[DC] Computational Design of Smart Lighting Systems for Visually Impaired People, using VR and AR Simulations

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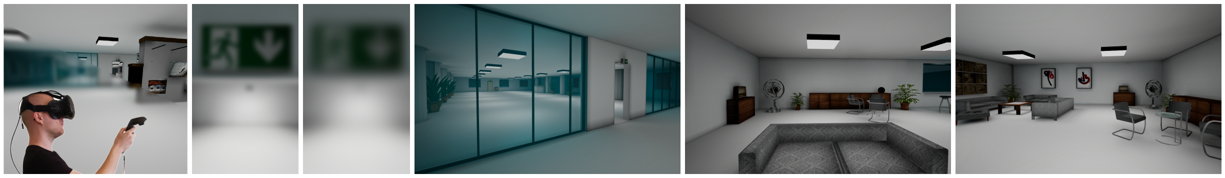

Figure 1: In our research work, we conduct user studies in VR, simulating vision impairments like reduced visual acuity (as shown for the escape-route signs) in an immersive virtual environment with a physically plausible lighting simulation.

Abstract

This Doctoral Consortium paper presents my dissertation research in a multidisciplinary setting, spanning over the areas of architecture, specifically lighting design and building information modeling, to virtual reality (VR) and perception. Since vision impairments are hardly taken into account in architecture and lighting design today, this research aims to provide the necessary tools to quantify the effects of vision impairments, so design guidelines regarding these impairments can be developed. Another research goal is the determination of the influence of different lighting conditions on the perception of people with vision impairments. This would allow us to develop smart lighting systems that can aid visually impaired people by increasing their visual perception of their environment. This paper also outlines the concept for a tool to automatically generate lighting solutions and compare and test them in VR, as design aid for architects and lighting designers.

Index Terms: Computing methodologies—Virtual reality; Computing methodologies—Perception; Applied computing—Health informatics; Human-centered computing—User studies; Human-centered computing—Virtual reality;

1 Introduction

Recent data from the U.S. National Eye Institute (NEI) [8] show that approximately 26 percent of people over the age of 40 in the U.S. have some form of vision impairment that reduces their visual acuity and this number is expected to increase in the years to come. Currently, architectural design mostly ignores the needs of this significant portion of the population [4]. There are international standards and norms in place that provide specifications for lighting design and emergency signposting. However, the fact that only some mention adaptations for people with vision impairments in their informal appendices shows that effects of these impairments are not always taken into account. Proper tools to measure the effect of vision impairments are missing. Such tools could also enable the development of smart lighting systems – systems that control and adapt the illumination in a room according to user preferences or data from occupancy sensors and light sensors – which could improve the visual perception of people with vision impairments.

Lighting design – the development of a lighting concept – is a mostly manual, time-consuming process, that solely relies on the expertise of the lighting designer and their knowledge of the influence of certain lighting setups on the perception of people with vision impairments. User studies are needed to quantify these effects and derive guidelines from them, as well as use this data for automatic tools to assist lighting designers and architects in their work. However, conducting reproducible user studies on vision impairments requires a large number of participants with the exact same form and severity of impairments in order to quantify the effects of respective impairments on perception. Therefore, other, more efficient approaches are necessary. Virtual reality simulations of vision impairments could be used to conduct user studies with participants with normal vision and just graphically simulate the impairments. There has been some research ([1], [12], [5], [6]) on how to simulate vision impairments in recent years. However, most of this work is dedicated to demonstrational or educational purposes. Accurate simulations that could be used in user studies are – to the best of our knowledge – still missing.

