spectra I chose.

Fig. 59



Functional Form: Iterated

In May, I participated in a Berlin field trip with my class. Although I wasn't able to physically work on the prototype during this time, I used the time to think about the functional form that would enable flexible interaction with the design on a physical level. My previous prototype, presented during Progress Session two, was highly functional but not practical for the final version. I needed to iterate and find a suitable outcome for the exhibition as well. The requirements were to develop a system allowing physical interaction with the light while enabling height adjustment between 60 and 100 cm.

Reflecting on my early work and experimentation phase, I realized that a hybrid of the first and second approaches would provide great potential. This allowed me to use stacked cylinders for flexibility in setting the height and a spherical shape for rotation and tilt control of the reflector part.

Through simple sketches, I explored possible assembly options and stacking arrangements. I concluded that a spherical head placed on a cylindrical component would be ideal.

I began working on the final prototype version, with the most challenging aspect being to figure out how the mechanics would work. It was crucial that rotation and tilt were guaranteed while keeping the head secure on the cylinder.

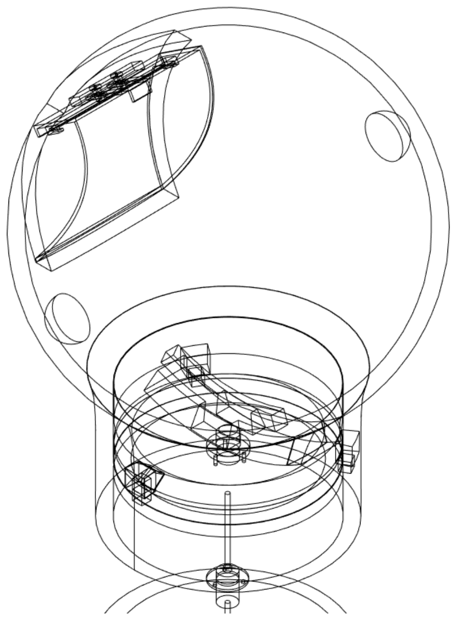


Fig. 60

Using CAD software, I designed a sliding mechanism that enables the spherical head to be tilted while a wedge prevents it from falling off. The entire sphere is placed on a rotator plate, which allows up to 360-degree rotation and can be secured inside the top cylinder. This mechanism makes it very easy to adjust the light where needed.

After working out the details, I started with the fabrication of the components. For my first and second prototypes, I used polystyrene, but precision was now crucial for the mechanism to function correctly. Therefore, I decided to create the top part of the luminaire using 3D prints. The bottom part, including height spacers, is made from a standard pipe from the hardware store, saving 3D printing material and time. As with previous prototypes, electronics and hardware became important again. For generating the code, I used ChatGPT again. This required detailed prompt engineering, as the code had become highly complex.

Fig. 61

Fig. 62

Fig. 63

Electronics and Sensors

I categorize the electronics of the prototype into four levels, that enable the design to interact in an intelligent manner with its environment. All of those components are hidden inside the modules and are not visible. Nevertheless, I consider them highly important, as this technology is the key to making all of this possible.

The main and central layer is the ESP32 microcontroller. It is the brain of the luminaire and will process the data, such as sensor input and communication with other luminaires. The ESP32 will be able to interconnect with its peers, creating a node-based network of the luminaires in the area. By assigning an ID and spatial data to every light, they can know exactly where they are positioned. The ESP32 will receive signals from two motion detector sensors installed in the head. For my prototype, I chose to use regular PIR IR sensors, as they are more affordable, but in a final product, it would make sense to opt for microwave sensors, as those feature advantages, such as velocity sensing of an approaching object.

The following logic for the luminaires‘ behavior will not be programmed in my final prototype, as it would be too time-consuming and difficult for me. Instead, I will display it through a virtual environment, as part of my exhibition concept. Nevertheless, I want to take a short moment to explain a possible logic of how it could enable interaction with the luminaires surrounding, when programmed in real life.

The two motion detectors are directed to opposite sides, so that they cannot detect the same object simultaneously. This allows the luminaire to sense a person approaching it through sensor A of luminaire A. At some point, detector A will lose the sensing and sensor B will take over. This allows the luminaire to calculate the direction and estimate the speed of the person. This data will then be transmitted to its next peer. Luminaire B will then start to increase slowly and gradually light levels, ensuring that the path is lit in front and behind one. This logic would continue throughout the series. But as already mentioned, for a final product, it could make sense to use microwave sensors, as they are more reliable and are used in similar systems.

Through the node-based network, luminaires will be able to detect activity on a larger spatial scale. If many people are detected, they will switch on to constant light and override the sensor logic. Additionally, they will shift their color temperature throughout the night, if Urban Mode is selected.

Fig. 64

Fig. 65

4.3.11 Spectra Modes

During this final phase of my process, I began to consider how I would integrate multiple LEDs to cover a wide range of the light spectrum, enabling me to compose the desired or required light spectrum on demand. However, I realized that it would not be possible for my final prototype as initially imagined due to technical limitations and costs.

However, from my early research, I already had a deep understanding of what colors and color temperatures would be interesting and worth using. I knew that red hues are preferable for the nocturnal insect world; green is perceived by our vision as intense due to the high sensitivity in this range; and white to warm white is a universally applicable color for urban areas.

Based on my research and analysis, I decided to implement three color modes:

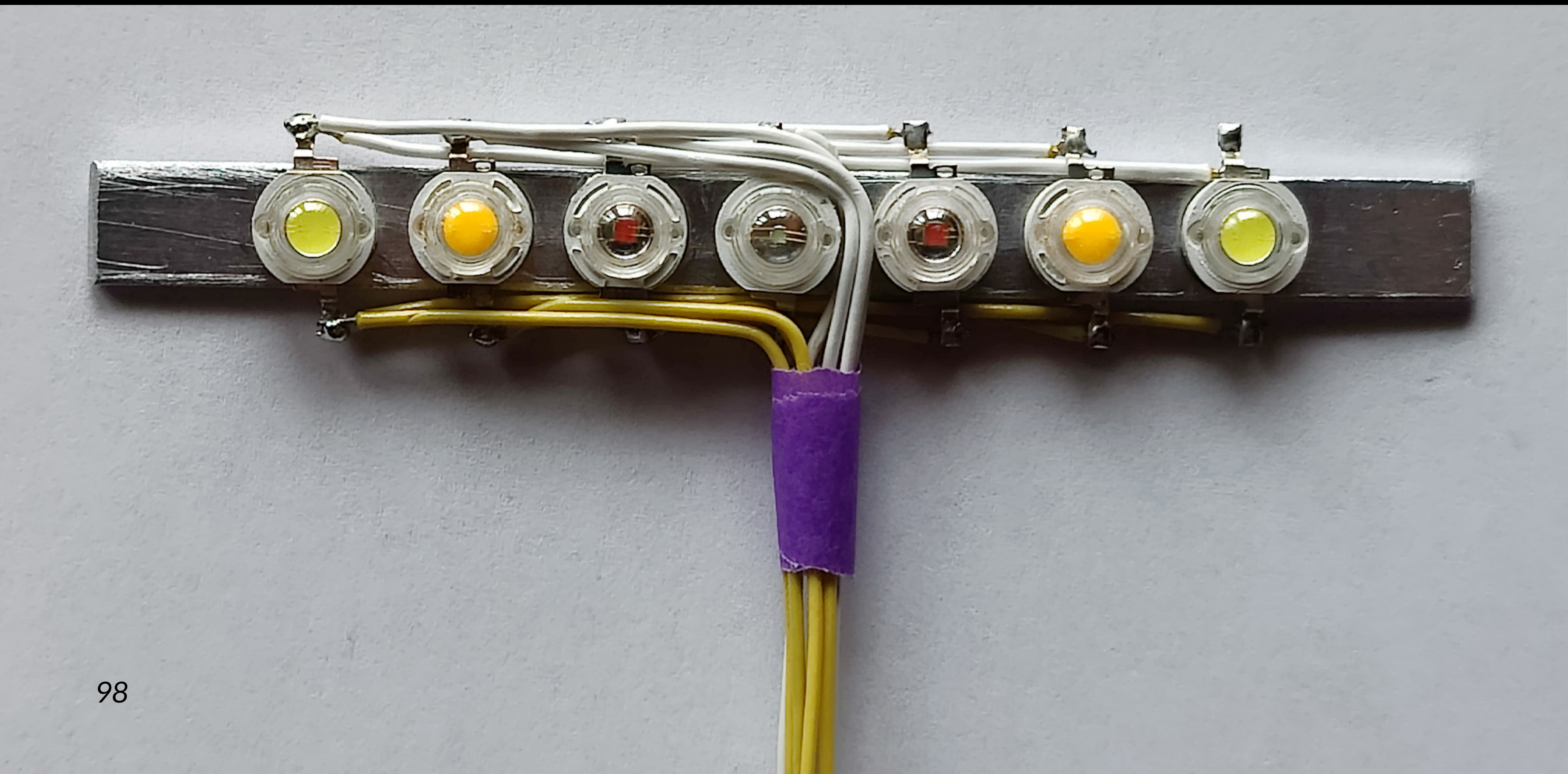
Eco Mode (using pure amber LEDs): tailored to high biodiversity areas.

