



MASTER THESIS

A research methodology for outdoor lighting: obstacle detection in the field

Research on how to design a valid methodology to investigate
obstacle detection for pedestrians under different lighting
conditions in a real-life setting.

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Preface

This report presents the result of my graduation project and forms the final accomplishment in the completion of the master Building Physics & Services at Eindhoven University of Technology. The aim of the research conducted in this thesis was to contribute to the creation of a pedestrian-friendly outdoor environment for everybody. Specifically, the objective was to develop a methodology that investigates obstacle detection in a real environmental setting.

Conducting this research was challenging at times but it was also rewarding, extremely interesting and enjoyable. This large project would not have been possible without the help and support of several experts. First, my sincere gratitude is expressed towards my supervisor committee, Juliëtte van Duijnhoven & Rianne Valkenburg, for their constant guidance throughout the entire project. Additionally, I would like to thank CROW, and specifically Richard Boerop, for his contribution to this project since this would not have been possible without their assistance. Next, I would like to thank Bart Melis Dankers (VISIO) and Maurice Donners (Signify) for their help and assistance during the field study preparation. Furthermore, I hugely appreciate the help I received from the municipality of Utrecht during this research, specifically Arthur Klink. I would also like to thank Wout van Bommel for all the hours he contributed towards the development of the mechanical devices to raise the pavement tiles during the field study. Next, I would like to thank the building lighting group of Eindhoven university of Technology for their advice. Additionally, I sincerely want to thank the participants and the guides during the field study, without them the conduction of this study would not have been possible. Furthermore, I hugely appreciate the advice and expertise of the following people during different phases of this project: Nico de Kruijter, John Mardaljevic, Gilles Vissenberg (Signify), Jan Diepens & Wim van Damme (VISIO). Finally, I want to express gratitude to my friends & family and specifically my boyfriend for their unconditional support and necessary distraction throughout this big project.

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Summary

Visual performance during nighttime should be optimal for all pedestrians to define a public space as 'safe' and 'accessible'. The visual performance of pedestrians can be studied with the use of an obstacle detection task. In previous studies, the obstacle detection task was studied in a laboratory setting where the visual performance was tested for different obstacle heights, target groups and lighting conditions. These studies, however, do not include the variability that characterizes a natural environment. The aim of this study was to develop and validate a methodology to investigate the obstacle detection probability for pedestrians in a real setting. The study was conducted with three different target groups in mind: adolescents (20-30 years), elderly (65+ years) and people with a visual impairment. The field study that was executed to validate the methodology was located in Utrecht where participants needed to perform an obstacle detection task in parallel with a facial expression recognition task under different LED lighting conditions. Besides validating the method, this study gave preliminary insights regarding the optimal lighting conditions to make the outdoor environment as accessible and safe as possible for everyone.

When looking specifically towards the findings related to the method validation, it was found that the methodology should include several parameters. First, the study should include a distraction task besides the obstacle detection task but the effectiveness of the distraction task should be tested with an eye-tracking device. Second, the study should comprise of at least 2 participant positions per luminaire type to increase the variability of the data. Third, the field study should include at least 3 trials per participant position and a practice trial should be added prior to the study. Fourth, the contrast level between the obstacles and the pathway should be measured for each obstacle, this was found to be one of the two main predictors for the obstacle detection probability. The obstacle detection rate increases significantly when the contrast level increases. The other main predictor for the obstacle detection probability, fifth, was the visual acuity of the participants. The visual performance decreases with a lower visual acuity level, specifically people with a visual acuity lower than 0.4 were not able to identify any obstacles. This indicates that there should be more focus on people with a visual impairment, the current lighting standards are not sufficient to create a safe environment for this target group. When looking towards the content-related findings, the main finding is that the path luminance should be uniformly distributed from the position of the participant up until the obstacles to be able to identify the obstacles. In general, from these findings, important first conclusions can be made regarding the creation of a safe public space at night but hopefully, more research will be conducted in the future to create an accessible space for everybody.

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1 Introduction

Public space should be accessible to everyone and public lighting is an important element for people to orientate themselves during darkness. The term 'accessible' means the ability to reach a specific destination in an easy and safe manner (Dictionary, 2022). To achieve this optimal and safe navigation at night, Kuyk & Elliott (1999) identified the visual extent (how far a person can see) and the scanning ability (whether all objects in the near environment can be seen) as the two most important predictors.

All pedestrians should be able to carry out these two tasks in an outdoor environment. If this is not possible, the risk of falling increases rapidly. This is becoming an increasingly prominent issue due to the constant rising number of people with a visual impairment. Visual impairment is mainly a problem of the elderly people, 79% of the visually impaired persons in the Netherlands are 65 years or older (Resnikoff et al., 2004). Due to the aging effect of the world population, this number of elderly people is enlarging rapidly. In 2019, there were 703 million people aged 65 years or older. This number is expected to double to 1.5 billion elderly people within the next 30 years (Bank, 2019). It is, therefore, expected that between 2010 and 2050, there will be a massive growth in people with age-related eye diseases (Bourne et al., 2021; Norgate, 2012). Due to this rising number of people with a visual impairment, the number of reported falls are increasing rapidly (Choi, Kang, Shin, & Tack, 2014). A study in the USA concluded that each year over one third of the elderly aged over 65 fall and more than 10 percent of these falls result in injuries which require medical attention (Oxley, O'Hern, Burt, & Rossiter, 2018). Of these falls, more than 70 percent occurs in the exterior environment while elderly people and people with a visual impairment only spent around 90 minutes on average outside each day (Li et al., 2006). Furthermore, more than 50 percent has been linked to outdoor walking behavior (Uttley & Fotios, 2017). This is not surprising since 70 percent of the older adults report walking as their main choice of physical activity (Li et al., 2006).

The most reported cause of a fall is tripping over an obstacle (Campbell et al., 1990). The risk of tripping is dependent upon three main factors. First, it is dependent on environmental factors such as slippery conditions and obstacles on the road (Bentley & Haslam, 2001). Outdoor falls occurred most often on sidewalks, curbs and streets due to their uneven surfaces (Li et al., 2006). Second, personal factors can influence the risk of tripping. People are often rushing, distracted or tired when they fall (Schaefer, Schellenbach, Lindenberger, & Woollacott, 2015). Third, the risk of tripping while walking increases when there are poor lighting conditions or poor contrast between the footpath and an obstacle (Owen, 1985). A study from Boyce (1985) has defined that a minimum illuminance of 1

lux should be sufficient to reduce the risk of tripping in the outdoor environment for all ages. Their study, however, did not include people with a visual impairment who require a higher illuminance level than average (Cornelissen, Kooijman, Dumbar, Van der Wildt, & Nijland, 1991).

Currently, there has been an increasing focus upon the development of appropriate lighting conditions for visually impaired people. The general demands are: uniform lighting, high contrast between the footpath and the adjacent objects, and more energy falling in the blue spectrum since human vision is most sensitive to short wavelengths (blue light) in scotopic vision (Boyce, 2003). There are, however, currently no precise lighting recommendations for people with a visual impairment (Wolska & Sawicki, 2014). Creating such recommendations is challenging since the individual differences between people with a visual impairment are large (Rahm & Johansson, 2018).

One of the potential solutions to achieve the previously mentioned demands, is the transition from traditional lighting such as mercury lamps and high-pressure sodium lamps towards LED lighting. The main reason for this trend is the lower energy-use of LED lighting. Furthermore, LED promises a longer life span, more and faster control in light level and better color rendering. (Sweater-Hickcox, Narendran, Bullough, & Freyssinier, 2013). It is possible that with LED lighting a more optimal lighting climate could be achieved that meets the demands of all different target groups. There is, however, more research needed regarding the exact lighting conditions under LED lighting. There is, for instance, a constant growing concern that LED lighting causes a rising level of glare which results in stress and discomfort to people (Kasahara et al., 2006; Liu et al., 2015; Tashiro et al., 2015). This can increase the risk of falling for people with a visual impairment due to the lack of visual orientation at night.

The risk of falling under different LED lighting conditions can be studied by performing an obstacle detection task. An obstacle is defined as a variation between the footpath and the adjacent areas (Fotios & Uttley, 2018). The most common encountered obstacles are uneven pavements in the footpath (Frith, Thomas, & Agency, 2010). Whether an obstacle is detected depends among others on the height of the obstacle, the age of the observer, the luminance and the type of light (Uttley, Fotios, & Cheal, 2017).

Several studies have already been conducted to investigate the difference in obstacle detection under different light conditions at various age levels (Fotios & Cheal, 2009, 2013; Mao & Fotios, 2021; Rahm & Johansson, 2018; Uttley et al., 2017). During these studies the researchers identified the relation between the obstacle detection rate, the obstacle height, and the illuminance

level of the luminaire. The main limitation of these studies, however, is that they are all laboratory studies which means they do not include the variability that characterizes the outdoor environment.

1.1 Research aim

The main aim of this study is to develop a methodology to investigate obstacle detection for pedestrians in a real environment. To validate the method developed during this project, a field study will be performed. Besides validating the method, this study can give preliminary insights regarding the optimal lighting conditions to make the outdoor environment as accessible and safe as possible for everyone.

Overall, this study will specifically focus on the visual performance of people in the form of an obstacle detection task. In this way it will be possible to (1) validate the method that will be developed in a real-life setting and (2) provide recommendations regarding the lighting requirements for a good visual performance under LED lighting.

The main research question (1) to be answered is: *“How to design a valid methodology to study obstacle detection for pedestrians under different lighting conditions in a real-life setting?”*. There are, however, several sub-research questions. (1a) *“How does the path luminance affect the visual performance of pedestrians during an obstacle detection task?”* (1b) *“What is the effect of different contrast levels of the obstacles on the visual performance of pedestrians?”* (1c) *“How does visual performance change with age and a visual impairment?”* Elderly and people with a visual impairment, in general, have eye deterioration which means that it is expected that the visual performance decreases (Fotios & Cheal, 2009). Furthermore, it is expected that this decrease in performance is highest for a light source where the luminance and the uniformity is low. (Cornelissen, Bootsma, & Kooijman, 1995). The contrast level needs to be high to optimize the visual performance (Patla & Vickers, 1997).

The next section, chapter 2, will be a summary of the currently existing literature which is required to develop the methodology to investigate obstacle detection. Furthermore, the final version of the methodology will be described. Next, in chapter 3, the field study to validate the method will be discussed. In chapter 4, the result section will be described which consists of two parts. First, the results to validate the developed method will be discussed. Secondly, the additional content-related results from the field study will be described. Finally, chapter 5, the discussion section describes the main lessons for the development of the methodology.

2 Research for design

To be able to develop the optimal methodology to measure the visual performance, literature research is needed. First, the main parameters that influence the visual performance should be mapped to make sure they were all considered during the design-stage of the method. When all these parameters are defined, the focus will shift towards the specific requirements that are needed to create an accessible space. This part is separate in two sections: (1) the task requirements which discusses the tasks that people need to be able to perform in an outdoor environment to define the space as accessible, (2) the lighting requirements that are needed to be able to perform those tasks. This paragraph is based on the previously defined parameters, all of these variables have an influence on the required lighting conditions for an optimal visual performance. For instance, the defined parameter 'age' could have an influence on the required lighting conditions; the optimal luminance values are higher when the pedestrians are older. In subchapter 2.3, different possible measurement methods are discussed to investigate the visual performance in different lighting conditions. This makes it possible to see whether the defined lighting requirements are still valid under different conditions. Finally, in the last section of this chapter the design of the developed methodology will be highlighted.