In our research, we try to close this gap by introducing a new methodology to conduct user studies with simulated vision impairments. We leverage cutting-edge VR and eye-tracking hardware to simulate complex vision impairments and investigate the influence of different illumination conditions on visual perception under vision impairments. Furthermore, we provide a framework to automate the placement of luminaires and sensors for smart lighting systems that are specifically targeted at increasing the perception of people with vision impairments. We plan to integrate our methods into a software tool that can be used as design aid for lighting designers and architects to improve and accelerate their workflow through automation and optimization, provide additional information about accessibility in respect to vision impairments and serve as tool to compare and validate existing or newly generated designs of smart lighting concepts. Preliminary results indicate that our methods to simulate vision impairments can be used in user studies to identify problems in current norms or regulations, and that more research is necessary to better understand the effects of vision impairments on perception.

2 Related Work

Since our research topic spans multiple disciplines, we have to consider related work in different areas, from simulating vision impairments over lighting design to building information modeling.

2.1 Simulating Visual Impairments

There has been some research on simulating vision impairments in AR or VR in recent years ([1], [12]) based on photographs of the U.S. National Eye Institute or images from online simulators and

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using modern game engines. Lewis et al. for example simulate eye diseases in a 3D game, using the Unreal Engine 3 [5] or the Microsoft XNA framework [6] to raise awareness and give unimpaired people an understanding of the effects of visual impairments. We also decided to use a game engine (Unreal Engine 4) to implement our simulation, but in contrast to Lewis et al., who do not provide any possibilities to control the severity of symptoms, our simulation can be calibrated to different levels of severity and is adjusted to each individual users visual acuity. The most influential work for our research in this area was done by Hogorvorst et al. [2], who modified 2D images in order to give people with normal sight an impression of the problems people with vision impairments face every day. They used the *Landolt C* in their eyesight tests and found a linear correlation between a just recognizable threshold for blurring an image and visual acuity. These findings build the basis of our simulation of reduced visual acuity.

2.2 Lighting Design

The efficient and aesthetic placement of luminaires in a virtual 3D scene, under the consideration of light conditions and costs, is called *lighting design*, and has recently received increased scientific attention ([7], [11]). The work by Schwarz et al. [11] is targeted at lighting design for procedural modeling and extends the presented workflow in this field, using a shape grammar with lighting design capabilities. Aesthetic conventions can be met by describing illumination goals that have to be achieved under certain constraints, such as specifications of luminaire models or installation sites. The system then procedurally generates illumination configurations for building facades. Related work in this area mostly try to achieve a concrete lighting result by relying on a direct specification or adopting a painting paradigm to provide the desired illumination result as input to the algorithm as proposed by Lin et al. [7] or Zmugg et al. [16]. Furthermore, other approaches only consider abstract lights, while Schwarz et al. [11] use real luminaires in their approach and support relating multiple luminaires, which results in a complex constraint satisfaction problem. A stochastic approach is applied to sample the subspace of luminaire configurations that satisfy all given constraints. This optimization strategy serves as the basis for our optimization to generate smart lighting system setups.

2.3 Building Information Modeling (BIM)

The concept of *Building Information Model (BIM)* has been invented in order to improve information management and speed up workflows in capital facilities industry. A BIM is a data set that typically combines various views on a facility project with specific information for different disciplines and serves as a shared knowledge resource between disciplines, enabling collaboration and exchange of information between different stakeholders [10].

BIM has gained more importance in architectural design and construction workflows in recent years through the use of BIM data in research regarding energy and lighting simulations. One example is the work of Yan et al. [15], which provides the possibility of energy simulations by connecting *Building Energy Models (BEM)* with BIM. Integration possibilities of BIM into daylight simulations tools were investigated by Kota et al. [3], who developed a prototype that integrates *Revit*, which is used as BIM tool, into daylight simulation tools like *DAYSIM* or the ray-tracing software *Radiance*. Similarly, Ock et al. [9] conducted research on *Building Energy Management Systems (BEMS)*, using BIM for daylight simulations in combination with weather data to generate control patterns for BEMS.