Urban Mode (1800K to 6000K LEDs): designed for general urban areas, with adjustable color temperature to suit nocturnal environments.

Low Intensity Mode (using pure green LEDs): an experimental mode that encourages the use of green light at very low intensities, leveraging human night vision capabilities.

These three modes are discussed in detail in the concept chapter.

Fig. 66



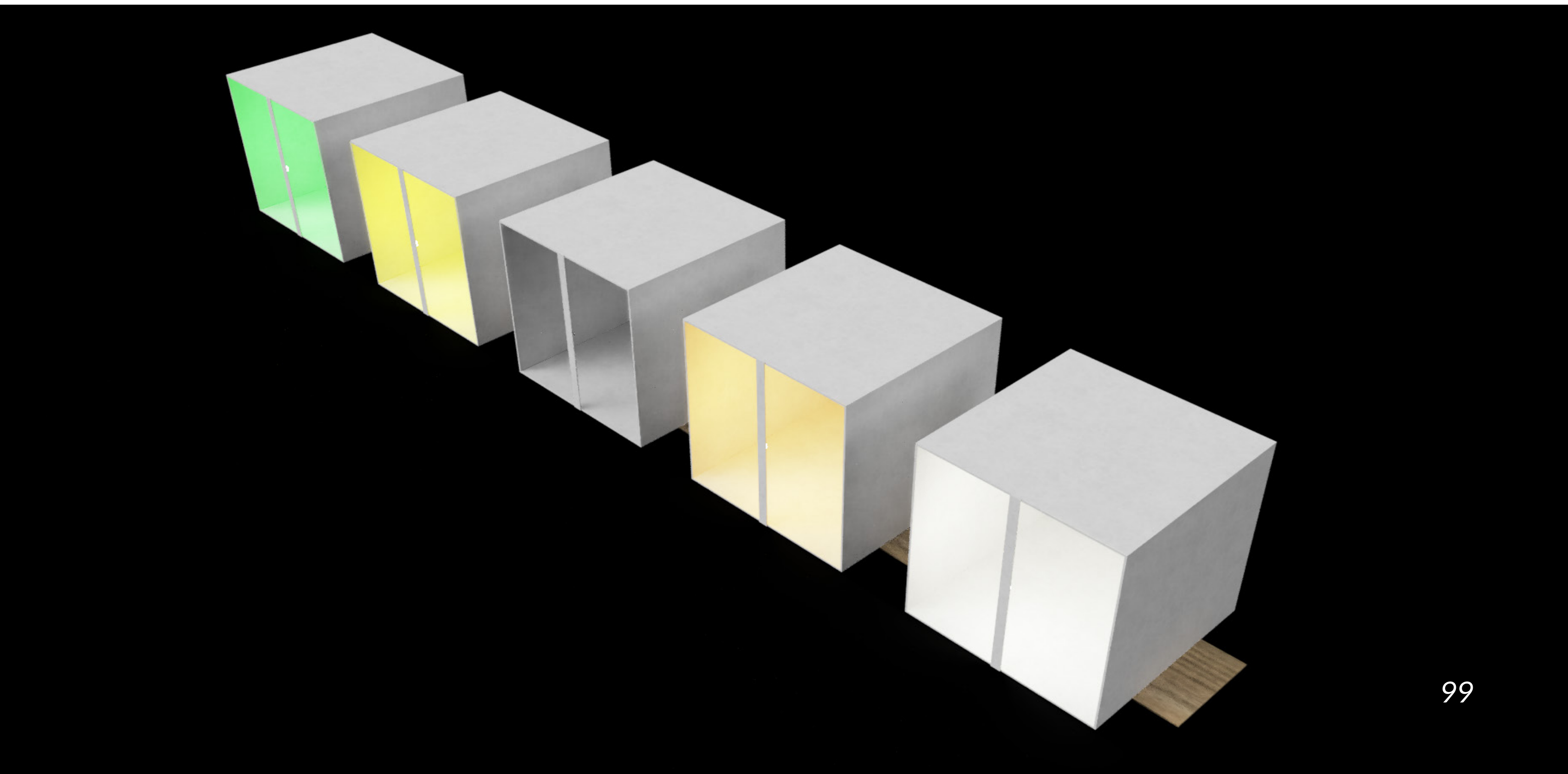
Attraction of Insects by Different Light Spectra

To evaluate the impact of the light spectra I chose, I conducted a real-world test with insects to gain valuable insights into how local nocturnal insect communities would react to the different light sources.

During my research, I was guided by PD Dr. Eva Knop, a scientist specializing in biodiversity and the ecological impacts of light pollution, to Vincent Grognuz. Grognuz is a PhD student in their team at Agroscope. His PhD project focuses on "*quantify[ing] the indirect impact[s] of artificial light at night on the structure of diurnal plant-pollinator interaction networks [through] large-scale field experiments as well as garden and greenhouse studies to unravel the underlying mechanisms*" (*Eva Knop - People*, n.d.). Throughout my process, I got in touch with Grognuz several times. He helped me answer questions I had, especially regarding the tests I planned doing with the insects.

Before building and setting up my experiment, I discussed with him the best solution for my experiment. I proposed three setups: planar, circular, and linear. Grognuz recommended a linear setup using boxes equipped with sticky tape, so I built them out of cardboard, with dimensions of 10x10x10 cm. Each box was equipped with an internal LED representing one of the three modes I would later use in the prototype. This resulted in four boxes with an amber, green, 1800K, and 6000K LEDs. A fifth box served as a baseline with a dummy LED that remained off.

Fig. 67



To ensure consistent light levels, I used a TSL2591 lux meter connected to an Arduino and aimed for ±170 lux on all boxes using current and voltage regulation. The inside walls of each box were covered with fly-trapping sticky tape to capture potential insects visiting the chambers during the night.