2.1 Determinants of visual performance

There are different parameters that have an influence on the visual performance of people (Bommel, 2006). To determine all these parameters a literature research was performed. In figure 1, an overview can be seen of all the parameters that were found during this study.

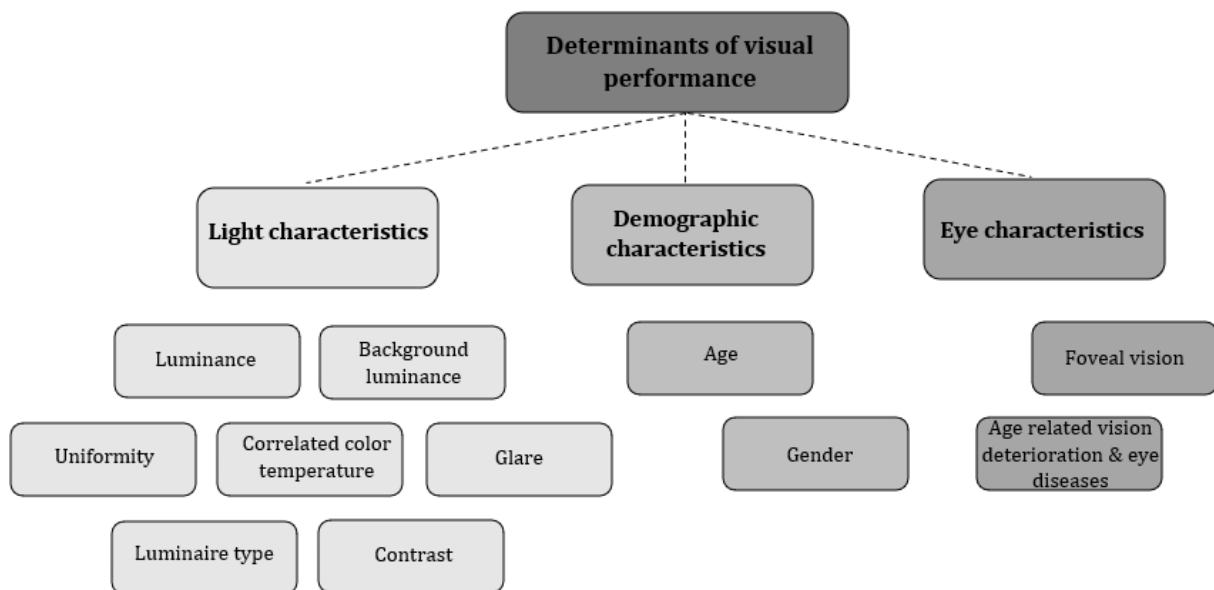


Figure 1 - Schematic overview of all the determinants of visual performance.

The parameters are subdivided into separate sections: lighting characteristics, demographic characteristics, and eye characteristics. In the next section the parameters will be discussed separately. At the end of each individual determinant for visual performance, a conclusion will be drawn regarding the importance to include that specific parameter in the method to be developed. It is possible that some parameters can be disregarded to simplify the method without compromising in the reliability of the methodology.

2.1.1 Light characteristics

Luminance

Luminance (cd/m^2) is the quantity to express the amount of light reflected from a surface per unit area in a direction. In simple words, it is the apparent brightness of an object towards the human eye (Lennie, Pokorny, & Smith, 1993). Numerous studies have investigated the influence of luminance on the visual performance of people (Fotios & Cheal, 2013; Jaschinski, 1982; Vries, 1943). In general, the visual performance of people worsens with a decreasing luminance. The minimum luminance needed to perform a task, however, can differ between people with and without a visual impairment. (Nelson, Aspinall, O'Brien, & Scott, 2001). For the design of the current methodology, the luminance at all positions within the field of view needs to be considered to study whether the visual performance worsens for a decreasing luminance, specifically the path luminance between the participant and the obstacle is an important variable.

Background luminance

Background luminance (cd/m^2) is the luminance of the area beyond the light source (Miller & McGowan, 2015). In general, visual performance worsens when there is a high variation between the source luminance and the background luminance. An increase in background luminance will decrease the discomfort and increase the visual performance (Donners, Vissenberg, & Geerdinck, 2015). It is, however, challenging to determine the background luminance so this is often taken into account as a static average value (Kohko, Ayama, Iwata, Kyoto, & Toyota, 2015). In the current methodology, the difference between the luminance near the obstacles and the background luminance will be measured for different luminaire types to study its effect on the visual performance of the participants.

Uniformity

Uniformity is the ratio of the minimum lighting level to the average lighting level at a specific surface. When the uniformity is high, the horizontal illuminance is evenly distributed. Furthermore, when the lighting conditions are uniform, a lower illuminance is required compared to a non-uniform situation (Narendran, Freyssinier, & Zhu, 2016). However, the most optimal level of uniformity is

highly dependent on the environment. Research has indicated that non-uniform lighting can make the environment feel more visually pleasing and can increase the feeling of privacy (Flynn, 1988). However, when the main aim is to have a safe and secure environment, a high uniformity is preferred ($U0 > 0.6$) (Johansson, Pedersen, Maleetipwan-Mattsson, Kuhn, & Laike, 2014). When looking specifically at visual performance, an outdoor study from Johansson et al. (2011) indicated that people can orientate themselves better when the light was uniformly distributed. For this specific methodology, it is interesting to test whether the visual performance of people is better if the area between two light source sources is uniformly lit.

Correlated color temperature

There is a high level of variation between the correlated color temperature of different light sources. Warm light sources have a low correlated color temperature in the range of 2000-3000 K, while cool light sources have a high correlated color temperature in the range of 4000-6000 K. A study from Jin et al. (2015) indicated that dark adaptation time increases when CCT increases. Color discrimination, however, increases when CCT increases. Overall, for street lighting a CCT of around 3000 K is optimal to have a decent color discrimination and adaptation time. For this methodology, all streetlamps are set to a CCT of 3000 K.

Luminaire type

Various luminaire types can be used in the outdoor environment. Currently, there is a transition from traditional lighting such as mercury lamps and high-pressure sodium lamps (HPS) towards LED lighting. The main reason for this transition is the higher energy efficiency of LED lighting. LED luminaires can save energy consumption by more than 50% compared to HPS lighting (Huang, Lee, Jeng, & Hsieh, 2012). Furthermore, LED lighting promises a longer live span, better color rendering, more and faster control and a higher degree of freedom in design (Sweater-Hickcox et al., 2013). Outdoor LED lights are, however, also characterized as causing more glare compared to the traditional lighting types (Higashi, 2012; Villa, Bremond, & Saint-Jacques, 2017). The level of glare, however, varies between different LED light sources. In this methodology, different LED light sources will be used to investigate their difference in visual performance.

Glare

Glare is defined as a “condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance’s, or by extreme contrasts” (CIE, 2019). In general, there are two different types of glare, disability glare and discomfort glare. Disability glare is a blinding phenomenon where the vision is reduced due to stray light in the eye. Discomfort glare is described as the sense of discomfort caused by glare due to an

unsuitable distribution or range of luminance's (Donners et al., 2015). Only disability glare is a determinant for the visual performance since discomfort glare does not impair the vision of people (Veitch & Newsham, 1996). The fact that glare is a prominent issue for LED lighting is mainly related to the small light emitting surfaces of LED lights. This can lead to high luminance values at a small surface area which results in the visualization of lines or matrices in the light source (Behar-Cohen et al., 2011; Kasahara et al., 2006). The study from Kasahara et al. (2006) showed that increasing the number of LED lights within the same area of a light source reduces the level of glare significantly while maintaining the same level of illuminance. During this research, both disability glare and discomfort glare will be considered to investigate its relation with the visual performance of the people.

Contrast

Contrast is the difference in luminance between two adjacent surfaces (Whittle, 1994). An increase in contrast, in general, increase the visual performance of people. The minimum contrast that is required to perform tasks adequately is, however, dependent on several factors. First, people with a visual impairment often experience a lower contrast sensitivity. This means that they require a higher contrast ratio, this is also the case when people age (Parkin & Smithies, 2012). Furthermore, the overall brightness of the environment is relevant, the contrast ratio needs to be higher when the overall brightness level is low (Jenness & Singer, 2008). Finally, the material characteristics can have a big effect on the visibility of an object. For instance, the texture and color of an object needs to be considered (Bierings & Jansonius, 2019). In this study, contrast will be an important factor to consider. It will be investigated whether an increase in contrast between the obstacle and the adjacent area increases the visual performance of people.

2.1.2 Demographic characteristics

Age

In previous studies, age is considered as one of the main predictors of the visual performance for people (Fotios & Cheal, 2009; Rahm & Johansson, 2018). Aging influences almost all physiological processes. Especially the deterioration of vision has an effect on the visual performance of people, this will be discussed in greater detail later in this chapter. Another prominent change when people age is related to the body composition, body fat increases while body muscle and bone tissue decreases with age (Kalyani, Corriere, & Ferrucci, 2014). This lowers the overall mobility of elderly people. Furthermore, cognitive regions in your brain such as memory processing declines. The result is that elderly people need more time to process and remember new incoming information. Another effect is that elderly people are more easily distracted than young people (University of Southern

California, 2018). For the current methodology, the visual acuity of all participants will be monitored but age will also be considered as a separate variable since there are more physiological processes that could have an influence the visual performance of elderly people.

Gender

Whether a difference in gender influences the visual performance is still a topic for debate. A study from Janz et al. (2001) found that females in general report more problems with vision than males. Furthermore, demanding visual activities had a higher negative effect on their quality of life than for males. The reason for this finding is, however, not completely understood. One theory is that females have a general feeling of insecurity after dark which means they have a higher demand for optimal lighting in the environment (Bierings & Jansonius, 2019). Overall, there is not enough evidence that there is a clear difference in visual performance between males and females. For the current methodology, this potential difference will be disregarded due to the lack of clear evidence.

2.1.3 Eye characteristics

Foveal or peripheral vision

The center of gaze is called the fovea. This area has a peak density of cones which results in the highest possible visual acuity (Curcio, Sloan, Kalina, & Hendrickson, 1990). This number of cones rapidly declines towards the periphery while the number of rods is becoming increasingly dominant. This influences the visual performance, basic functions such as visual acuity and contrast sensitivity peak at the fovea and decline towards the periphery (Stewart, Valsecchi, & Schütz, 2020). Therefore, the localization of objects is harder when using peripheral vision. The performance of peripheral vision is also dependent on viewing distance, contrast, reflectance and lighting conditions (Sammarco, Reyes, Bartels, & Gallagher, 2009). When the light levels drop, the peripheral vision is increasingly dominated by rods. If the vision is dominated by rods, the scotopic vision instead of the photopic vision dominates (see figure 2). This influences the scotopic/photopic (S/P) ratio which measures the amount of emitted light that is useful to the human eye (Maziarka, Bena, & Wachta, 2018). For a light source, this indicates that if the S/P ratio is higher, there is more stimulation of the rods relative to the cones (Fotios & Cheal, 2009). This means that if the lighting has a high S/P ratio, the peripheral vision works more effectively (Lingard & Rea, 2002). Peripheral vision is also dependent on age, the human eye changes as a person gets older. The visual field of people decreases every 10 years with one to three degrees which indicates a reduction of around 20 degrees when people are 70 years old (Åsman & Heijl, 1994). A study from Sammarco et al., (2009) found that peripheral vision declines by age but the decline can be limited by using bright LED lighting. This study also found that the angle at which targets were located has a significant effect on the detection

time due to a constant reduction of vision further away from the fovea. It is vital that both foveal and peripheral vision are used optimally to create the best visual performance. In this methodology, both the foveal and peripheral vision of the participants will be tested under different lighting conditions.