In our earlier work [14] we took the approaches of Yan et al. [15] and Kota et al. [3] one step further by integrating BIM into our light planning software HILITE [13], which provides physically plausible lighting simulations of complex scenes and allows interactive changes. We plan to also use HILITE for the light simulations necessary for the projects described in this paper.

3 Research Approach

The topic of this thesis is placed in an interdisciplinary setting between architecture and computer science, namely computational design. Our research is driven by architectural design needs and implemented using computer graphics algorithms and VR techniques. In order to contribute in the this interdisciplinary research field, we formulated the following research questions:

- *Q1: How can simulations be used to evaluate and quantify the effects of vision impairments on visual perception?*
- *Q2: How do different lighting conditions affect the visual perception of people with vision impairments and how can smart lighting systems help to improve their perception of their environment?*
- *Q3: How can the placement of luminaires and sensors be automated to provide a lighting designer with solutions that are already optimized to certain constraints like visual impairments?*

We subdivided our research into three projects, each one targeted at answering one of the three research questions above. We set up a research plan and identified the necessary steps for each project to achieve the corresponding research goals. The following sections outline the content of these projects.

3.1 Project 1: A VR-based User Study on the Effects of Vision Impairments on Recognition Distances of Escape-Route Signs in Buildings

In our first project we aim to answer research question *Q1*. The main goal of this project is the development of a methodology to investigate effects of vision impairments on perception. In order to quantify effects of such impairments, we need to conduct user studies. However, finding a large number of user study participants who have the exact same form of vision impairments, which allows a reliable quantification of the effects of respective impairments, is cumbersome. For this reason, we chose a different approach and decided to conduct our user studies in VR and graphically simulate the visual impairments. Thus, a realistic simulation of the effects of vision impairments is necessary. For user studies in VR, we also need a highly immersive environment to mimic real-world conditions and a high-quality lighting simulation to achieve a high level of realism. As use case for this project, we chose to evaluate the maximum recognition distance of escape-route signs in buildings under the influence of vision impairments.

3.1.1 Approach

For our VR user study, we used participants with normal or corrected sight (wearing contacts or glasses) and graphically simulated a reduced visual acuity (we refer to our recent publication [4] for further details on demographics or our user study protocol). Our VR simulation starts for every user study participant with an eyesight test in VR. A common sign that is used for eyesight tests in medicine is the *Landot C* or *Landolt ring*, which has a gap at 1 of 8 possible positions (see Figure 2). The correct position of the gap in the Landolt ring has to be identified and indicated via track pad input on a HTC vive controller by the user. The size of the ring corresponds to a visual acuity level, so if we want to test for a certain level of reduced visual acuity we just use the corresponding size of the Landolt ring. Hogervorst et al. [2] determined a relation between the σ parameter of a Gaussian blur and the visual acuity

Figure 2: *Landolt C* (also known as *Landolt ring*)

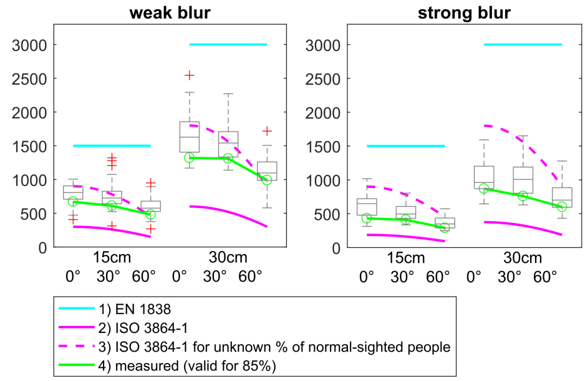

Figure 3: Comparison of our measurements of recognition distances to different norms and standards. Reprinted from [4]

of a person. Following these findings, we simulate a reduced visual acuity by applying a Gaussian blur to the image, the size of which we determine during our eyesight test.