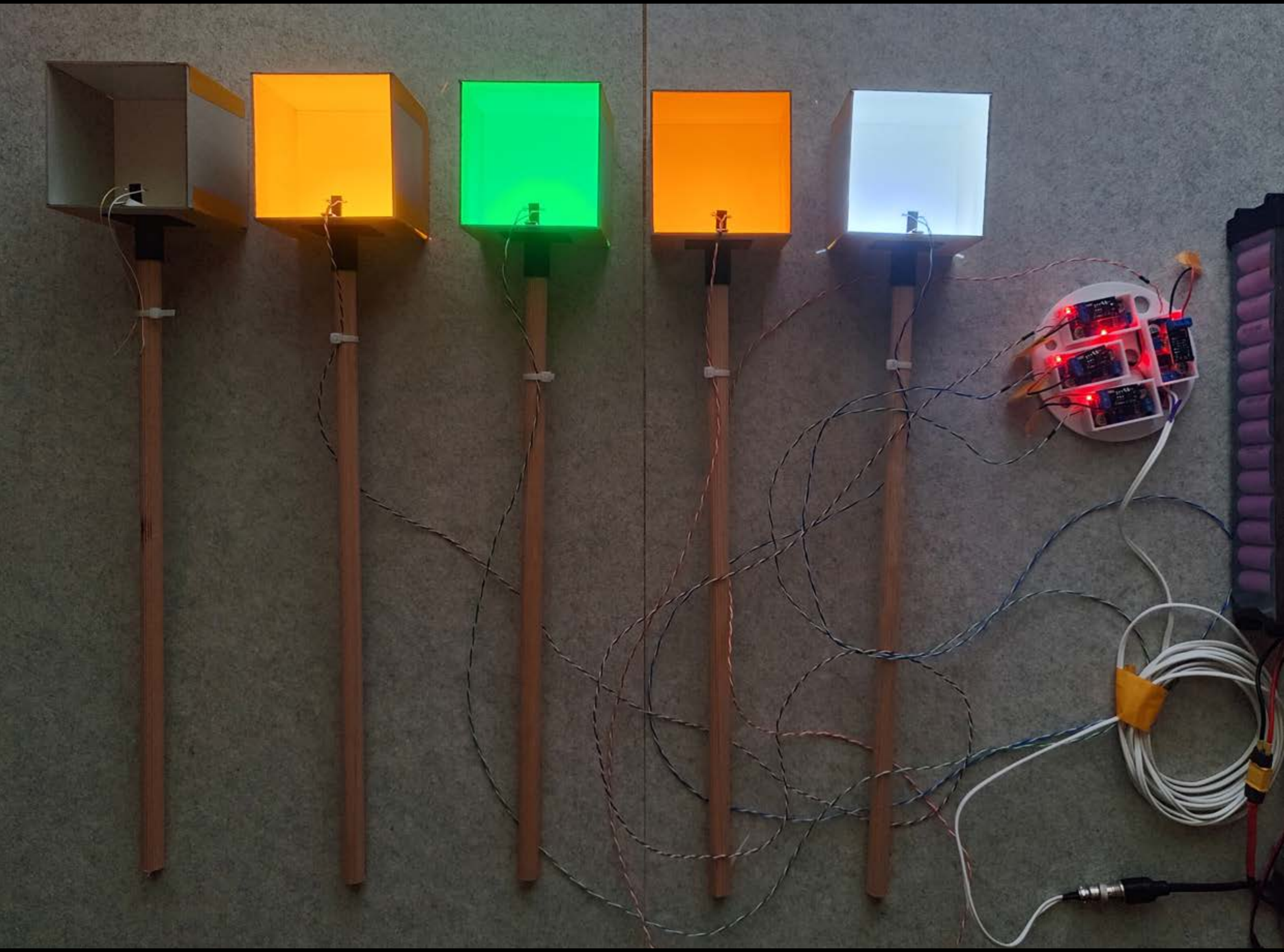


Fig. 68

On the evening of May 4th, I installed the boxes with attached poles, 40 cm above ground level and a spacing of about 30 cm in a location featuring large meadows and nature around.

At 10 pm, I started the experiment by turning on all LEDs and removing protection from the sticky tape. It was already dark at this time.

Fig. 69

The next morning, I arrived at the location at 5:10 am to find that some boxes had caught insects. To prevent potential insects from entering the box while traveling home and contaminating the data, I sealed all openings with tape.

Fig. 70

When I returned home, I cut open the sides of the boxes and laid them flat to take high-resolution images of the surfaces containing the insects. I then imported these images into Photoshop and manually tagged all identifiable insects with a magenta blob. For the spots where I was unsure, I had to visually inspect the specific box with a magnifying glass. After this step, I used blob detection with Python to count the insects reliably.