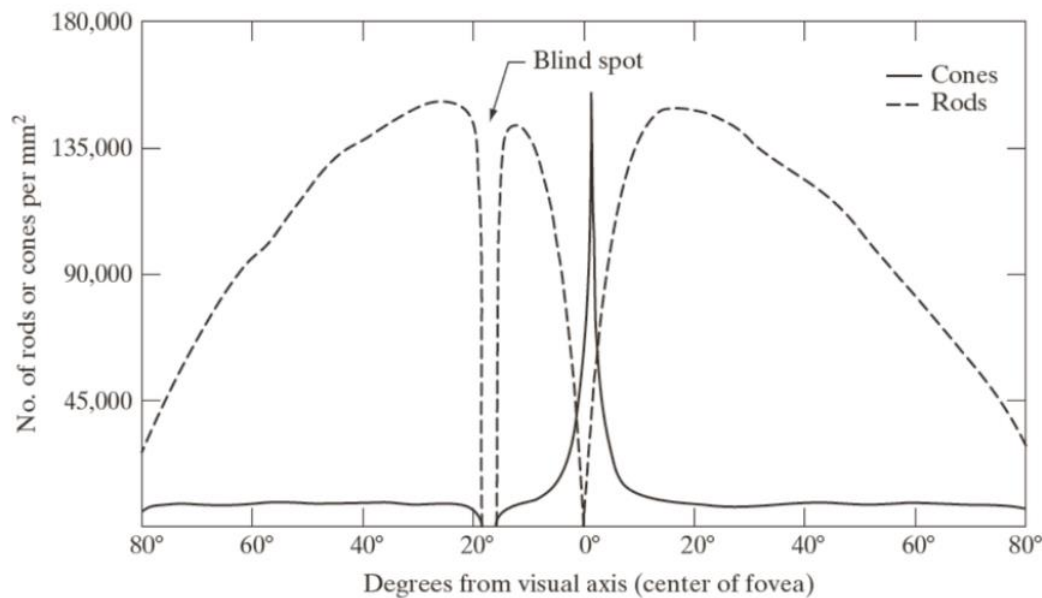


Figure 2 - Distribution of the rods and cones on the human retina.

Age related vision deterioration & eye diseases

Vision deteriorates with age; this has several reasons. First, the quality of vision reduces due to the reduction of the illumination at the eye that reaches the retina. Furthermore, light that does reach the retina is scattered in the eye which increases the contrast thresholds for elderly. This scattering is prominent for the blue part of the spectrum which means elderly experience a yellowing effect (Fotios & Cheal, 2009). This yellowing effect is further enhanced by the yellowing of the lens in the eye. Third, at low light levels the ability to dilate the pupil is greatly reduced for elderly (Hamel, Okita, Higginson, & Cavanagh, 2005). Finally, muscles around the lens are decreasing in their flexibility which makes accommodation more difficult. Due to this reduced vision and contrast sensitivity, the visual performance of people decreases when becoming older. As previously mentioned, when people age the chance to acquire a severe visual impairment also increases.

The three most common eye diseases are: cataracts, glaucoma, and age-related macular degeneration (Attebo, Mitchell, Cumming, & Math, 1997). Cataracts happen when proteins and fibers inside the lens break down which results in a cloudy vision (Krishnaiah et al., 2005). Therefore, cataracts are often paraphrased as “clouding of the normally clear lens” which reduces the central vision (Eichenbaum, 2012). Glaucoma is described as the loss of “peripheral vision” as if one is

looking through a straw (Chandler & Grant, 1979). Several studies have shown that the resolution of vision is also greatly affected for people suffering from glaucoma (Hawkins, Szlyk, Ardickas, Alexander, & Wilensky, 2003; Pacheco-Cutillas, Sahraie, & Edgar, 1999). A study from Hu et al. (2014) even indicated that patients more frequently complain regarding the need of more light and having a blurry vision than regarding the loss of peripheral vision. Finally, age-related macular degeneration is characterized by developing central scotomas which is a blind spot in the central of your foveal vision (Brown, Zadnik, Bailey, & Colenbrander, 1984). Other frequently mentioned symptoms are the loss of contrast sensitivity, reduced acuity, and reduced color vision (Applegate, Adams, Cavendar, & Zisman, 1987; Kleiner, Enger, Alexander, & Fine, 1988).

Overall, several studies have already indicated the severe impact that these eye diseases have on your visual performance, especially at night (Kuyk & Elliott, 1999; Nelson et al., 2001). For the current methodology, participants with different types of eye diseases will be included in the study to investigate the difference in visual performance at night.

2.2 Requirements for visual performance

From all the parameters that are previously discussed, the requirements for an optimal visual performance in an outdoor public space can be defined. This part will be separated in two sections: (1) the task requirements which explains the tasks that people should be able to perform outside to realize a safe navigation through the outdoor environment. (2) the lighting conditions that are required to perform those exact tasks.

2.2.1 Task requirements

Public lighting has one common purpose for all road users, it enhances the visibility and perception of safety for people (CIE, 2010). The specific tasks that need to be performed while being outside are, however, very different. The main gaze direction of the motorist is the road ahead and is assisted by headlights of the vehicle (Bommel, 2015). Pedestrians, however, lack any additional lighting but they should still be able to detect obstacles (physical security), identify the intentions of others (social security) and be able to orientate themselves in the near environment (Rea, 2000). A study from Fotios et al. (2015) investigated the critical tasks of pedestrians by measuring their gaze behaviour. The footpath resulted by far in the highest number of fixations (33%) followed by fixations on other people which contributed to 15% of the critical fixations. This indicates that especially knowledge regarding the luminance distribution on the path is vital. Furthermore, it can be concluded that pedestrians often look at other people which means they are distracted and are not able to detect potential obstacles at the pathway.

2.2.2 Lighting requirements

As mentioned, pedestrians need to be able to perform various tasks when walking outside at night. The CIE (2010) states that a minimum illuminance level of 0.4 lux should be sufficient to be able to walk safely across a footpath. The perceived safety of participants, however, increases when the illuminance increases up to 10 lux (Boyce, Eklund, Hamilton, & Bruno, 2000). There is currently, however, less clarity regarding the luminance requirements especially on the footpath. The main reason for this is the inconsistent character of a footpath which result in different reflectance's and therefore different luminance levels throughout the path. A study from Bierings & Jansonius (2019) found that visual complaints are higher when the luminance at the path is lower than 0.01 cd/m². For people with an eye disease, however, the visual complaints were already prominent for values up until 0.04 cd/m². The luminance level to achieve an adequate visual comfort should be higher than 0.2 cd/m². When looking specifically towards the visual performance of different critical tasks, it becomes clear that the lowest illuminances are needed to ensure physical security. The obstacle detection rate increases rapidly between 0.2 and 2 lux, depending on the reflectance of the obstacle this corresponds to a luminance between 0.01 cd/m² and 0.1 cd/m² (Bierings & Jansonius, 2019; Fotios & Cheal, 2013). During the facial expression recognition task, the luminance at the face should be 1 cd/m² to be able to correctly identify the expression at 10 m distance. (Fotios, Yang, & Cheal, 2015). The preferred CCT to recognize faces has also been studied, in general, white light with a CCT higher than 4000 K is optimal (Raynham, 2007).

For people with a visual impairment, however, these values are often too low (Cornelissen et al., 1995). A study from Johansson et al. (2011) tested the visual orientation, facial recognition and obstacle detection rate under the present lighting requirements of Sweden which is a minimum horizontal illuminance of 7.5 lux. This was adequate for adolescents and elderly, but all severe visually impaired participants were not able to perform any of the tasks.

The lighting requirements that were discussed in the previous section will be compared with the results from the field study that will be conducted. From this, it will be concluded whether the current lighting requirements are still accurate in a more realistic set-up for both the obstacle detection task and the facial recognition task.

2.3 Measurement methods for visual performance

To create a public space that is accessible to everyone, the visual performance of the people in that environment should be as optimal as possible. A first step to achieve this was discussed in subchapter 2.1, the parameters that influence the visual performance of people should be considered

during the measurements to determine whether the parameters indeed have the predicted effect on the visual performance. Furthermore, the lighting requirements that were discussed in the previous section should be included. This will make it possible to investigate under what conditions the current lighting requirements are accurate and for which parameters they need to be adjusted. For instance, if the parameters 'age' is included in the study it is possible that the lighting requirements are sufficient for young adults but that they are not sufficient for adults with an age over 65 years.

2.3.1 Models

Visual performance is always measured with objective research methods. As mentioned, for optimal navigation, people should be able to: orientate in the environment, recognize faces, and detect obstacles. Several studies have already been conducted to investigate these tasks under various lighting conditions. These will be discussed in more detail below.

Visual orientation

Visual orientation of the area allows pedestrians to read house numbers and road names (Johansson et al., 2011). A wide range of studies have been conducted to test the influence of several lighting characteristics on the visual orientation. A study from Mattsson et al. (2020) investigated the visual orientation of people with impaired vision after dark. Overall, it was found that LED lighting resulted in a higher score for the observation of items than HPS lamps. Another type of visual orientation task was performed by Rahm & Johansson (2018) who performed a sign reading task where the detection distance of different street names was measured. Overall, it was concluded that people in general are much better at recognizing signs than at recognizing facial expressions. This is mainly related towards the simplicity of the task; signs have a higher difference in contrast level than facial expressions which makes the identification easier.

Facial expression recognition

Facial recognition is considered to be a vital visual task for pedestrians after dark, it promotes a perception of security to be able to judge another's intentions (Markvica, Richter, & Lenz, 2019). Facial recognition has been previously studied both in the field and in laboratory settings. Often researchers studied the distance at which respondents can guess the identity or gender of a certain face. However, the ability to recognize a face is not relevant for the safety of pedestrians. The thing that matters is to recognize the intentions of the people that are approaching (Fotios & Raynham, 2011). It has therefore been suggested that the recognition of facial expressions is a more relevant task. In a study from Rahm & Johansson (2018), participants were instructed to walk towards a women's face up until they could discern the facial expression of the women's face. Overall, it was

found that people aged between 19-31 years could discern faces at larger distances, with an average distance of 7 m while people with an age between 62 and 77 years old could discern the facial expressions only at an average distance of 3.5 m. Another study of Rahm & Johansson (2021) concluded that similar lighting conditions were appropriate for orientation and accessibility but not sufficient for facial expression recognition which is required for the perception of safety. One reason for this is the difference between vertical and horizontal illuminance, for the facial recognition task vertical illuminance is relevant while for the creation of an accessible space horizontal illuminance is the most relevant variable. A study of Hastenberg et al. (2021) replicated the study of Rahm & Johansson (2018) in a field setting. The mean age of the participants in their study was 46.3 years old. Here, a mean detection distance between 5.8 and 6.3 was found for each luminaire type.

Obstacle detection

An obstacle is defined as a variation between adjacent surfaces and the footpath (Fotios & Uttley, 2018). There are many different types of obstacles that people can interfere with in the outdoor environment. For instance, uneven pavements, a hole in a pavement, construction works and bicycle racks (Fotios & Cheal, 2009). The most encountered obstacle in daily life are uneven pavements in the footpath (Frith et al., 2010). Most studies, therefore, focus on the detection of obstacles in the form of uneven pavements. There are three different methods which are often used to measure the level of obstacle detection.