There are a number of factors that influence the visual acuity of a person in VR. The resolution of the HMD already induces a mild vision impairment and the fixed focal distance creates a vergence-accommodation conflict, that can make the user's eyes tired over time and possibly reduce their visual acuity. Another issue is a possible misplacement of HMD that can reduce the sharpness of the image. We recognize all of these factors and add our Gaussian blur on top of them. This means, we stepwise increase the blur of a participant's vision (that is already reduced due to the factors mentioned above) until a certain size of the Landolt C, that corresponds to a certain level of reduced visual acuity, can not be recognized anymore. This methodology allows us to calibrate the vision of all our user study participants to the same level of reduced visual acuity, thus enabling us to take measurements and perform statistical analyses on the results. In this work, we conducted a series of tests with clear vision and different levels of blurred vision and measured the maximum recognition distances of escape-route signs people could reach with different reduced vision conditions.

3.1.2 Results

We took measurements for 15 and 30 cm high signs, each at 3 different viewing angles. The results are shown in Figure 3. The vertical axis shows the distance in centimeters at which the participants recognized the signs. The figure shows that current norms and standards do not sufficiently or accurately take vision impairments into account. Therefore, means to conduct user studies and evaluate current norms and standards in respect to vision impairments are vital to create more inclusive and accessible environments. A detailed analysis of our measurements and the validity of our data, can be found in our paper [4].

3.2 Project 2: Effects of Illumination on Visual Perception under Vision Impairments in Virtual and Augmented Reality

In this project, we plan to investigate how the effects of complex, gaze dependent vision impairments can be measured and simulated in VR and AR. Once we have a realistic simulation of complex vision impairments, we can investigate how different lighting conditions affect the visual perception of people with vision impairments. This will also allow us to evaluate if smart lighting systems can help to improve the perception of the environment of visually impaired people and answer research question *Q2*. In order to answer this research question, the following components have to be combined:

1. Methodology to investigate different lighting scenarios
2. High-quality lighting simulation
3. Realistic simulation of vision impairments
4. Highly immersive environment (to conduct user studies)
5. Simulation of smart lighting systems
6. Smart lighting concepts that are specifically designed to improve visual perception
7. Quantification of effects of different lighting conditions on visual perception (user studies)

While components 1-4 can be taken from our previous work [4], components 5-7 are yet to be developed. In this project we will start by simulating complex vision impairments in VR and video-see through AR. We chose VR and AR in order to efficiently conduct user studies, following the methodology of our previous work [4], by graphically simulating reduced visual acuity and other vision impairments. This methodology allows us to investigate the visual perception of participants under different lighting conditions as well as with different visual impairments. We will use cutting edge VR and AR hardware, as well as eye-tracking devices, since the majority of perceptual effects are gaze dependent and therefore require eye tracking in order to simulate these effects correctly.

3.2.1 Approach

Our first step will be to develop realistic simulations of complex, gaze dependent vision impairments, using eye-tracking with the HTC Vive pro and the Pupil labs eye-tracker We will implement eyesight tests in VR to determine a participant's visual acuity, field of view, contrast sensitivity and other aspects of human vision. Building upon these tests, we will implement means to realistically simulate impairments to these aspects of human vision. Following the methodology from our previous project [4], we plan to develop calibration procedures to calibrate these vision impairments of different users to the same level, which allows us to conduct user studies in VR and properly quantify the effects of vision impairments. A simulation of complex vision impairments in video-see through AR will serve as aid for design processes in architectural fields as well as for demonstrational or educational purposes. The second part of this project is to simulate and investigate different lighting conditions in VR. We will use our high-quality lighting simulation, calculated with HILITE [13], in a highly immersive VR environment. In order to investigate different lighting scenarios, we will then develop metrics to rate the quality of a lighting scenario. Finally we will simulate the behavior of smart lighting systems in VR and conduct user studies to investigate the influence smart lighting systems can have on the visual perception of people with vision impairments. A further extension of this work to simulate smart lighting systems in video-see through AR will require a reconstruction of the real world and elaborate relighting techniques to dynamically change the illumination in the scene, which is displayed in the AR headset.