Fig. 71

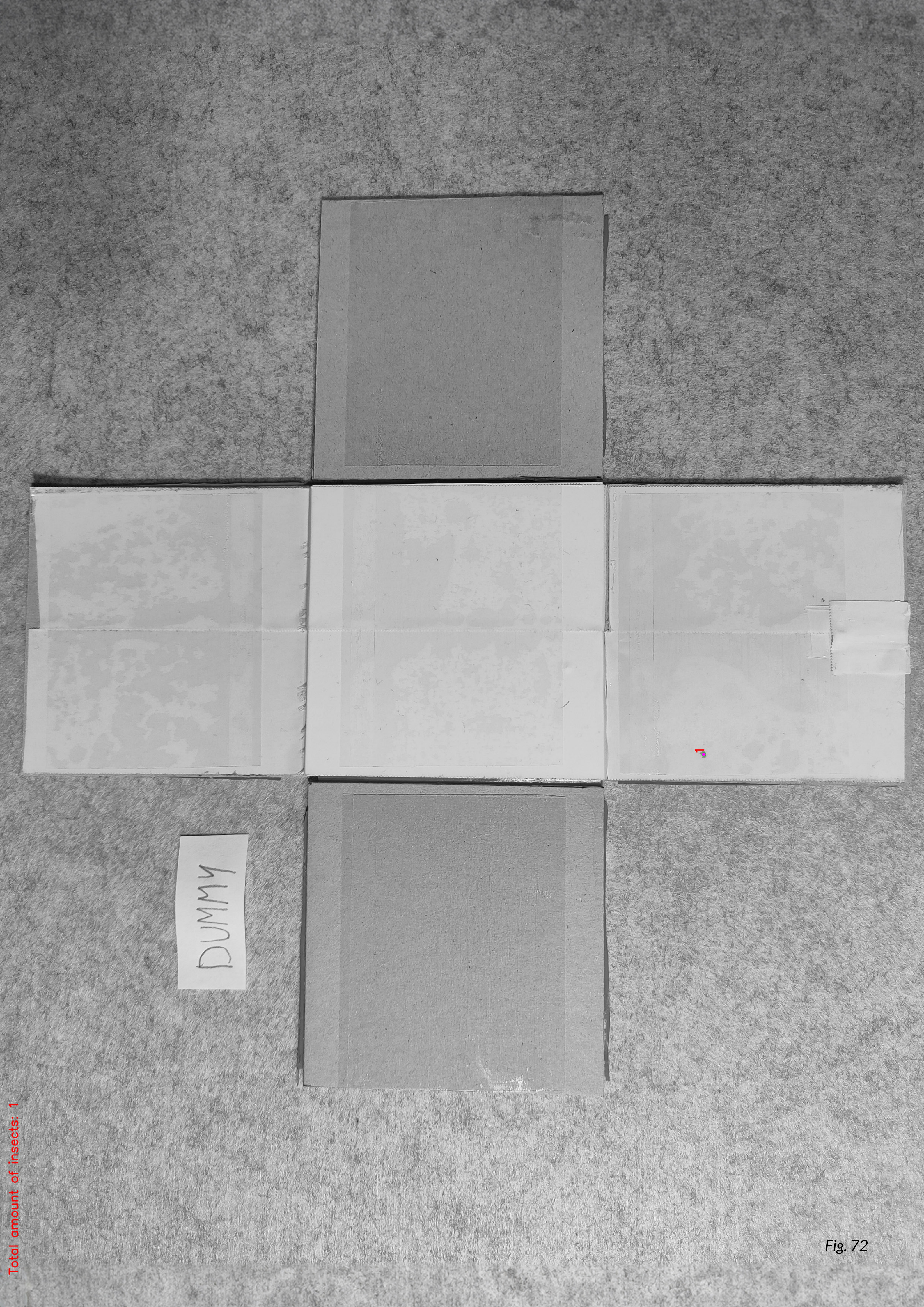


Fig. 72

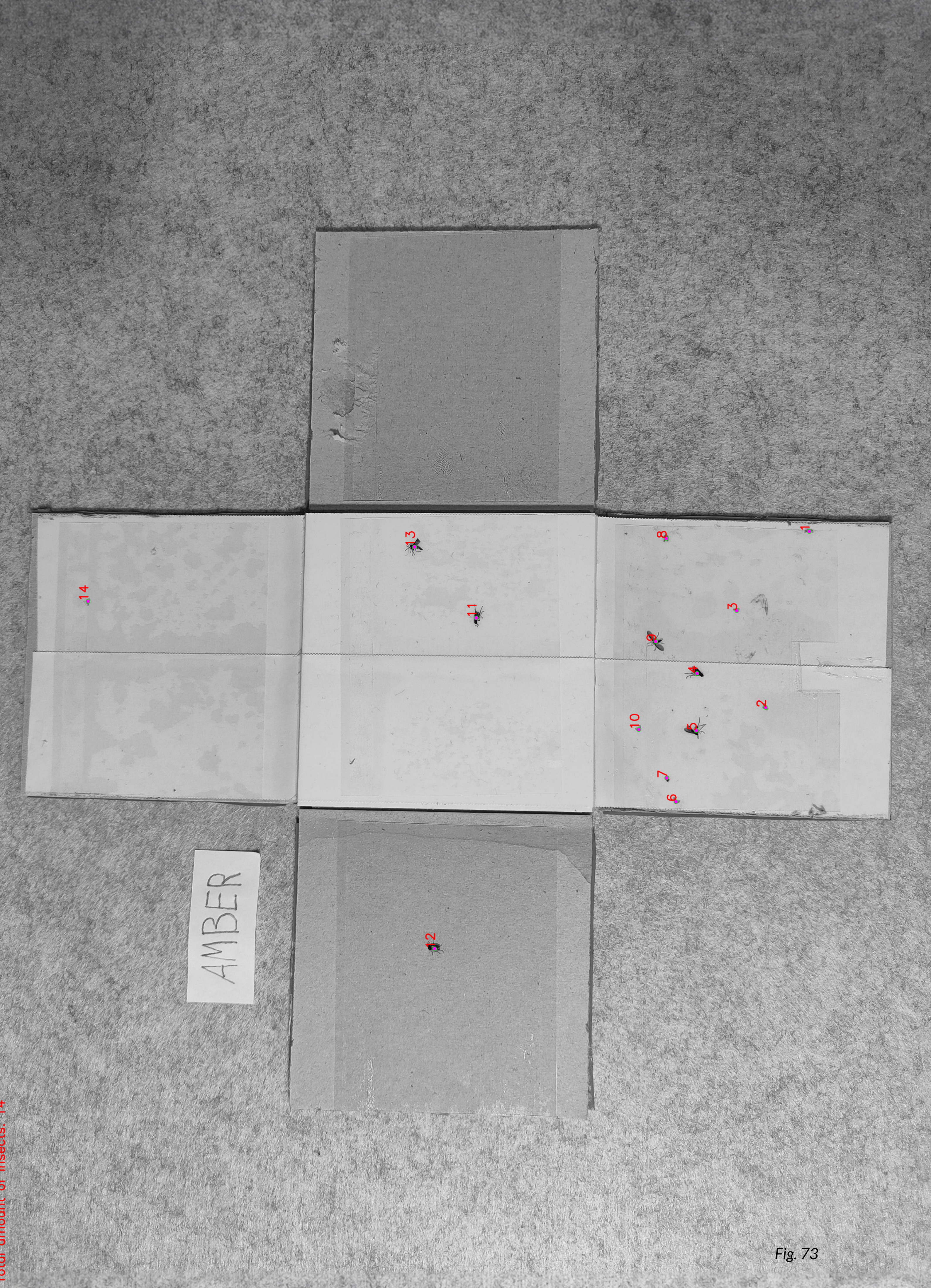


Fig. 73

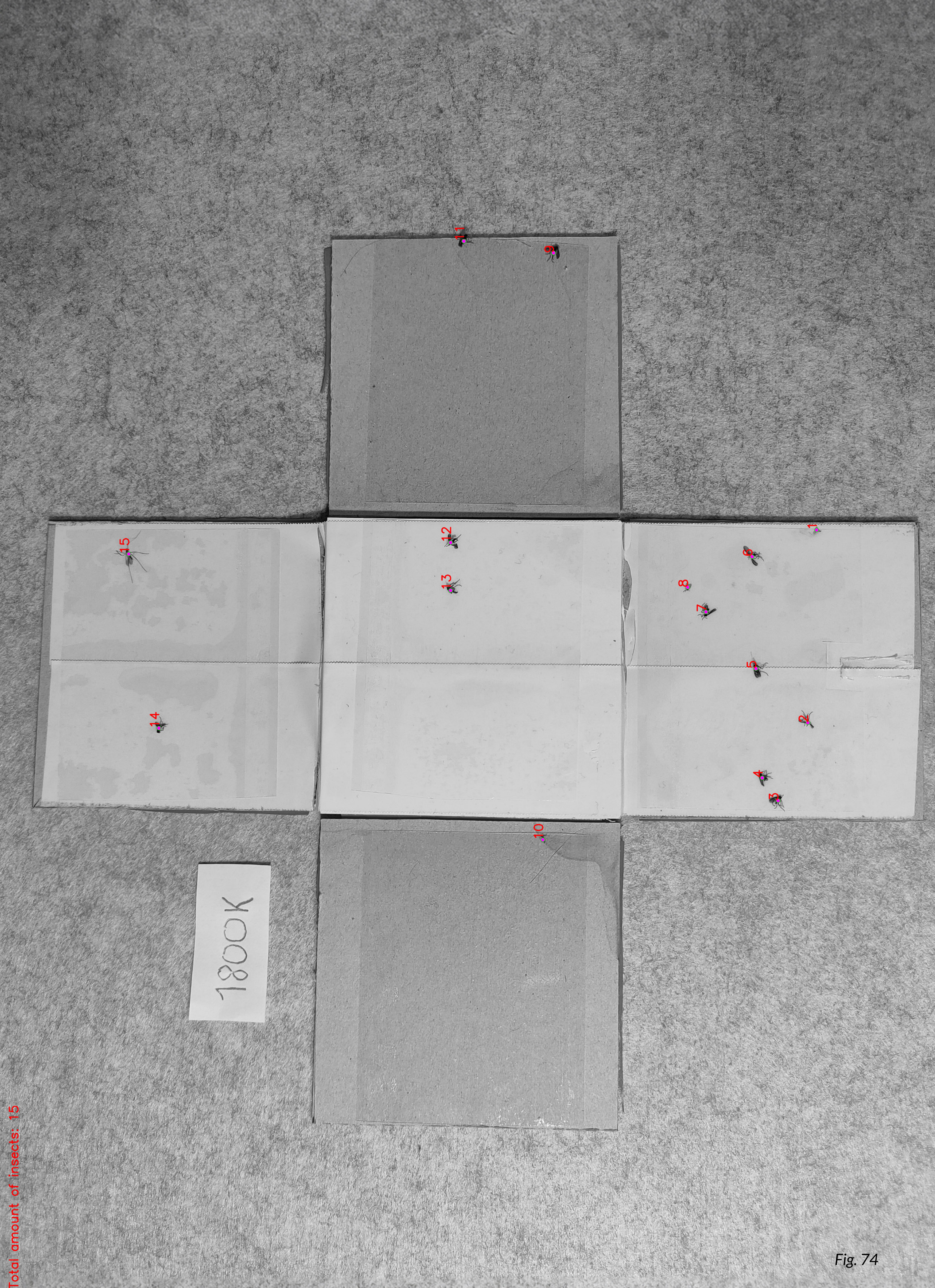


Fig. 74

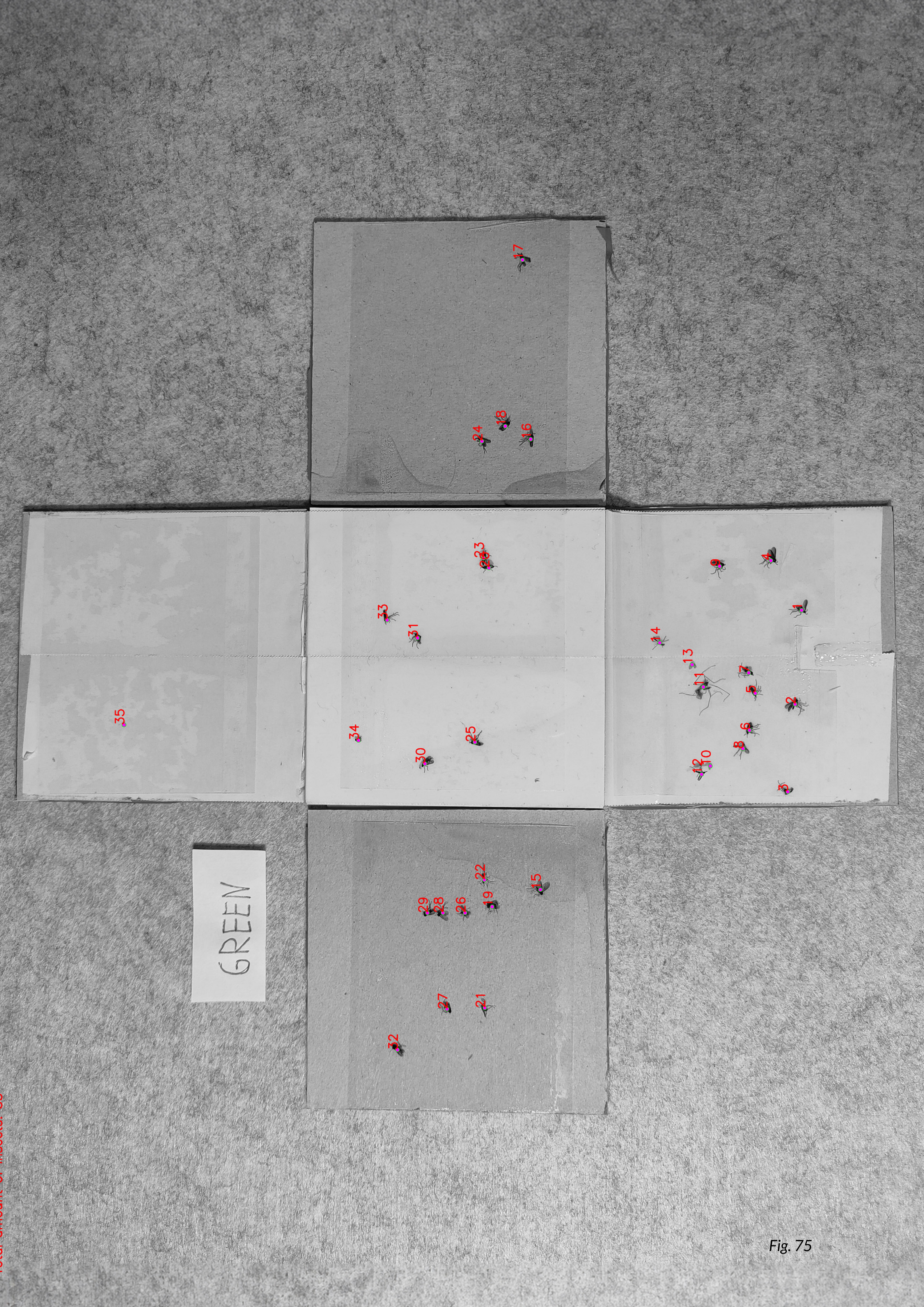


Fig. 75

Fig. 76

Results:

Dummy LED Box: **1 insect**
Amber LED Box: **14 insects**
1800K LED Box: **15 insects**
Green LED Box: **35 insects**
6000K LED Box: **113 insects**

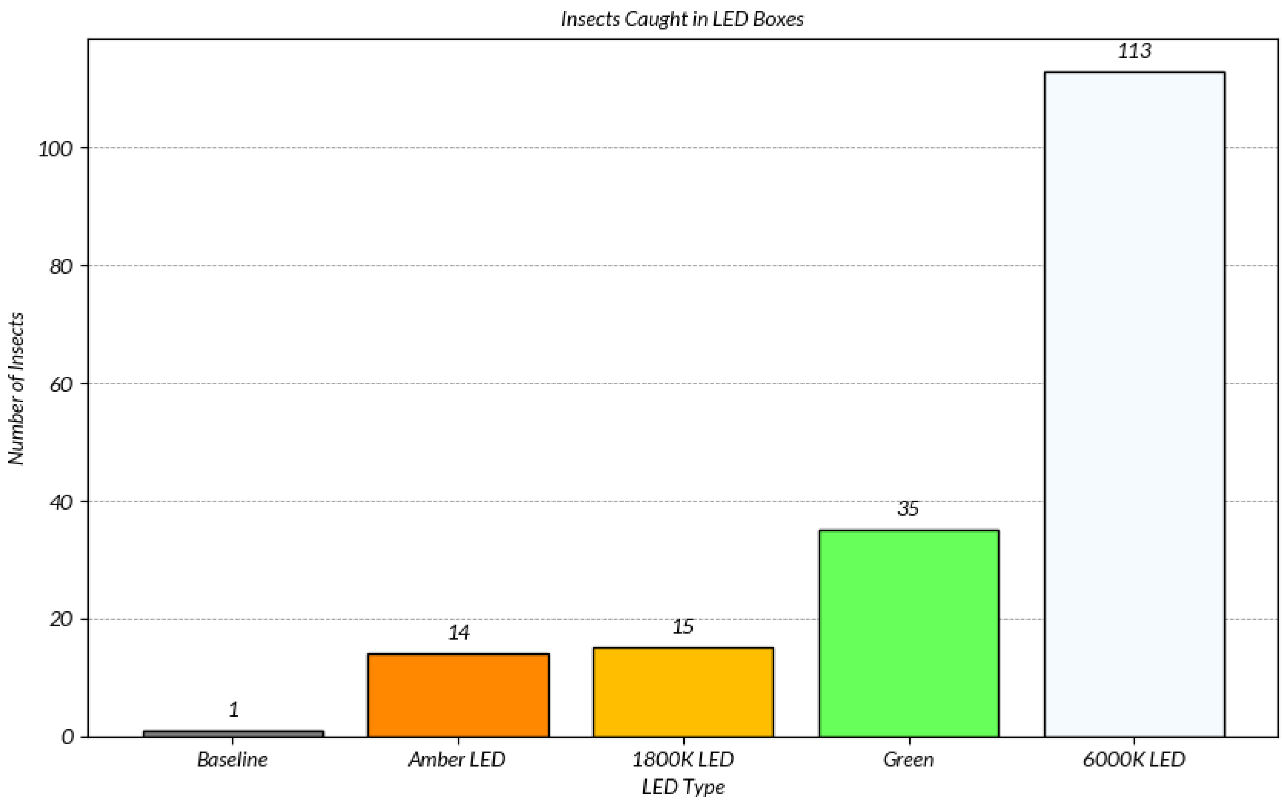


Fig. 77

Analysis and Interpretation:

The box containing the pure white LED with a color temperature of 6000K captured the most individuals, with 113. The green box captured 35 insects, followed by 1800K and amber. The baseline with the dummy LED had captured one single insect.

I was not surprised to find that the 6000K LED attracted the most, but the difference was exceeding my expectations. This is likely due to the fact that this type of LED already contains a high proportion of blue light.

Green showed a significant drop-off in attraction, with only 35 insects caught. The results for 1800K and amber LEDs were comparable, indicating that these options may not be as effective at attracting insects. Therefore, it is likely that my light could have a significant positive impact if Eco Mode or Low Intensity Mode is selected, or if the Urban Mode is tuned to a warmer color temperature.

As mentioned earlier in my Concept chapter, full 6000K should only be used where necessary.

Regarding the green light, I think there is potential to further reduce its attractiveness as the Low Intensity Mode would likely require very low light intensities in real-world scenarios.

As 1800K and pure amber LEDs showed similar results in my test, one might assume they are equivalent. However, it‘s crucial to consider that the 1800K LED still emits a broader spectrum than the amber LED, including a few green and blue components. In contrast, the amber LED has a much narrower spectral output.

This could have dual benefits: not only would it preserve the nocturnal environment by the effects of ALAN on an ecological basis, but it would also make it easier for scientific observations of the night sky by allowing more effective filtering of the light.

4.3.13 Ethical Considerations

Unfortunately, the chosen experimental setup for this project involved terminating insects, which initially seems contradictory to my overarching goal of protecting nocturnal environments and minimizing harm. This ethical dilemma led me to extensively consider alternative approaches that would preserve insect life. However, these alternatives proved too complex, and after thorough discussions with my advisor, Grognuz, and considering the time constraints, I went with the sticky box setup. This decision was not made lightly, as it involved balancing the practical limitations of my project with my ethical concerns.

All of this makes me highly value and appreciate the results, even if they ultimately translate into mere numbers and statistics at the end. The setup provided data that is very valuable and demonstrates the effectiveness of the light spectra modes selected for my design. I am convinced that by adopting innovative solutions like those proposed in my prototype, we can eventually substantially enhance our nocturnal ecological environment situation. It’s staggering to realize that, under our current lighting infrastructure, it is estimated that every summer about 1 trillion insects are killed in Germany alone due to the effects of artificial light at night (G. Eisenbeis & A. Hänel, 2009).

4.3.14

Final Prototype in Pictures

Fig. 78

Fig. 79

Fig. 80

Fig. 81

Fig. 82a

Fig. 82b

4.4 Exhibition Concept

To effectively showcase my prototype in a suitable environment and manner, it is crucial to carefully consider my exhibition concept. One of the main challenges will be to find a way to represent the luminaire in a setting that simulates a real-world scenario. As my prototype would not be a standalone object in a real landscape installation but rather part of a series, I have decided to create a virtual nocturnal environment to simulate multiple luminaires and their behavior.

The exhibition will feature a table with three projected scenarios representing potential use case scenarios for my three spectra modes. Each scenario will be accompanied by a token reader that allows visitors to select one of the scenarios, which will adapt the luminaire's color and brightness accordingly.

In addition, the table will showcase how visitors can physically interact with the head mechanism to precisely set the light according to pathway characteristics.

The exhibition will also feature a mockup or recreation of a real path on the floor. The plan is to virtually extend this pathway into the virtual environment projected onto the wall. This virtual environment should not only transport visitors to a nocturnal setting but also demonstrate how a series of luminaires interacts with pedestrians walking by. As the physical prototypes feature two motion detectors, these could be used to trigger animations when someone enters the exhibition. Additionally, I plan to use the projection to showcase the difference my design approach could make compared to standard street lighting for pathways.