The first method is investigating the gait pattern of participants when they approach and step-over an obstacle. In a study from Chen et al. (1991) it was found that older adults are more conservative when they approach an obstacle. They have a significantly slower walking speed towards an obstacle and have a shorter step length than young adults. Elderly people, furthermore, put themselves in more risk when stepping over an obstacle by placing both the leading and trailing feet farther from the obstacle edge (Begg & Sparrow, 2000). This indicates that elderly have a smaller toe clearance and less correction time when stepping over an obstacle, this was also found in a study from Cho et al. (2013). This riskier stepping behavior, however, is only found under reduced ambient lighting conditions with values between 1-3 lux horizontally on the path (Hamel et al., 2005). Another important parameter that was studied by making use of the gait pattern was the relationship between the height of an unseen obstacle and the chance of foot contact (Best & Begg, 2008). They concluded that an obstacle with a height of 20 mm or higher would almost certainly lead to foot contact while an obstacle with a height of 12-15 mm would likely lead to foot contact and therefore trip probability. Below this region the chance of foot contact decreases, the probability of foot contact is

47% for an obstacle height of 10 mm. After this value, the trip probability reduces rapidly with a 1% chance of foot contact for an obstacle with a height of 5 mm.

Another method is measuring gaze fixation towards an object to see when people fixate their gaze towards an obstacle. A study from Patla & Vickers (1997) concluded that the frequency of obstacle fixation is significantly related to the obstacle height. The reason for this is the greater probability of tripping over a higher obstacle due to a lack of foot clearance (Patla, 1997). Another study from Patla & Vickers (2003) found out that people have a gaze fixation towards an obstacle in the approach phase up until two steps ahead. Next the fixation abruptly reduces up until zero. Fotios & Uttley (2018) found that obstacles tend to be detected approximately 3.4 meters ahead to be able to cross the obstacle without a necessary change in gait pattern.

A final method is to measure the variation in the detection of an obstacle with different lighting and obstacle conditions. An experiment from Fotios & Cheal (2009) measured off-axis obstacle detection in a laboratory study in which obstacles were raised in a booth. Off-axis detection was used since the visual space of people is mapped using peripheral vision (Inditsky, Bodmann, & Fleck, 1982). They measured 14 different obstacle heights, 3 different illuminance levels, 3 different lamp types and 6 obstacle positions. Participants were asked to fixate towards a point while stating the location of the raised obstacle in the booth. From this experiment it was found that obstacle detection depends on the S/P ratio of the lamp. The visual performance increases for low illuminance levels when the S/P ratio is higher. The reason for this is the fact that street lighting falls in the mesopic range which means the spectral sensitivity is dominated by rod photoreceptors outside the fovea. This means that vision increases when the S/P ratio is higher. There were also statistically significant effects found between different age levels and the height of the obstacle but only for low illuminance levels (below 1 lux). This means that for low light levels, the obstacle detection rate decreases with an increasing age and a decreasing height of the obstacle. A study from Rahm & Johansson (2018) validated the results from the previously mentioned study but this time with a lamp post instead of uniform lighting. They concluded that indeed a higher S/P ratio leads to an increase in obstacle detection probability. A study conducted in 2013 from Fotios & Cheal defined a norm for obstacle detection. They defined that for an obstacle height of 25 mm at 6 m, an illuminance of 0.62 lux is required for a 95% detection probability for young adults (< 34 years old) with HPS lamps. All these studies used a fixation point but there was uncertainty whether participants maintained their gaze on the fixation mark during the study. This was investigated in a study from Fotios, Uttley, & Cheal (2016) by using an eye tracking device while replicating the two previous

studies. Overall, it was concluded that in less than 0.9% of the frames the fixation was directed towards the obstacle which indicates that participants maintained a high degree of fixation.

To make the obstacle detection task better applicable to a real-life setting, Uttley et al (2017) replicated the study of Fotios & Cheal (2009) but this time with a dynamic fixation point and a moving treadmill to create a more realistic setting. The results found in this study were comparable with the previous studies. An even more realistic fixation point was used in the study from Mao & Fotios (2021). In this study, a facial recognition task was executed in parallel with an obstacle detection task. The reason for executing this study was that they found that people often fail to detect an object because they are distracted (Fotios, Robbins, Fox, Cheal, & Rowe, 2021) but previous studies did not consider a realistic detection task. The study from Mao & Fotios (2021) used a 3D face model with four different emotions as a fixation task where participants were instructed to focus on identifying the emotions of these faces while they used off-axis detection to detect obstacles (see figure 3 for a schematic overview). Obstacles can be raised at floor level while the facial expression can be altered by an experimenter through a rotating wheel (figure 3), there were also control conditions where no obstacles or facial expressions were shown. These null-conditions were added to investigate the tendency of people to randomly respond when they are unsure regarding the detection of a variable. Overall, it was found that the need to carry out two tasks led to a reduction in the performance of the peripheral obstacle detection task but not for the fixation task. This previously discussed study will be the main inspiration during the development of the methodology for obstacle detection in a real environment. In the next chapter, the exact factors that are taken from their and other studies during the development of the methodology will be discussed.

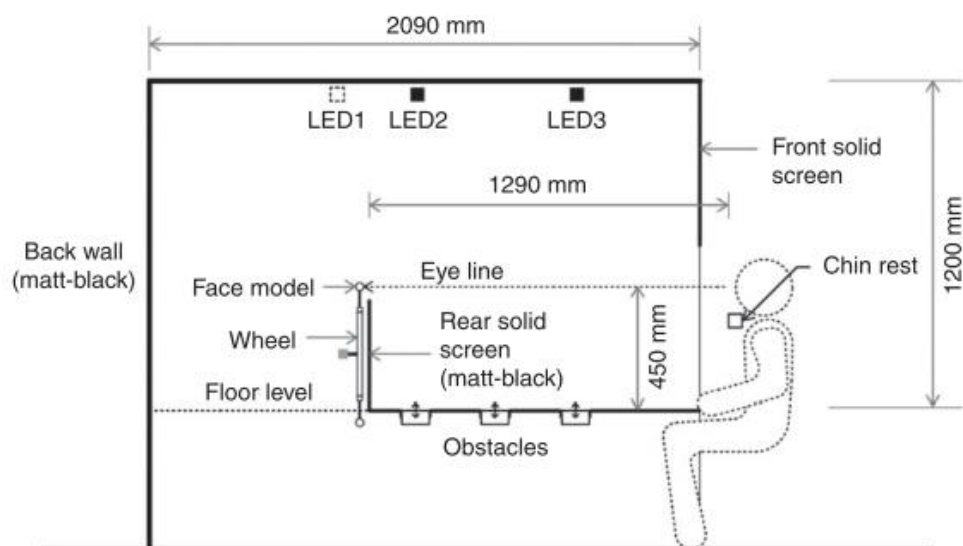


Figure 3 - Schematic overview of the experimental set-up of the study from Mao & Fotios (2021)

2.4 The obstacle detection method in the field

The main aim of this study is to develop and validate a methodology to investigate obstacle detection for pedestrians in a real environment, this will make it possible to measure the visual performance of people and create an accessible outdoor environment. The main dependent variable that will be measured during the field study is the obstacle detection rate. The obstacles will be raised pavement tiles, this will mimic the real situation as optimal as possible. Furthermore, this will reduce the contrast difference between the adjacent area and the raised obstacle which is also done in the studies that are executed in a laboratory setting (Fotios & Cheal, 2009, 2013; Uttley et al., 2017). The height that the pavement tile will be raised to create an obstacle is based on the study from Best & Begg (2008) who concluded that an obstacle height of 10 mm has a 47% probability of foot contact and this decreases rapidly when the obstacles are lower. In other words, 10 mm is suggested to be the minimum critical height for a trip hazard. Therefore, the obstacles will be raised for 10 mm during this study. People, however, do not always fixate their gaze towards the footpath to notice these obstacles. This indicates that preferably, the participants in the study should be able to detect the obstacles with their peripheral vision during the obstacle detection task. To stimulate the use of peripheral vision during the obstacle detection task, a distraction task is added. This task is a facial expression recognition task which is replicated from the study from Mao & Fotios (2021). For the facial expression recognition task, varying emotions and identities will be used to reduce the predictability of the task.

For the obstacle detection task, several different obstacle positions will be used as in the study from Fotios & Cheal (2009). This will counter a possible tendency to fixate on a specific target area so it reduces the predictability. The exact distance between the participants and obstacles is around 3.4 meters, since this is the distance that obstacles should be detected to be able to cross the obstacle without a necessary change in gait pattern (Fotios & Uttley 2018). The distance between the participant and the facial expression that needs to be identified is 6 meters. This distance was based on the study results from Hastenberg et al. (2021) since this was found to be the mean identification distance for participants with a mean age of 46.3 years. The field study should be conducted at two different positions per luminaire type to investigate the behavioral differences between two light sources and its effect on the obstacle detection probability. Specifically, for each luminaire type, one position with a positive contrast and one position with a negative contrast level should be included.

The obstacle detection task should be executed multiple times under different LED lighting conditions and different positions to increase the reliability of the measurements. During each trial

participants are asked to identify the facial expression and detect obstacles for 3 seconds before they need to give the answer. These 3 seconds is the average time required for a fixation which is followed by a saccade (Holmqvist et al., 2011). In the study from Fotios & Cheal (2009) a total of 144 trials and 18 null conditions were included for each participant. This will be challenging during a field study but a good balance should be found between practical feasibility and the reliability of the measurements. The number of obstacles that are raised (range = 0-3) and the emotions that are lifted are randomized for each individual trial. There will also be control trials where no obstacles are raised, these were added to assess the response bias of people (Mao & Fotios, 2021). This can investigate whether people start to respond randomly when they are not sure about the stimulus detection.

A last aspect of the methodology are the specific participants that should be included in the study. It is expected that there is a big difference between the visual performance of adolescents, elderly people and people with a visual impairment (Nelson et al., 2001). It would be interesting to include all target groups in the study to meet the goal set in the beginning and make the outdoor environment an accessible place for everyone.

In figure 4, a schematic overview of the previously discussed methodology can be seen. In this overview, all the variables that were discussed in the previous section are highlighted with a letter. In table 1, all these variables and their specific characteristics are summarized. In chapter 3, the choices that were made for the field study with regards to these variables will be tested.