3.3 Project 3: Automatic Design of Smart Lighting Systems

In order to answer research question *Q3*, our third project will be targeted at developing methods to find optimal placements of luminaires and sensors for smart lighting systems. These automatically generated smart lighting setups will be optimized to certain constraints, including vision impairments, by building upon the knowledge gained from *Project 2*. The illumination produced by the resulting setups will then be simulated in VR to allow comparing, testing and interactively modifying these solutions in VR.

With this project, we want to provide lighting designers with simulation support in the design phase by integrating physically plausible lighting. The goal of our approach is to automate the placement of lighting objects, sensors, and actuators in architectural spaces, based on given functional requirements and BIM data. Finally, we will generate, optimize and interactively evaluate light scenes for activities that take place in these spaces.

3.3.1 Approach

We identified the following steps as required parts of this project:

1. Integration of BIM data as input for lighting simulation
2. Physically plausible lighting simulation
3. Daylight simulation
4. Use of real-world luminaires
5. Import of real-world geometry (to allow comparisons)
6. Incorporation of constraints to find valid setups, based on:
   - BIM data
   - Official regulations and norms
   - Effects of vision impairments on perception
7. Optimal luminaire and sensor placement for smart lighting systems
8. Interactive modifications in VR

As related work ([15], [3]) has shown, there are different methods and tools that already allow BIM data as input for lighting simulations. We plan to build upon our earlier work [14] and use HILITE [13] to calculate our physically plausible lighting simulation, based on information derived from imported BIMs. HILITE also features a daylight simulation, which we can take into account in our optimization step, and allows us to use real-world luminaires. In order to validate our simulations, we will use 3D models and BIM data of real-world buildings and compare our simulations to real-world conditions. Our optimization algorithm is based on the approach of Schwarz et al. [11] and additionally takes complex lighting simulations, including indirect light, into account. Furthermore, the constraints from our optimization will be derived from BIM data, official regulations and norms regarding indoor lighting, and our own findings from the previous projects regarding the effects of vision impairments on perception. Our algorithm will then yield solutions for luminaire and sensor placement for smart lighting systems, optimized to the given constraints. Finally, these solutions will be presented in a VR simulation that allows the user to compare different solutions and make interactive modifications.

4 Current and Expected Results

Our recent work [4] has shown that none of the current standards and norms, regarding the placement of escape route signs, accurately take vision impairments into account. More empirical data and research is needed to determine the exact influence of vision impairments on recognition distances in order to create new, more accurate regulations and we believe that VR simulations are a good way to do this. Our second project on the effects of illumination on visual perception under vision impairments is still in the planning phase. Following the findings of this project, we expect to be able to derive guidelines for the placement of luminaires in real life (taking different perceptual factors into account) for our third project, which is focused on the automatic placement of luminaires. This will allow us to also develop smart lighting concepts that are specifically designed to improve visual perception for visually impaired people. Finally, we expect our research to yield:

- new methodologies to conduct user studies on perception under vision impairments, using VR simulations,
- detailed analyses of the influence of different lighting condition on the visual perception of people with vision impairments in VR and AR,
- VR simulations of smart lighting systems that allow lighting designers to compare, validate and interactively adapt different lighting concepts, and
- a method to automatically generate optimal smart lighting system setups according to given constraints, such as the influences of vision impairments and the effects of illumination on visual perception.

Acknowledgments

I would like to thank my supervisors Michael Wimmer and Georg Suter for their guidance and supervision and Henry Fuchs for his help and enthusiasm to give valuable input and feedback on my research. Furthermore, I would like to thank Steven K. Feiner for supervising me during my research stay at Columbia University, giving me the possibilities to use the latest VR/AR and eye-tracking technologies in his lab and to learn from his expertise in the field of VR and AR research.