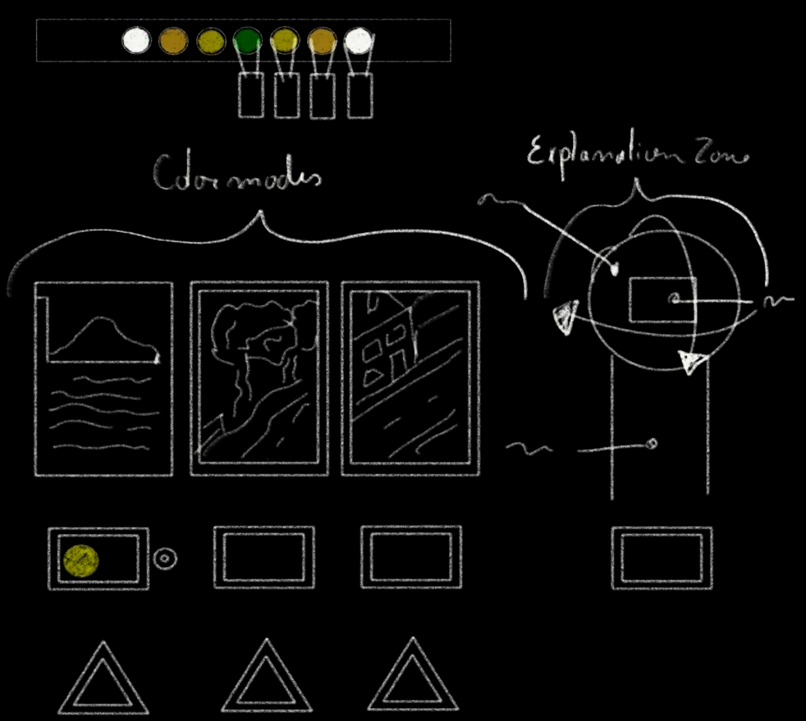


Fig. 83

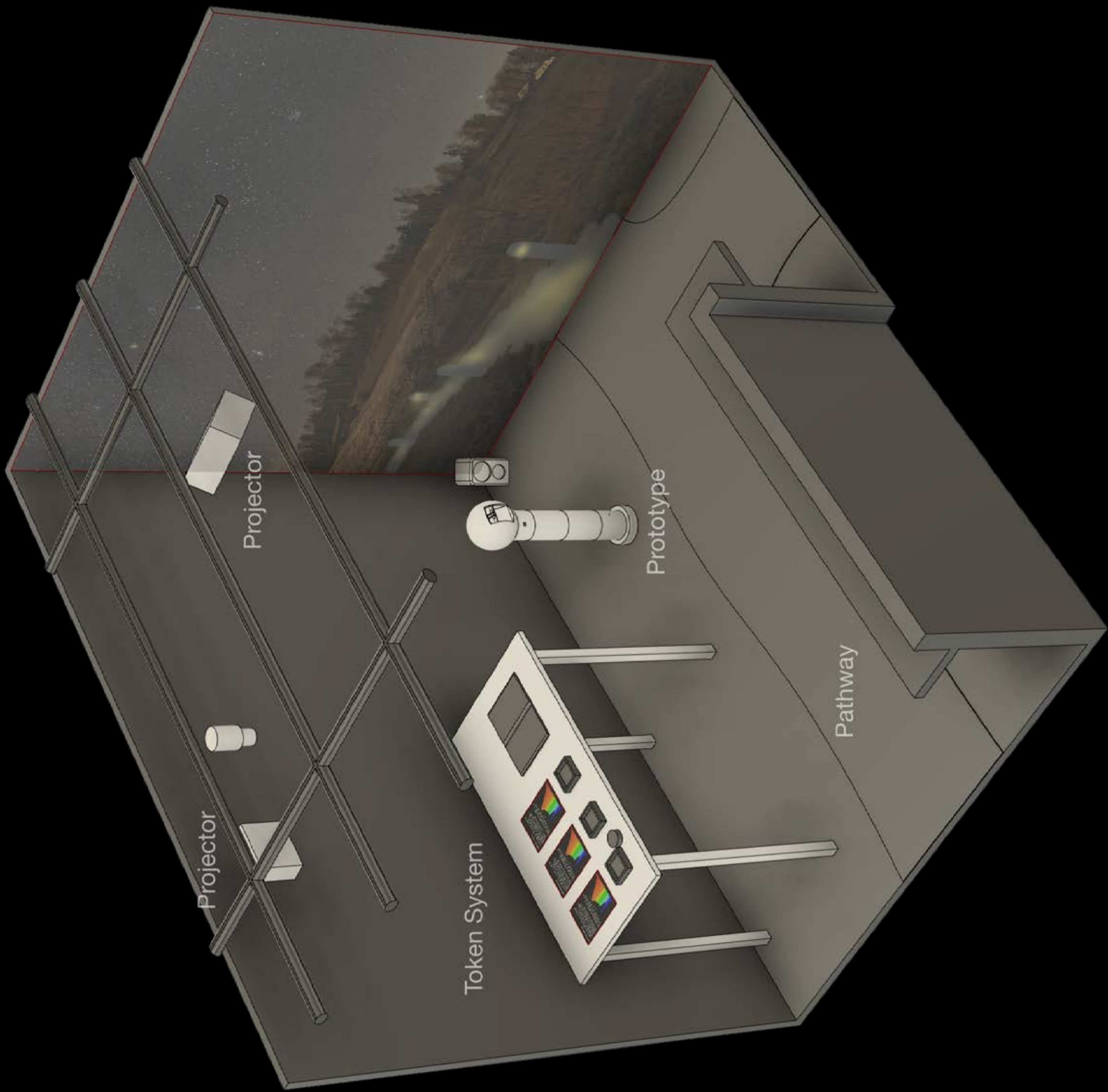


Fig. 84

5 Reflection and Evaluation

Fig. 85

Finding Anchor in a Complex Issue

The advancement of modern society brought numerous advantages, including the widespread use of artificial light, enhancing our daily lives and night-time activities. Artificial light can be seen as a tool, allowing the use of the additional time of the night. This already dates back thousands of years, with the earliest recorded use of fire, but its impact accelerated significantly with the invention of electric lighting in the 19th century (Bellis, 2019). The introduction of LED technology further amplified its presence, making artificial light a ubiquitous feature of modern life. However, as with any tool, we must consider that its benefits can come with a cost, especially if used unthoughtfully and if we do not consider potential negative consequences.

For Artificial Light At Night, it is the disruption of intricate processes, happening during the night, but it is also about losing a heritage that has been fundamental to human culture and history since the beginning.

A fascinating thing about light pollution was for me, the fact that compared to other environmental issues, we could get rid of it instantly by simply switching off the lights.

As this is not applicable in a real-world scenario, we have to find a middle ground. Considering that we live today in a world with an abundance of technology, I chose to set off on a journey to explore potential ways to improve the situation.

During my research phase, I realized through observations and the literature I reviewed, that light pollution is a complex issue, from its effects on the environment to the diversity of light sources it stems from. Especially, the realization that there were an uncountable number of different light sources at night, made it clear to me that I would need to focus on a specific scenario or use case. It was important for me to find an anchor point that I could tackle, where the short time frame of less than six months of my BA could provide an outcome, with the potential to make a change in the real world. I have noted in the Research Chapter that there is a large number of works and projects that deal with and around awareness-raising. I believe it is necessary to have these works in the first place, but it is equally necessary to have real implementations improving the issue.

My observations gave me a lot of insights and I saw a specific scenario that could be explored for my BA. It was the scenario of pedestrian pathways that were isolated from main roads and reliant on dedicated night-time illumination. These pathway scenarios often used standard lights, such as street lights or other non-optimized solutions, contributing to light pollution.

As interaction designers, we are set up with a broad range of skills and knowledge, that can range over multiple fields and domains. When it comes to the process, one of our skills is to see the broader picture and quickly find potential connections within systems.

For me, it was realizing how I could use my skills and knowledge, ranging from rapid prototyping to electronics over my insights and experiences I had gathered over the years, regarding light and how it interacts with our physical environment around us. This led me down a path, to develop a new luminaire concept, for the mentioned scenarios, that would respect the needs of the natural environment, but also fulfill our basic needs for safe locomotion at night. To achieve this goal I would need to address several criteria:

1. Providing an overall design approach that is adaptive and customizable by…

a. …allowing light to be set precisely only where needed.
b. …allowing for height adjustment of the light.

2. Providing a method to use minimal light intensities by…

a. …eliminating glare and blinding, enhancing human night vision.
b. …leveraging human night vision by using appropriate light spectra.

3. Providing a method to reduce the attraction of insects by…

a. ...using special light spectra modes.

Prototypes

Throughout my process, I developed three main prototypes. They always marked for me the outcome of that time frame and its end. I gained new insights and experience from them, which I was able to explore further in next iterations.

Although I am able to identify three main prototypes, each iteration was accompanied by numerous smaller iterations on the specific components and experiments. This already started very early, with the first experiments I conducted in February. Those experiments gave me insights into possible ways of how we could use ALAN differently, and it provided my tool and method kit that I could use to build upon the foundation I laid out during the concept seminar.