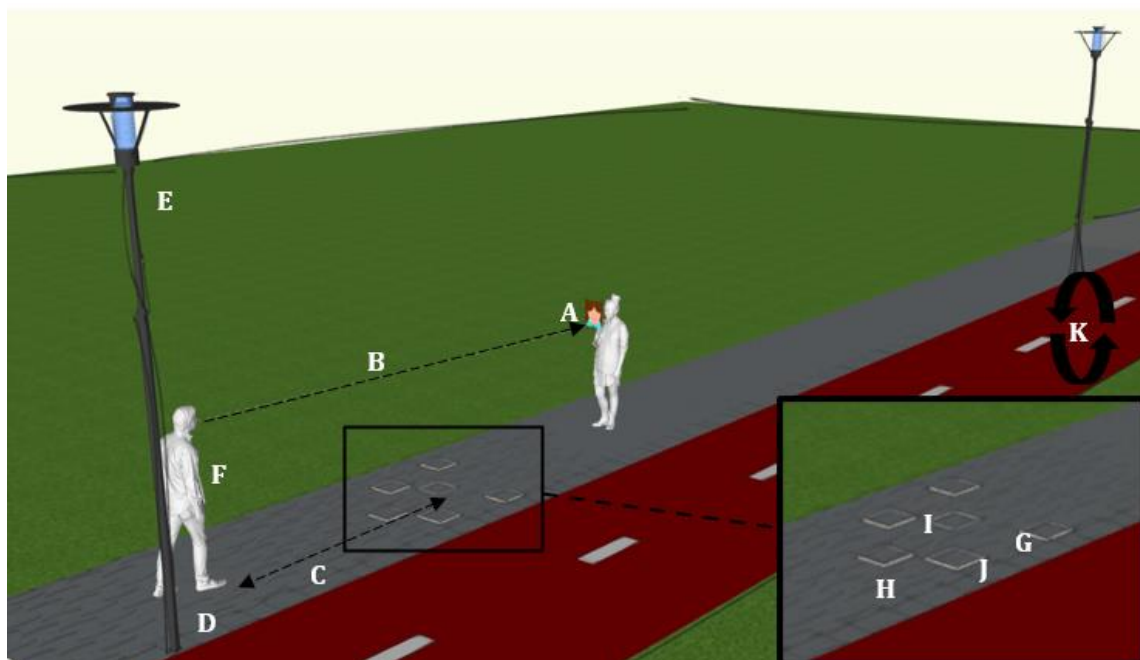


Figure 4 - Schematic overview of the included variables in the developed methodology

Table 1 – An overview of all the included variables in the developed methodology

Letter	Variable
A	Distraction task
B	Distance participant - distraction task
C	Distance participant – obstacles
D	Participant position
E	Luminaire type
F	Target group
G	Obstacle height
H	Obstacle contrast
I	Obstacle positions
J	Number of obstacles raised per trial
K	Number of trials

3 Field study

3.1 Design

This field study was mainly conducted to validate the methodology that was discussed in the previous chapter. The study was conducted in collaboration with CROW, VISIO, Signify and the municipality of Utrecht. The field study was developed with three target groups in mind: adolescents, elderly people, and people with a visual impairment to investigate the effect of age and visual acuity on the visual performance of people. The main dependent variable that was measured during the field study is the obstacle detection rate. The other dependent variable is the facial expression recognition rate. The specific variables related to these two tasks are visualized in table 2 and figure 4. In table 2, the choices that were made for this field study are summarized for each variable. All these variables will be discussed in more detail in the upcoming chapter.

Table 2 - An overview of all the included variables and the choices made regarding these variables for the field study

Letter	Variable	Choices made for field study
A	Distraction task	A facial expression recognition task
B	Distance participant - distraction task	6 meters
C	Distance participant – obstacles	3.4 meters
D	Participant position	2 different participant positions (negative and positive contrast)
E	Luminaire type	7 LED luminaires with different diffusers
F	Target group	11 adolescents with a visual acuity > 0.6 12 elderly people with a visual acuity > 0.6 9 visually impaired people with a visual acuity < 0.6
G	Obstacle height	+/- 10 mm
H	Obstacle contrast	$\frac{\text{Average luminance of the (visible) sides of the obstacle}}{\text{Average luminance of the top of the obstacle}} \rightarrow$ should be above 0.3 for a decent visibility.
I	Obstacle positions	6 different obstacle positions (left, right and in the center)
J	Number of obstacles raised per trial	Between 0-3 raised during each trial
K	Number of trials	3 trials per participant position

Other variables that were considered during this study are: environmental characteristics (lighting type & weather), deterioration of the eye and the demographic characteristics (Age, gender, and length). As discussed, these variables can all influence the visual performance of people. This study also measured some subjective variables such as the environmental perception and the level of experienced discomfort glare since these are some objectives that partners in this study are

interested in. It will be interesting to investigate the relation between the subjective evaluation of an environment and the objective performance in that environment. This study was approved by the ethical committee of Eindhoven university of Technology (see Appendix I)

3.2 Setting

This field study was executed for five consecutive nights from 07-03-2022 till 11-03-2022 from 18:30-22:00. The location of the study was 'Buurthuis de Boog' (Gambiadreef 60, 3564 ES Utrecht) and the Carnegiedreef in Utrecht. In Utrecht at the Carnegiedreef, 10 different smart LED diffusers have replaced the original streetlighting which provides a unique opportunity to evaluate and compare different lighting conditions. Seven of these lights are located at the south side of the street and three are located at the north side of the street. For this study, only the seven luminaire types at the south side were used since the other three luminaire types were located at a bicycle path instead of a footpath. This is not relevant for our project since the focus is on pedestrians and not on cyclists. There are two light sources of each type of streetlighting which are positioned 22 m apart. For an overview of the situation, see figure 5. During the field study a black screen was installed between the road and the bicycle path, that was located at the south side of the road, to block light from upcoming car headlights. Furthermore, this bicycle path was blocked for any cyclists.



Figure 5 - Schematic overview of the location of the field study. The letters A till G represent the different luminaire types which are used for this study. The location of the black screen is highlighted with a dotted black line and 'Buurthuis de Boog' is highlighted in the North-East of the image.

3.2.1 Lighting conditions

For this study seven different luminaires were used. The luminaires are all mounted at a height of 4 meters above the ground. All the luminaires are LED lights with a CCT of 3000 K and a S/P ratio of 1.2. The paper from Raynham (2007) concluded that a CCT higher than 4000 K is most optimal for facial expression recognition but the current luminaires were prior to the study already fixed at a CCT of 3000 K. An overview of all the luminaires with the corresponding luminous intensity diagrams can be seen in table 3.

- Luminaire A is the Rechlaternen type 3750 15 W RL AR led, luminous flux of 1560 lumen.
- Luminaire B is the Philips Citysphere BDP782 RB 1 xLED20-4S/830 DSP, luminous flux of 2000 lumen.
- Luminaire C is the Schreder Alura 33394S LED 5068, luminous flux of 3681 lumen.
- Luminaire D is the Innolumis Ariane 730-16 Area Clear, luminous flux of 2049 lumen.
- Luminaire E is the Innolumis Ariane 730-16 Area Frosted, luminous flux of 1967 lumen.
- Luminaire F is the Lightronics Prunus-A4-indirect-LED, luminous flux of 1700 lumen
- Luminaire G is the Disano Polar 1205 LED 3K CLD, luminous flux of 8050 lumen.

For the visualization of all the luminaire types, see Appendix II.

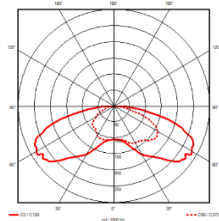
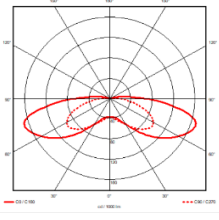
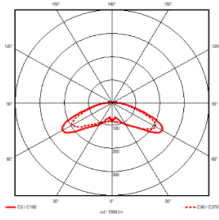
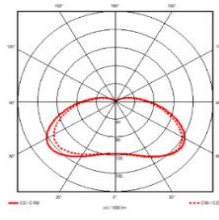
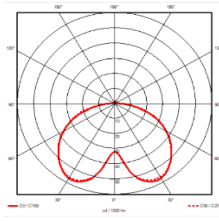
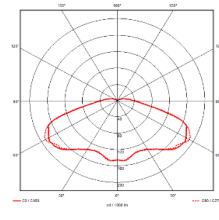
3.2.2 Eye measurements

The eye measurements were performed at the 'Buurthuis de Boog' and took around 20 minutes per participant. Overall, there were five different measurements performed:

1. Binocular visual acuity (ETDRS 2000, vertical illuminance: 500 lux at 4 meter (eye level))
2. Binocular contrast sensitivity (Vistech, vertical illuminance: 500 lux at 3 meter (eye level))
3. Binocular confrontational field of view and Amsler test (central 10 degrees, 500 lux at 0.3 m)
4. Monocular scattered light (with C-quant)
5. Pupil size (500 lux)

The complete measurement document can be seen in Appendix III. In this file all the results from the five different measurements were documented for each participant separately.

Table 3 - Overview of the 7 different luminaires (luminous intensity diagram, luminous flux and CCT)

Symbol	Name	Luminous intensity diagram (cd)	Specifications
A	Rechlanternen	Not available	CCT: 3000 K Luminous flux: 1560 lm
B	Philips Citysphere		CCT: 3000 K Luminous flux: 2000 lm
C	Schreder Alura		CCT: 3000 K Luminous flux: 3681 lm
D	Innolumis Ariane Clear		CCT: 3000 K Luminous flux: 2049 lm
E	Innolumis Ariane Frosted		CCT: 3000 K Luminous flux: 1967 lm
F	Lightronics Prunus		CCT: 3000 K Luminous flux: 1700 lm
G	Disano Polar		CCT: 3000 K Luminous flux: 8050 lm

3.2.3 Visual performance task

For the visual performance task, the participants were guided towards the Carnegiedreef in Utrecht. This part of the field study took place in the evening from 19:30-22:00 with a sunset time between 18:34 and 18:40.

The task was executed at two different positions for each of the seven luminaire types. Position 1A was located at 1 meter in front of the luminaire (participant position), the facial expression recognition task needed to be performed at 6-meter distance which means the experimenter was located at 7 meters in front of the luminaire. At position 1, the luminaire was behind the participant. Position 2A was located at 7.5 meter from the luminaire (participant position) which means 2B was at 1.5 meter from the luminaire (experimenter position). At position 2, the gaze direction of the participant was towards the luminaire. In figure 6 & figure 7, the positions are visualized in a schematic overview.