This research is enabled by the Doctoral College Computational Design (DCCD) of the Center for Geometry and Computational Design (GCD) at TU Wien and by the Competence Center VRVis. VRVis is funded by BMVIT, BMDW, Styria, SFG and Vienna Business Agency in the scope of COMET - Competence Centers for Excellent Technologies (854174) which is managed by FFG.

References

[1] H. C. Ates, A. Fiannaca, and E. Folmer. Immersive simulation of visual impairments using a wearable see-through display. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, pp. 225–228. ACM, 2015.

[2] M. Hogervorst and W. Van Damme. Visualizing visual impairments. *Gerontechnology*, 5(4):208–221, 2006.

[3] S. Kota, J. S. Haberl, M. J. Clayton, and W. Yan. Building Information Modeling (BIM)-based daylighting simulation and analysis. *Energy and Buildings*, 81:391–403, 2014.

[4] K. Krösl, D. Bauer, M. Schwärzler, H. Fuchs, G. Suter, and M. Wimmer. A VR-based user study on the effects of vision impairments on recognition distances of escape-route signs in buildings. *The Visual Computer*, pp. 1–13.

[5] J. Lewis, D. Brown, W. Cranton, and R. Mason. Simulating visual impairments using the unreal engine 3 game engine. In *Serious Games and Applications for Health (SeGAH), 2011 IEEE 1st International Conference on*, pp. 1–8. IEEE, 2011.

[6] J. Lewis, L. Shires, and D. Brown. Development of a visual impairment simulator using the microsoft XNA framework. In *Proc. 9th Intl Conf. Disability, Virtual Reality & Associated Technologies, Laval, France*, 2012.

[7] W. C. Lin, T. S. Huang, T. C. Ho, Y. T. Chen, and J. H. Chuang. Interactive lighting design with hierarchical light representation. *Computer Graphics Forum*, 32(4):133–142, 2013. doi: 10.1111/cgf.12159

[8] NEI Office of Science Communications, Public Liaison, and Education. Prevalence of Adult Vision Impairment and Age-Related Eye Diseases in America. `https://nei.nih.gov/eyedata/adultvision_usa`. Accessed: 2018-07-08.

[9] J. Ock, R. R. Issa, and I. Flood. Smart building energy management systems (BEMS) simulation conceptual framework. In *Winter Simulation Conference (WSC), 2016*, pp. 3237–3245. IEEE, 2016.

[10] N. I. of Building Sciences. National BIM Standard – United States 2007-2015. `https://www.nationalbimstandard.org/faqs`. Accessed: 2018-07-09.

[11] M. Schwarz and P. Wonka. Procedural design of exterior lighting for buildings with complex constraints. *ACM Transactions on Graphics (TOG)*, 33(5):166, 2014.

[12] J. Väyrynen, A. Colley, and J. Häkkilä. Head mounted display design tool for simulating visual disabilities. In *Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia*, pp. 69–73. ACM, 2016.

[13] VRVis Research Center. HILITE. `www.vrvis.at/projects/hilite`. Accessed: 2017-02-13.

[14] A. Walch, K. Krösl, C. Luksch, D. Pichler, T. Pipp, and M. Schwärzler. An Automated Verification Workflow for Planned Lighting Setups using BIM. In *REAL CORP 2018–EXPANDING CITIES–DIMINISHING SPACE. Proceedings of 23rd International Conference on Urban Planning, Regional Development and Information*, pp. 55–65. CORP–Compentence Center of Urban and Regional Planning, 2018.

[15] W. Yan, M. Clayton, J. Haberl, J. WoonSeong, J. Bun Kim, K. Sandeep, J. Bermudez, and M. Dixit. Interfacing BIM with building thermal and daylighting modeling. 2013.

[16] R. Zmugg, S. Havemann, and D. W. Fellner. Towards a voting scheme for calculating light source positions from a given target illumination. 2010.