Looking back, I recognize that shortly after my initial experiments, the development of my first prototype helped me significantly, to find my direction. It marked also the moment when I was determined to pursue a use case scenario of pathway illumination. This prototype made me realize where I would need to iterate to improve its performance, but also how I could make the interaction with its components more flexible.

I consider phase two, during which the second prototype was developed, as the most significant one of my entire process. During this period, many things developed as the time pressure was still manageable. This resulted in the opportunity to explore many possible features for my final outcome. However, I also had to set priorities, where I wanted to focus. During the process I explored the potential of a touch surface to temporarily request higher light levels to increase visibility and the functionality to connect a phone to the prototype. This could have allowed me to involve the public, giving insights about my project and the issue of light pollution. As these possible branches of my prototype could have required the time and dedication of an entire Bachelor work, I decided to no further iterate on them and concentrate on the other aspects that had become important. Nevertheless, the exploration of this phase provides me with a scope of possibilities that I can explore further, if the project continues after my BA.

Another important part of my prototypes were user tests. This started with my early testing during phase two. The results allowed me to assess the performance of my reflector and explore how colors would affect visibility. In retrospect, I would like to reconduct those user tests in a more thorough and extensive manner with my final luminaire design if more time was remaining. As my work is centered strongly around non-human actors, I decided that it would be beneficial to use the remaining time to conduct attraction tests with insects. The reason for taking this decision was that the light spectra modes are an important part of my concept. I found it necessary to underline my decisions regarding the light spectra I chose, with actual data. I believe the data shows that the spectral modes, if chosen correctly, can significantly contribute to an improvement.

If I had to redo the experiment, I would also choose a non-lethal way, possibly by using a series of cameras for each box and using machine learning to count the insects.

During my process, I tried to stay on a route that would provide me at the end with a realistic outcome which could be implemented in the real world. I think this was the right decision to make. Nonetheless, if I were to redo my project, with my current insights and more time, I would probably try to incorporate more speculative aspects, as those can be an excellent trigger for new ideas.

Answering my Research Question

At the end of my research phase, I had a question in mind for which I wanted to find answers. I formulated my research question as follows:

How might we develop a better solution for artificial light at night for pathways, respecting the nocturnal needs of both non-human and human actors in our ecosystem?

In my case, the answer to this question is a prototype that took the form of a customizable outdoor luminaire. This luminaire distinguishes itself from other common designs, as it is designed with environmental consciousness in mind. This resulted in a prototype that features the following control mechanisms and characteristics:

A mechanism to direct light for where it is needed without spillover.

A slider to set the cutoff and width of the light beam.

A spacer module to set the required height for the light.

The ability to choose from three different spectral modes.

The possibility for luminaires to interconnect.

Sensors to improve the light usage.

A reflector that produces no glare.

5.4 Contribution to Interaction Design

My studies in interaction design, over the past three years, have shown that it is a highly diverse field with many intersections in other disciplines. Even today, I find it challenging to explain the field concisely to someone outside of it.

I believe it is up to the individual, in the end, to form their own definition of what interaction design means and how we can contribute to it, as everyone involved shapes it with their own background story and personal focus. With this said, I came to the conclusion that in the bigger picture, especially in regard to my BA project, it means for me to contribute by doing a service for our natural environment. It means improving a situation for everyone involved. In my case, the focus is shifted towards non-human actors. But by working for our natural environment, the ecosystem, we are doing in the long term a favor to ourselves. A view through the window of our spaceship, the night sky, makes us realize that we are all together on this journey, flying through space.

I have identified three different levels of interactions in my work, contributing to the pool of examples, of what interactions can mean on different scales.

On the first level, we identify the physical, hands-on interactions with the design itself, as part of the product. This would happen between the first user, the customer, and the design. It includes rotating the head mechanics, setting the LED slider, and the specific spectra modes. These interactions allow for a precise use of light with the intention to facilitate the intelligent use of artificial light at night and are part of the product service.

The second level includes the non-physical interactions happening between the end user and the luminaire. By walking along the pathway, we would trigger the behavior of the design and in return receive the appropriate levels of illumination for safe locomotion in the area. This level also includes the communication that could happen between the luminaires as a system, exchanging data, such as the lighting logic and, in a possible further development, the exchange of other environmental data.

Above the second level, I identify the large-scale and long-term relationships that we as a society would engage in, between us and the natural environment. With our current lighting system, we go as well into a relationship, but that one is destructive. By deploying an approach such as I propose, we can find the balance between the best for both sides. I believe that over large spatial scales and long terms, we can thus help the ecosystem to rehabilitate, closer to its original state.

My work could therefore also be considered as a case study, that we not only can contribute to interaction design by adding new interactions but also through removing specific ones that cause harm and destruction.

5.5 Next Steps

If my BA project continues after my degree, I would like to address these following next steps. First, it would be beneficial to get into contact with more experts in the field. I now have a high-fidelity prototype, including its documentation at my disposal. It provides a clear communication piece which I can use to showcase my ideas. I believe that by getting into exchange with more experts across the field, it could spark new ideas. Here, one of my main goals is to get into contact with the International Dark-Sky Association. As the association is set up internationally, they could provide an excellent way for outreach. A fantastic opportunity could be to present my work at one of their annual conferences, happening next in November 2024.

As the research also costs money, it would be necessary to raise funds from potential investors as well. Therefore, a large outreach is needed.

To develop a product that is, in the end, production ready, a collaboration with industrial designers, engineers, and coders would be required as well. My prototype can be used as an instance to demonstrate which requirements and functionalities need to be taken into account for the development of a final product.

Personally, I would like to invest more time and research into the development of special light spectra modes for local areas. This could take the form of a database that contains information about which precise spectrums should be used for the specific location, with even more control over the light. I am quite skilled in prototyping when it involves technicalities and this could be a very interesting direction to pursue.

Another important point I want to address after my BA relates to Artificial Intelligence. As AI is heavily on the rise and will find its way into society in many ways, I think it will become necessary to do research on how it could benefit my work. I believe it holds great potential for the management of an intelligent luminaire network.

All in all, my studies in interaction design, including the tools, methods, and design thinking I have acquired, have equipped me with unique skills. Combined with my prior knowledge, these skills enable me to pursue a unique career in the field of light pollution.

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Derer F. (n.d.). *Raupe des Braunwurzmönchs* [Photograph]. NABU. Retrieved from https://hamburg.nabu.de/tiere-und-pflanzen/insektenschutz/index.html

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7 Appendix

Interview Findings

Interview with Jérôme Mayer, February 14th, 2024

Main Discussion Points (summarized):

Alternative Lighting Concepts: Fribourg has been experimenting with unique lighting solutions such as phosphorescent stones and small lamps with solar panels. These efforts are part of a broader light strategy developed over two years aimed at combating light pollution.

Phosphorescent Stones and Solar Lamps: The city tested phosphorescent stones and solar-powered lamps that require no external electricity, making them ideal for areas without power access, such as riversides. These solutions are environmentally friendly and have been well received by the public, especially for pedestrian paths where no vehicular traffic is present.
The solar-Powered LED Lights were described by the public as romantic and reminiscent of candles, creating beautiful pathways. However, it has been found, that the solar powered lamps are more suited for a general purpose than the phosphorescent stones.

Maintenance and Sustainability: The innovative lighting elements, such as the phosphorescent stones, are designed for durability and low maintenance, embedded in concrete with built-in batteries where necessary.

Public Feedback: The feedback from residents has been mostly positive, particularly regarding the increased beauty and sufficient lighting for walking. An online survey showed that about three-quarters of responses were positive towards the new lighting methods.

Dimming Streetlights and Energy Efficiency: In response to the energy crisis, Fribourg has dimmed streetlights by up to 70% during certain hours and fully turned off 10% of streetlights. The city is exploring smart lighting systems to programmatically adjust light intensity, aligning with new cantonal energy laws mandating reduced lighting at night.

Motion Sensors Integration: Fribourg is integrating motion sensors with new and existing LED streetlights to adjust lighting based on movement. This smart technology allows for customizable lighting levels, enhancing energy efficiency and reducing light pollution.

Smart City Features: The motion sensors are part of a broader „Smart City“ initiative, allowing for programmable lighting adjustments.

This system can vary light intensity based on time, presence, and other factors, significantly contributing to the city's adaptive lighting strategy.

Traffic-sensitive Lighting: For larger roads, the city uses traffic cells and systems that adjust lighting based on traffic volume, ensuring that lighting levels are optimized for safety and efficiency.