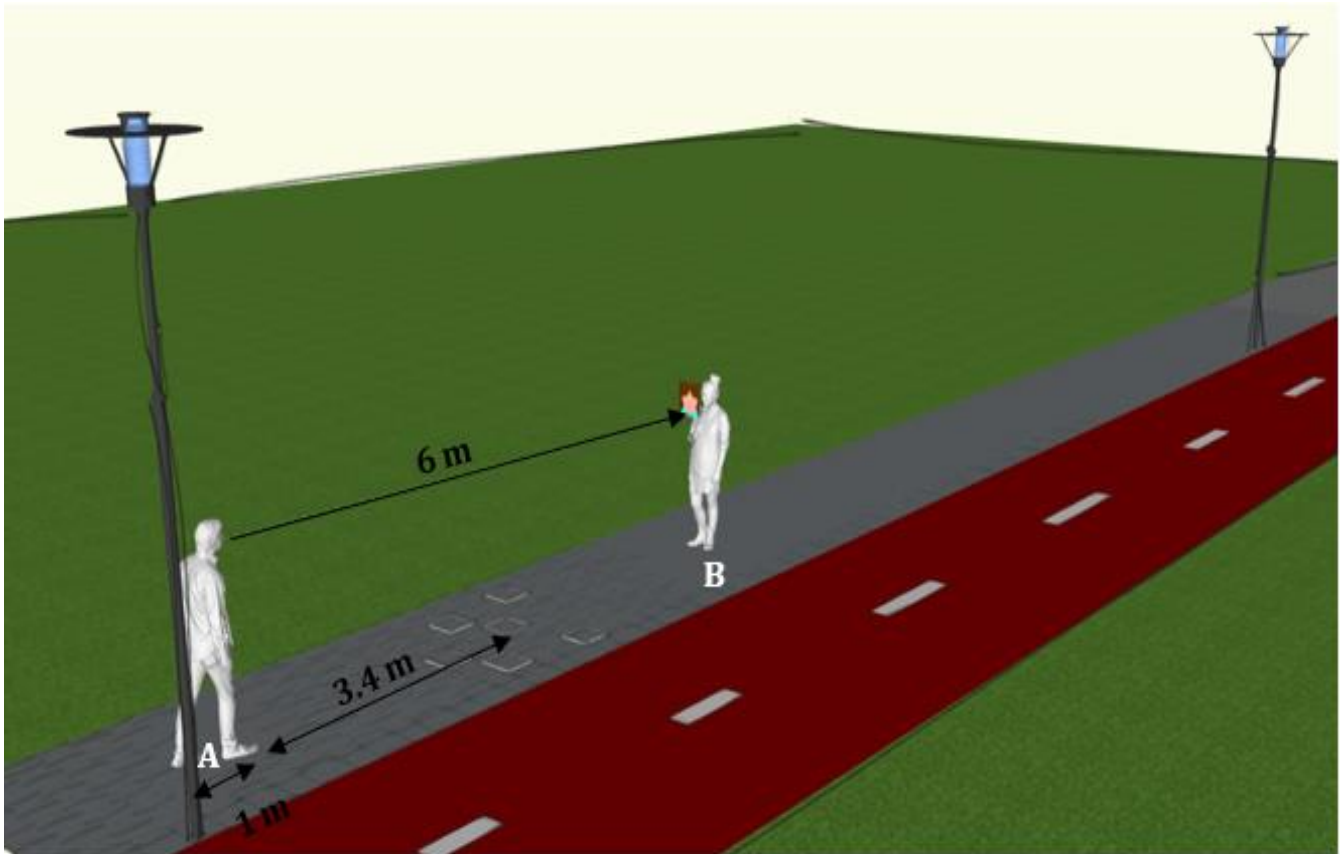


Figure 6 - Schematic overview of the experimental set-up for position 1. The letters A en B represent the position of the participant and of the 2nd experimenter with an in-between distance of 6 meters. The obstacle positions are visualized with an average distance of 3.4 meters.

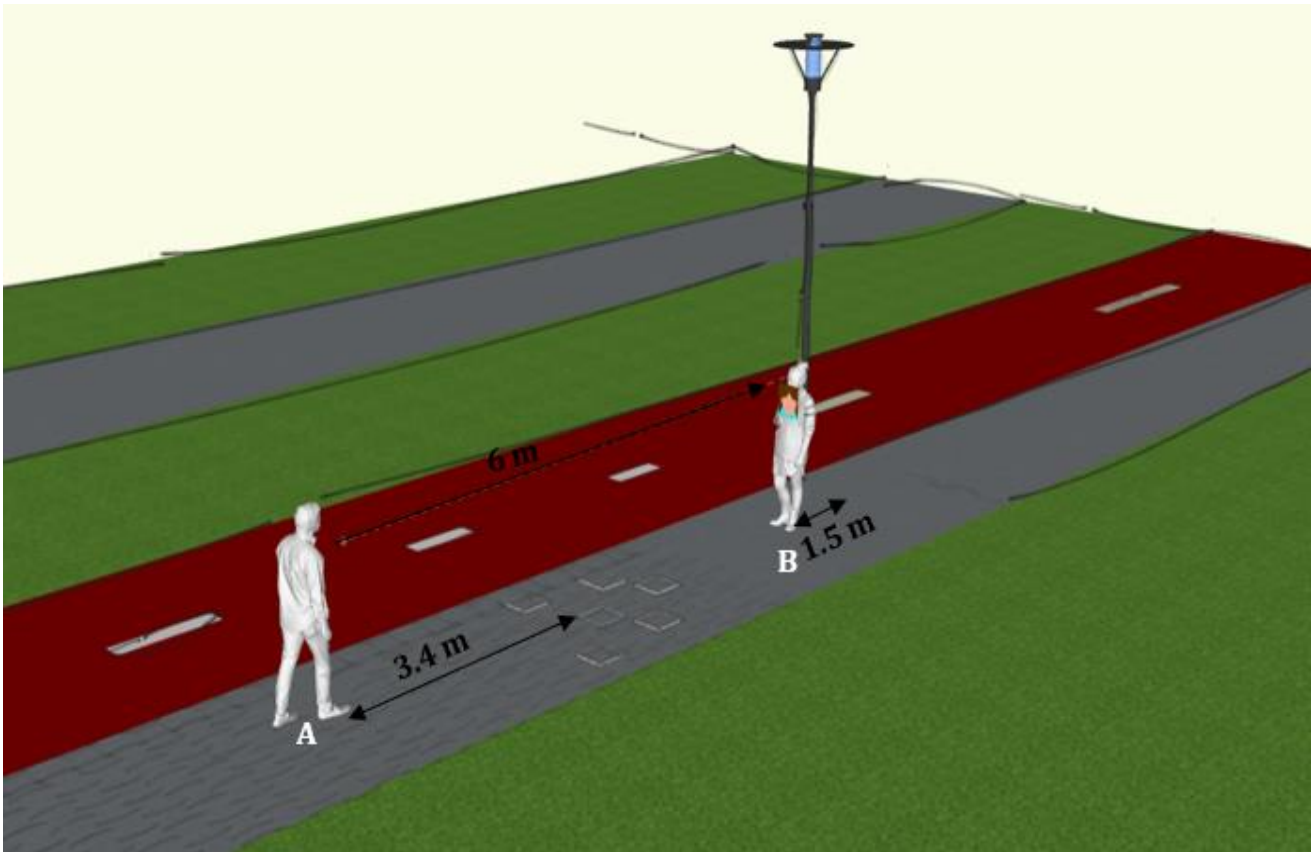


Figure 7 - Schematic overview of the experimental set-up for position 2. The letters A and B represent the position of the participant and of the 2nd experimenter with an in-between distance of 6 meters. The obstacle positions are visualized with an average of 3.4-meter distance.

For the obstacles of the obstacle detection task, six rows of pavement tiles were used and one obstacle was positioned per row. There were two obstacles positioned at the left, two at the right and two at the center of the footpath. In general, the obstacles for the obstacle detection task were positioned from 2.5 to 4.0 meter from the participant to replicate the distance of 3.4 meter which was previously mentioned. However, this is not the only relevant distance. Both the distance at the ground (from the participants' foot to the obstacle) and the distance from the eye to the obstacle are relevant to consider. Furthermore, since the participant turns around when moving from position 1 to position 2, the precise distance towards the obstacle varies between the two positions. The precise location of each obstacle is:

- Obstacle 1:
 - Position 1: Ground distance = 3.97 m. Distance from eye = 4.32 m.
 - Position 2: Ground distance = 2.51 m. Distance from eye = 3.04 m.
- Obstacle 2:
 - Position 1: Ground distance = 3.68 m. Distance from eye = 4.05 m.

- Position 2: Ground distance = 2.80 m. Distance from eye = 3.28 m.
- Obstacle 3:
 - Position 1: Ground distance = 3.30 m. Distance from eye = 3.72 m.
 - Position 2: Ground distance = 3.00 m. Distance from eye = 3.45 m.
- Obstacle 4:
 - Position 1: Ground distance = 3.06 m. Distance from eye = 3.50 m.
 - Position 2: Ground distance = 3.35 m. Distance from eye = 3.76 m.
- Obstacle 5:
 - Position 1: Ground distance = 2.77 m. Distance from eye = 3.25 m.
 - Position 2: Ground distance = 3.65 m. Distance from eye = 4.03 m.
- Obstacle 6:
 - Position 1: Ground distance = 2.42 m. Distance from eye = 2.96 m.
 - Position 2: Ground distance = 3.91 m. Distance from eye = 4.26 m.

An overview of the six obstacles from the viewpoint of position 1 can be seen in figure 8. The obstacle positions seen in this figure are identical for each luminaire type.



Figure 8 - Visualization of the different obstacle positions from the viewpoint of position 1.

Overall, there were seven different luminaire types which results in the need for 42 mechanic devices, which were made at Eindhoven University of Technology. These devices were able to lift the original pavement tile by +/- 10 mm to create an 'obstacle'. These obstacles could be raised or lowered by a remote control. See Appendix IV for a visualization of the mechanical devices. The height that the

individual obstacles, however, were raised at each side varies for each obstacle due to the variability of a field study. The exact height that all the 42 obstacles were lifted was measured for each side. These heights will be included in the final data analysis since this (probably) influences the visibility of the obstacles. The exact height of each side of the 42 obstacles can be seen in Appendix V.

For the facial expression recognition task, there were three different emotions used which are 'Anger', 'Fear' and 'Happiness'. The facial expressions were taken from the FACES database where an old male, young male, old female, and young female were selected for each of the three expressions. This resulted in a total of 12 different photographs (see Appendix VI). These were printed at A4-sized paper and presented at eye-height (1.70 m), to create a realistic situation that simulated the approach of an actual person. The position of these facial expressions is at 6 meters from the experimenter which is either at 7 meter or 1.5 meter from the luminaire. This exact distance was replicated from the study from Hastenberg et al. (2021) since this was found to be the mean identification distance.

For participants with a visual impairment all positions are the same, the only difference is that an E-hook is used that could be directed either towards the 'Left', 'Right', 'Up' or 'Down' (Appendix VII). The size of this E-hook was dependent on the visual acuity of the participant:

1. For a visual acuity smaller than 0.15, the E-hook had a height of 35 cm
2. For a visual acuity of 0.15-0.25, the E-hook had a height of 17.4 cm
3. For a visual acuity of 0.25-0.4, the E-hook had a height of 11.6 cm
4. For a visual acuity of 0.4 or higher, the E-hook had a height of 7.0 cm

3.2.4 Environmental perception task

The level of discomfort glare, contrast sensitivity and subjective evaluation of the environment were measured at the center between the two light sources of the same type (Position 3) (figure 9). The contrast sensitivity was measured using a sign which was located at 2 meters from the second fixture of the same light type. This sign has six rules with letters and each line decreases in contrast threshold (see Appendix VIII). The precise questions that were asked to measure the level of discomfort glare and subjectively evaluate the environment will be discussed in section 3.4.3.

3.2.5 Photometric measurements

The light conditions during the field study were measured using a Canon EOS 77D luminance camera with EX Sigma circular fisheye lens. To create an HDR-image, the DSLR Remote Pro Multi-Camera software was used in combination with the Oracle VM virtual box software. The measurements were performed at each of the participant positions (three positions per luminaire)

with the obstacles both raised and lowered. The photos were taken with the use of a tripod at a height of 1.7 m since this is considered the average eye height of a person. The handheld Minolta Luminance Meter LS-100 was used to calibrate the results from the luminance photographs. This handheld was used during the same time as the luminance camera on six different reference points (Appendix IX).

Overall, all measurements were performed at three of the five evenings to consider the influence of time and weather. The measurements were performed on Tuesday 08-03-2022 from 21:00-22:00, on Wednesday 09-03-2022 from 19:15-20:15 and on Thursday 10-03-2022 from 20:15-21:15.