Color Temperature Strategy: Fribourg has developed a color temperature strategy to minimize the impact on biodiversity and human health. Different areas of the city use varying color temperatures to mimic natural light conditions historically prevalent in those areas, such as warmer tones in historical districts and cooler tones in commercial zones.

Commercial and Central Areas: In the commercial areas of the city, where there are many shops and buildings, a color temperature of 3000 Kelvin is used. This is considered a warm white, which is welcoming and comfortable for shopping areas and busy streets.

Historic Areas: For the historical parts of the city, a slightly warmer color temperature of 2700 Kelvin is chosen. This temperature is intended to mimic the ambiance of firelight, providing a cozy and historically resonant lighting that enhances the aesthetic of these areas without overwhelming the senses.

Areas Near the River: In places close to the river, where the impact on the natural environment is a significant concern, an even warmer and softer color temperature of 2200 Kelvin is selected. This orange-red light is much less disruptive to wildlife and helps to reduce light pollution, creating a calm and serene atmosphere.

Safety and Security: Despite concerns, there has been no increase in safety issues in areas with reduced or no lighting. The local police have not reported problems due to decreased lighting, suggesting that well-considered reductions in light pollution do not compromise public safety.

Homogeneity in Lighting: A consistent lighting strategy across the city aims to enhance safety and comfort, addressing the issue of light pollution without compromising visibility and security.

Long-term Implementation: The city acknowledges that fully implementing this comprehensive light strategy will take 10-15 years and require significant investment. However, certain aspects, like the Smart City boxes, are being implemented more rapidly.

Early Positive Outcomes: Preliminary observations suggest a reduction in light pollution, particularly along the river, indicating potential benefits for biodiversity.

Interview with Vincent Grognuz, March 12th, 2024

Main Discussion Points (summarized):

Concerns Over Standard Lighting in Biodiverse Areas: There were concerns about the widespread use of standard streetlamps in areas rich in biodiversity, suggesting that such practices may not consider the adverse effects on local ecosystems, especially at night.

Potential Solutions and Innovations:

Exploring lighting designs that minimize ecological disruption, such as lights with a sharp cutoff to prevent spillage into natural habitats, glare-reducing reflectors, and adjustable light temperatures to lessen impacts on wildlife.

Smart lighting technologies were acknowledged for their potential but also criticized for inadvertently affecting large wildlife, indicating the need for more nuanced solutions.

Broader Ecological Considerations:

The importance of dark corridors for wildlife movement was emphasized. Findings from GPS tracking studies on deer in Geneva suggested that even small illuminated roads can significantly disrupt wildlife movement.

There is ongoing interest in understanding how light pollution affects nocturnal raptors and other wildlife, with initiatives in Switzerland aimed at tracking and mitigating these impacts.

Light Spectrum and Wildlife: The effects of different parts of the light spectrum on wildlife were discussed, with a general consensus that all artificial light can disturb nocturnal animals. Red light, while less disturbing for mammals, might not be ideal for plant communities.

Future Directions:

The potential for adaptive lighting solutions tailored to specific environmental needs and species protections was explored, with an emphasis on protecting sensitive species like bats.

The conversation suggested a need for interdisciplinary research and innovative designs that consider the full spectrum of ecological impacts of light pollution.

Understanding Insect Behavior: Recent research revealed why insects are attracted to lamps, highlighting a natural navigational behavior disrupted by artificial light sources, leading to exhaustion or death.

Innovative Lighting Designs: We had a discussion on developing a spiral reflector that completely hides the light source, preventing direct visibility and potentially reducing insect attraction. This aligns with minimizing the impact on insects while providing necessary illumination.

Pedestrian Lighting Considerations: For pedestrian paths, there was consideration for using lower-height lights or lights placed directly on the ground, which could reduce the impact on insects flying at higher altitudes and still provide adequate guidance and safety for people.

Biological and Environmental Sensing: The potential for street lamps to serve dual purposes by incorporating bioacoustic sensors or other environmental monitoring tools was discussed, enabling widespread data collection on wildlife such as birds and insects.

Spectral Sensitivity of Insects: Our conversation touched on insects‘ spectral sensitivity and how certain wavelengths might be less attractive to them, suggesting opportunities to develop lighting that minimally impacts insect behavior while maintaining human visibility and safety.

Testing and Evaluating New Lighting Solutions: Suggestions were made for experimental setups to test the effectiveness and ecological impact of new lighting designs, comparing them against traditional and non-illuminated controls to assess insect attraction and behavior.

Portable Street Lamps: The use of portable, solar-powered street lamps in experiments allows for flexible testing setups, facilitating direct comparisons between traditional, innovative, and control (no light) conditions to assess their effects on local ecosystems.

Detailed Observational Studies: Comprehensive observational studies aimed at understanding the interactions between plants and pollinators under different lighting conditions were described, building detailed interaction networks to identify specific influences of artificial light.

Importance of Nocturnal Pollinators: The crucial role of nocturnal pollinators, such as moths, in ecosystem health and crop pollination was highlighted, challenging the focus on diurnal pollinators like bees and butterflies alone.

Innovative Lighting Design Discussion: Exploration of lighting designs that minimize impact on wildlife, including a spiral reflector that conceals the light source and the use of red light to reduce disturbance to nocturnal animals.

Lighting's Impact on Animal Behavior: Observations on how different types of light (white vs. red) affect animal stress levels and behavior suggested that nocturnal animals are particularly sensitive to bright lights.

Adaptive Responses to Lighting: Anecdotal evidence and personal observations about how both humans and animals adapt to varying levels of artificial light were shared, with a particular focus on the difference in perception between day and night.

Community Initiatives to Reduce Light Pollution: A mention was made of a city that turns off its street lamps during certain nighttime hours to mitigate light pollution, and the observable effects on terrestrial mammal behavior, including new movement corridors and changes in proximity to human settlements.

Interesting Points:

The use of red light seems to be less disturbing to nocturnal animals, including moths and barn owls, compared to white light. This suggests that red light might have a lesser impact on nocturnal wildlife, potentially because it's less visible or less disruptive to them.

Discussions on spectral sensitivity and the mention of insects having a drop in sensitivity around 500 nanometers (green spectrum) imply that insects' responses to light can vary significantly across the spectrum. This indirectly suggests that some insects might indeed respond differently to orange and red light compared to other wavelengths.

Moths and other nocturnal insects have evolved to navigate by keeping their back to the most illuminated part of their environment, traditionally the night sky lit by the moon and stars. This behavior ensures they fly in a consistent direction. However, artificial light sources such as lamps disrupt this navigational method. When a moth encounters artificial light, it attempts to align its back to the lamp, leading to disoriented flight patterns around the light source. This continuous, exhausting movement can result in the moth's death either due to exhaustion or by coming into direct contact with the light source. Recent research has shed light on this behavior, suggesting that the disruption caused by artificial lights is due to the moths' innate navigation system being tricked by the unnatural brightness of these lights, leading to fatal disorientation.

Q&A

Q: How do insects react to flickering caused by PWM?

A: Vincent wasn‘t sure, but he agreed that researching this would be intriguing.

Q: Would integrating environmental sensors into luminaires be interesting for research purposes? If so, what sensors would be useful?

A: He found the idea of integrating environmental sensors into luminaires highly beneficial. The concept of street lamps not only providing light but also serving as platforms for environmental monitoring was emphasized. Specifically, the inclusion of bioacoustic sensors was discussed. These sensors could collect large-scale data on wildlife, such as birds and insects, across different areas. Bioacoustic monitoring, coupled with AI advancements, allows for automatic species identification from their sounds, enhancing biodiversity monitoring efforts. Additionally, using radar for tracking insect migrations and other phenomena was mentioned, although incorporating such technology in street lamps is challenging due to size constraints.

Q: What methods could I use to determine my impact?

A: **Comparative Pollinator Collection:** Collecting all pollinators found in basic wildflower strips over three days across different lighting treatments (e.g., your new lighting system, a conventional one, and no light control) to compare the varieties and quantities of pollinators attracted or repelled by each setup.

A: **Observing Dead Insects:** Placing a large white sheet on the ground under the lighting systems overnight and counting the number of dead insects found in the morning. This method aims to demonstrate whether the new lighting system results in fewer deaths compared to conventional systems and the control setup.

A: **Mammal Observation:** If focusing on mammals, installing camera traps and monitoring the area for an extended period (suggested two weeks) to observe any changes in mammal behavior or presence due to the lighting systems.

AI Chat History for Code Generation and Additional Resources:

For full transparency and reproducibility of this research, the relevant AI-generated code, chat history, and workflow details, along with other supplementary materials, are available in the GitHub repository.

You can access these supplementary materials using the following link: https://github.com/Loic-Hommel/lumina-thesis