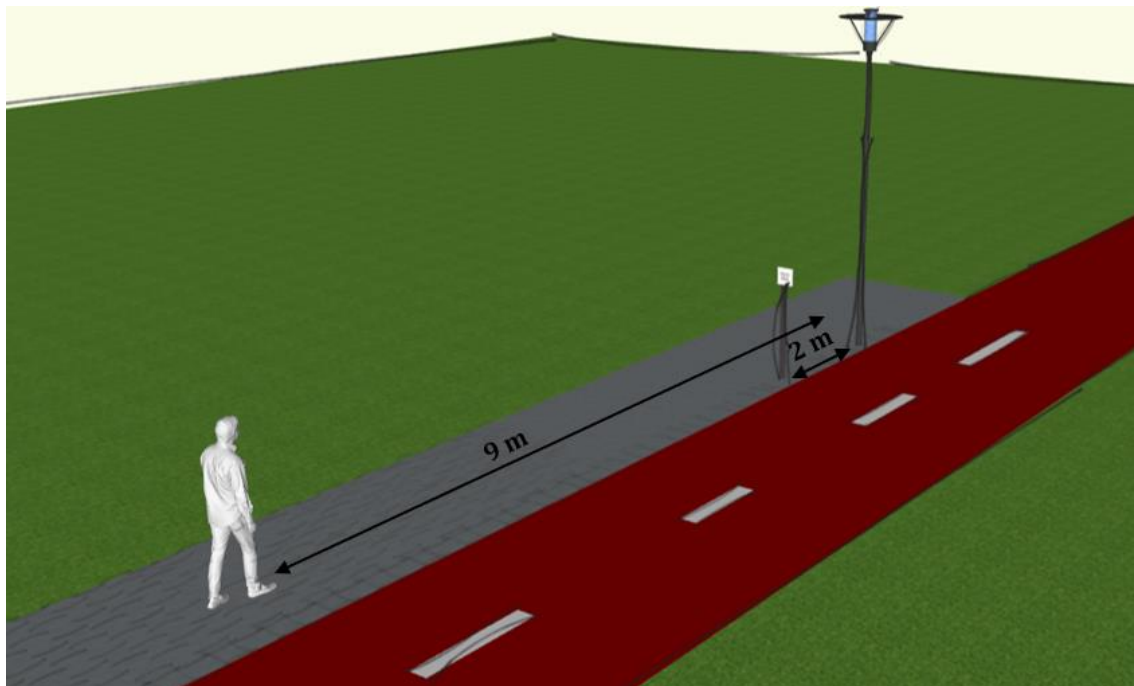


Figure 9 - Schematic overview of the experimental set-up for position 3. The participant is located around the center between the two luminaires distance and the Pelli-Robson sign is located at 2 m from the luminaire.

3.3 Procedure

During the field study, on average there were two participants arriving at the same time and there were three time slots during each night. In total there were 7 participants on Monday, 6 on Tuesday, 9 on Wednesday, 5 on Thursday and 6 on Friday.

3.3.1 Instruction phase

The start of the study was at Buurthuis de Boog in Utrecht, here the participants were welcomed with a drink. Next, all participants were informed about the study and had the opportunity to ask questions. When everything was clear they were asked to fill in the informed consent form (see Appendix X) and to answer a few demographic questions. Furthermore, their bank details were written down to be able to compensate them for their participation and travel expenses.

3.3.2 Eye measurements

After the instruction phase was completed, the participant was guided towards the eye measurements. These measurements took place at the Buurthuis de Boog in Utrecht and lasted around 20 minutes per participant. For each participant several different eye measurements were executed which were discussed in section 3.2.2.

3.3.3 Field study

When the eye measurements were all completed, the participants were guided towards the Carnegiedreef in Utrecht for the next part of the study. Before the start of the field study, the participants were instructed regarding the formulation of the positions of the obstacles. Obstacles could either be located 'far away' or 'nearby' and they could be located 'Left', 'Right' or 'Middle'. Another thing that was explained to the participant, was the fact that there were either 0,1,2 or 3 obstacles lifted. Furthermore, the potential answers during the facial expression recognition task were mentioned. This was explained to make sure the answers of the participants were consistent with the possible answers. Finally, the participants were explained that the facial expression recognition was the main task and the obstacle detection task was an additional task. When this was all clear for both participants, the second participant was guided towards luminaire B while the first participant started at luminaire A. The main reason for this, was to limit the influence of the participants on each other. Another important benefit is the expectation that people will perform the worst at the first luminaire type ('learning effect'). If all participants started at luminaire A, the data from this fixture would become unreliable but this factor is now reduced.

When both participants are located at their starting position, either at luminaire A or B they were asked to turn around towards guide 1. During this moment guide 2 lifts the obstacles and the emotion (or E-hook) of trial 1 position 1. The emotion is always held at eye height to mimic a realistic situation. The participant is now allowed to turn around and has 3 seconds to look at the facial expressions (or E-hook) and check for obstacles on the footpath. After 3 seconds the participant is asked to turn around and guide 1 writes down the facial expression (or letter direction) and the obstacles that were observed. During this time, guide 2 can lift the obstacles and the facial expression for trial 2 position 1. Overall, this procedure is repeated three times per position. Then, the participant and guide 1 move towards position 2 (at the same set of luminaires) with a gaze direction towards the luminaire. For this position, the same procedure is repeated for three trials. Overall, this results in six trials for each luminaire type per participant.

When the six trials of the luminaire are completed, the participant is guided towards the center between the two luminaires of the same kind. Here, the questions about the environmental perception are asked which are rated on a 5-point scale from completely disagree to completely agree. Next, the level of glare was questioned with the De Boer scale. Here, it was explained to the participant that '1' meant no glare and '9' meant the worst glare that you could possibly imagine. Finally, the participants were asked to look at a small sign in front of them with letters that reduces in contrast level. All the letters that they could read from this sign were read out loud and the number of rules was written down by guide 1.

This whole procedure was repeated for the seven different light sources. When this was completed, the participants were thanked for their participation and debriefed about the goals of the study.

3.4 Measurements

3.4.1 Obstacle detection task

During the obstacle detection task, participants were standing at a constant fixed position (indicated in figure 6 & figure 7). The experimenter who was standing at position B (lifts the obstacles) has a form for each luminaire at which all the trials per position are noted down. For each trial, the number of obstacles (between 0 and 3) as well as the positions of the obstacles (between 1 and 6) were randomized (see Appendix XI). The experimenter raised the obstacles that were supposed to be raised for the specific trial. The setup of the obstacles was unique for each participant. Next, the participants were allowed to look for 3 seconds and were then asked to turn around. Then they were questioned regarding the number of obstacles and the position of the obstacles they had identified. Overall, this was repeated three times per position at two different positions for seven different luminaires which results in a total dataset of 42 answers per participant. For an example of the questionnaire for one luminaire type, see Appendix XII.

3.4.2 Facial expression recognition task

During the facial recognition task, the participants were standing at a constant fixed position while the second experimenter holds a photograph at eye height. The emotion of this photograph was randomized and unique for each participant (see Appendix XI). The participants were allowed to look for 3 seconds and were then assessed on the correctness of the identification of the emotional expression. This was repeated three times per position, at two different positions for seven different luminaires which results in a total dataset of 42 answers per participant. For an example of the questionnaire for one luminaire type, see Appendix XII.

For the participants with a visual impairment, the measurements were executed in a similar matter but instead with an E-hook in a size that is suitable for the individual participant's visual acuity. The trials were once again randomized (see Appendix XIII).

3.4.3 Environmental perception task

During the environmental perception task, the participants were asked seven different subjective questions regarding their assessment of the environment for each specific luminaire type. These seven questions were based on a previous study from the municipality of Utrecht, to be able to compare the results from this study to the former study. The first five questions were rated on a 5-point scale from completely disagree to completely agree. The actual questions in Dutch can be seen in Appendix XII. In English translation, the questions were:

1. I can see enough from the nearby environment
2. I feel safe
3. The light quality is excellent
4. The surrounding area is lit adequately
5. With this type of lighting, I can walk across the path comfortably

The sixth question assesses the discomfort glare by using the reversed 9-point De Boer rating scale (Gellatly & Weintraub, 1990). This scale goes from just noticeable towards unbearable. For this study, the Dutch translation of the De Boer rating scale was used (Tekelenburg, 1980). The final question is a Pelli-Robson sign task at which participants need to look at a sign ahead at which the contrast is decreasing linearly. The participants need to state the number of readable lines, there are six lines in total which means the answer scale goes from 1 line to 6 lines (see Appendix XII).

3.4.4 Photometric measurements

With the HDR-image camera, specific values can be determined of the background luminance, minimal path luminance and source luminance. Another important thing that can be determined is the contrast between the obstacles and the nearby environment. Pictures are made at the participants positions both when the obstacles are up and down, in this way the difference in contrast can be calculated and this will most likely influence the visibility of the obstacle. The formula used to calculate the contrast level for each obstacle can be seen in (1).

$$\frac{\text{Average luminance of the (visible) sides of the obstacle}}{\text{Average luminance of the top of the obstacle}} \quad (1)$$

A visualization of this calculation can be seen in Appendix XIV.

In figure 10, an example of an HDR-image can be seen for luminaire D for either position 1 or position 2. Overall, the contrast was calculated for all the 42 obstacles at both positions. All the values can be seen in Appendix XV.

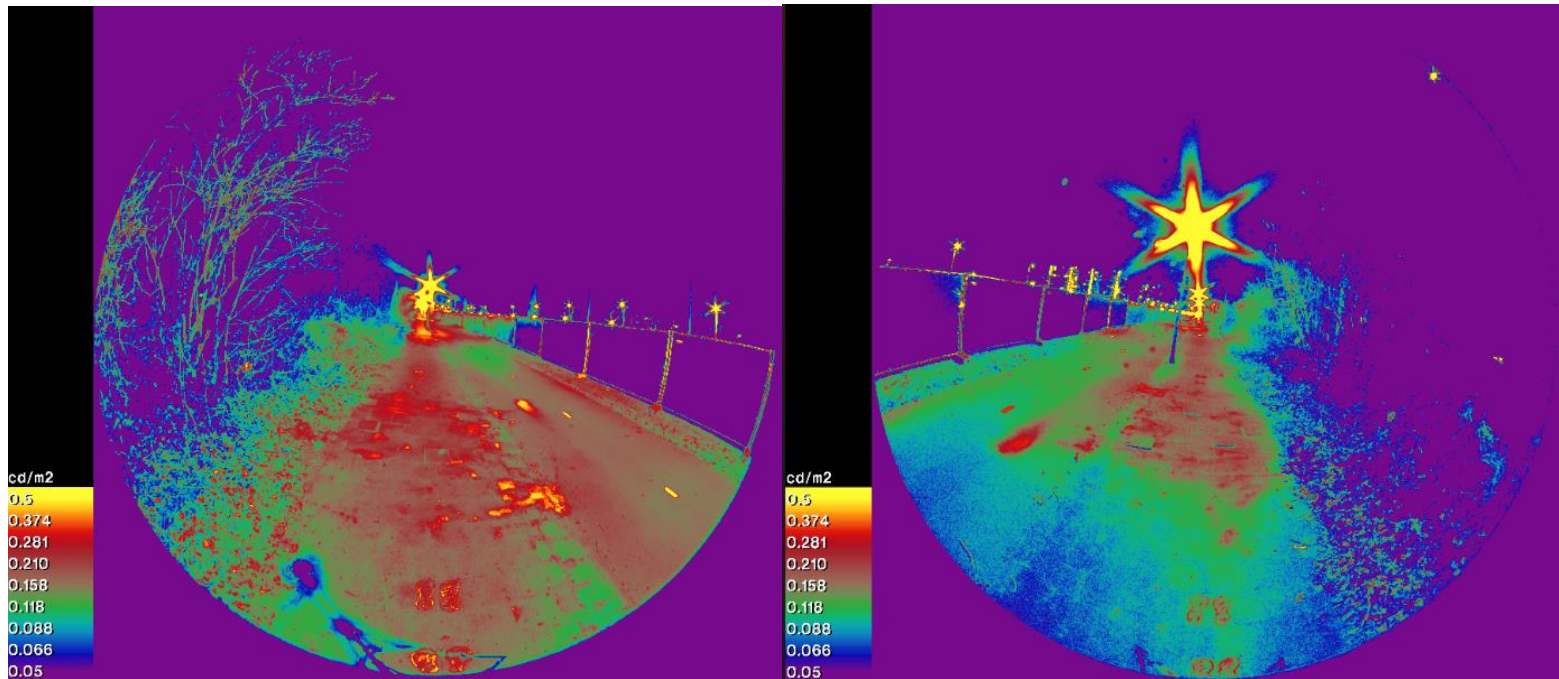


Figure 10 – Luminaire D from either position 1 (left) and position 2 (right)

3.5 Participants, Guides & recruitment

The participants from this study were recruited through several different methods. Most participants with a visual impairment were recruited through the institution 'VISIO'. The other participants were mostly contacts from CROW and were recruited through convenience sampling. The invitation to participate in the study, however, was also published in several local papers and posted on the LinkedIn page of an employee from CROW. Overall, 75% of the participants were inhabitants of the municipality Utrecht. In total, 32 participants were included in this study:

1. 11 adolescents with a visual acuity of at least 0.6, mean age of 25.9 (SD = 1.88, range = 21-29). Where 7 were female & 4 were male.
2. 12 people with an age over 65 with a visual acuity over 0.6, mean age of 70.2 (SD = 3.46, range = 65-78). Where 7 were female & 5 were male.
3. 9 visually impaired people with a visual acuity lower than 0.6, mean age of 63.0 (SD = 10.93, range = 48-81). Where 4 were female & 5 were male. These participants had several different eye diseases such as age-related macular degeneration, cataract, and glaucoma.

There were several different guides required during the field study. First, one guide who oversaw welcoming and instructing the participants. Furthermore, there was one employee from VISIO in charge of the eye measurements. Next, during the visual performance task there were two guides required per participant which resulted in an average of four necessary guides per night. Finally, one person was needed to perform the photometric measurements throughout the evening. All guides were mostly recruited through convenience sampling since they were friends and family from the main experimenter. The invitation to help during the field study, however, was also published on the Instagram of the TU/e light community. In total, 12 different guides were recruited who all assisted during one or multiple evenings.

3.6 Data analysis

3.6.1 Data preparation

Before the data analysis, all answer sheets were transferred to an online version in Excel. Two versions were made, one for the explorative analysis in MATLAB and one for the statistical analysis in SPSS. The dataset for the explorative analysis consists of one spreadsheet with the age, visual acuity, and gender of each participant. Furthermore, there were 32 spreadsheets with all the answers of each individual participant. For both the obstacle detection task and the facial recognition task, columns were added with the correct answers to all trials. Afterwards, the actual answers of the participants were added in separate columns. For obstacle detection, [1] was that the participants identified an obstacle and [0] is that they did not identify an obstacle at that position. For facial expression recognition, [1] is the emotion 'Anger', [2] is the emotion 'Fear' and [3] is the emotion 'Happiness'. Furthermore, the subjective rating of discomfort glare for each luminaire type was added and the ratings for the environmental perception questions. Two other variables that were added were the height and the contrast of each obstacle, these were included for each individual obstacle which indicates six separate columns per variable (six obstacles). The contrast levels were determined from the HDR-images that were made on 10-03-2022 from 20:15-21:15. These images were chosen after the difference in lighting conditions was checked between the various days and times that the HDR-images were made. For this analysis, no outliers were removed yet since this was an explorative phase.

For the statistical analysis, the data was all combined into one large spreadsheet which consisted of the data from all the participants. In this sheet, the visual acuity and age were added for each participant. For the facial expression recognition task, one column was added where [1] meant that the emotion was correctly identified and [0] meant that the emotion was not correctly identified.

For the obstacle detection task, a column was added for each obstacle which was based on the previous dataset that was made for the explorative analysis. In this column, a [1] was noted when the obstacle was raised and the participant identified the obstacle correctly. However, a [0] was noted when an obstacle was raised and the participant did not identify the obstacle. The [0] was also placed at positions when no obstacle was raised and the participants also did not identify an obstacle. The reason for this is that control trials were excluded from the statistical analysis since these were only included in the study to investigate and counteract the response bias of participants. Finally, when the obstacle was not raised but participants identified an obstacle, this was identified as an outlier. It is possible that due to a 'natural' obstacle in the pathway or a mechanical malfunction of the obstacle the participants did see an actual obstacle. An irregularity in the pathway was identified as a 'natural' obstacle if it was raised at least 5 mm above ground level. It is, however, also possible that the participants wrongly identified a flat pavement tile as an obstacle. It is impossible to determine this at this point and therefore this data will be excluded from the data analysis. A final column that was added regarding the obstacle detection task was the percentage of the trial that was correctly identified. For instance, if two obstacles were lifted at a specific trial and the participants identified one obstacle correctly than this trial was rated a score of 50%. Other variables that were added to this datasheet were: the environmental perception ratings, the subjective rating of discomfort glare, the contrast sensitivity sign ratings, the height of the obstacle and the contrast level of the obstacle. Furthermore, the variation in path luminance was determined from the HDR-image made at 10-03-2022. From these images, three variables were created: the average path luminance at the obstacle positions, the average path luminance at the participant positions and the difference in path luminance between these two variables.

After both excel sheets were finalized, a list was made with all the (potentially) interesting relations between different variables, these will be discussed in the upcoming section.

3.6.2 Explorative analysis

Two types of analyses were conducted during this research, an explorative analysis, and a statistical analysis. The first analysis was executed in MATLAB R2020a to get an overview of the results. Overall, all the (potentially) interesting relations were first analyzed by creating visualizations, boxplots and graphs, of specific parts of the dataset. All this was executed for the three different participant groups and overall, two different analyses were conducted:

1. Results which can validate the developed methodology, indicate potential improvements for the method and provide recommendations regarding the use of the methodology

2. Results from the field study that are more content-wise (e.g., the difference in visual performance for various luminaire types).

The analysis that was conducted for both parts will be discussed separately in the next section.

Validate the methodology

To validate the developed methodology several items were tested and analyzed during the field study. First, the number of trials which are necessary for each participant position. Due to time-constraints, three trials per position were used in this study. The difference in performance between these three trials should, however, be analyzed to indicate whether this number of trials is optimal. For example, if participants perform similarly in trial 2 and 3, trial number 3 might not be necessary to include. To analyze this, the correct obstacle identification value was calculated for each separate trial with formula 2. For example, if during a specific trial obstacle 3 and obstacle 5 were raised but the participants only identified obstacle 3 correctly, the correct obstacle identification value will be 0.5 trial.

$$\frac{\text{Number of obstacles correctly identified during a specific trial}}{\text{Number of obstacles raised during a specific trial}} \quad (2)$$

Afterwards, all the correct obstacle identification values for each trial (with either number 1, 2 or 3) were combined per luminaire type, which results in 7 (luminaire types) x 3 (trials) values for each participant. Next, the average obstacle identification percentage per luminaire type was calculated for either trial 1, 2 or 3 by taking the mean of the all the participant combined (formula 3).

$$\frac{\text{Sum(correct obstacle identification value for each participant)}}{32} \times 100\% \quad (3)$$

Finally, the seven average values for each trial (1,2 or 3) were combined in a graph where the luminaire types are positioned on the x-axis and the average percentage of trials correctly identified for each luminaire type on the y-axis.

Another item that was tested is the need to include a practice trial in the field study. During the experiment, no practice trial was included. If, however, the data indicates that people perform worse during the first (few) executed trials, this data is not reliable and adding a practice trial should be recommended for further research. Furthermore, it can also be tested whether people perform worse at the end of the study due to an increased fatigue. This relation will be tested by creating a spreadsheet where the sequence of luminaires instead of the luminaire types are included. Afterwards, the correct obstacle identification percentage was once again calculated with formula 2 but this time all the three trials will be considered in the same measurement. Afterwards, all the

correct obstacle identification values for each trial were combined per luminaire type, which means that there are 7 values per participant. From these values a boxplot was created where the sequence of luminaires is on the x-axis and the average number of trials correctly identified during each sequence is positioned on the y-axis for each participant. The boxplot will visualize the median and range of the average number of trials that are correctly identified during the experiment per sequence.

Thereafter, the analysis will focus specifically on the obstacles. First, the exact position of the obstacles was analyzed. In this field study, six different obstacle positions were chosen which were located at different distances either on the left, right or in the middle compared to the participant's position. It should, however, be tested whether all obstacles were at an optimal position during this study. If, for instance, one obstacle was hardly visible for all participants this might not be an optimal position for the obstacle. From this analysis, conclusions can also be made regarding the visibility of obstacles with different viewing angles from the participants' eye location. For this analysis, the number of times an obstacle at a certain position was correctly identified was calculated for each participant with formula 4. In this formula, if the obstacle was raised/identified it will be a (1) and if it is not raised/identified it will be a (0). This calculation was executed separately for the two different participant positions. This results in 6 (obstacle positions) x 2 (participant positions) values for each participant. These values were combined for each separate target group per participant position with formula 5. In the end, two separate graphs were created for position 1 and position 2 where the individual obstacle numbers are located on the x-axis. On the y-axis, the average percentage that this individual obstacle was correctly identified is displayed, this value was split between the three separate target groups.

$$\frac{\text{Specific obstacle identified}}{\text{Specific obstacle raised}} \times \text{number of trials} \quad (4)$$

$$\frac{\text{Sum(correct obstacle identification value for each participant in target group)}}{(\text{number of participants per target group})} \times 100\% \quad (5)$$

Next, the height of the obstacles will be analyzed. During the field study many variables are difficult to control. One of these variables is the height of the obstacles. The variance in height that the obstacles were lifted could influence the obstacle detection rate since people probably see obstacles better if they are raised higher. Furthermore, it is possible that both the sides and the front of the obstacle influences the detection rate but it also possible that only the front of the obstacle is relevant. The exact location of the obstacle could have an influence on the determination of the relevant sides of the obstacle. To investigate which sides of the obstacle should be considered during further research this analysis was conducted. The analysis was conducted separately for the three different sides (front, left, right). First, for each of the six obstacle locations formula 6 was used to determine the correct obstacle identification number per obstacle and these were immediately ordered in five different height ranges.

$$\frac{\text{Specific obstacle identified (height between } X \text{ \& } X)}{\text{Specific obstacle raised (height between } X \text{ \& } X)} \times \text{number of trials} \quad (6)$$

This resulted in five values for each participant where the number of times an obstacle was correctly identified was separated for different height ranges. From this, a boxplot was created for all three sides separately where the obstacle height was displayed on the x-axis in five groups. These groups were determined by taking a logical distribution from a high to low height (> 20 mm, 15-20 mm, 10-15 mm, 5-10 mm and < 5 mm). The average percentage of obstacles that was correctly identified in that height range was displayed on the y-axis for each individual participant. In the final part of the analysis regarding the height of the obstacle, all sides were considered combined by using formula 7.

$$\frac{\text{Obstacle identification rate (left side+front side+right side)}}{3} \times \text{number of trials} \quad (7)$$

Next, the influence of the contrast level between the tile that got lifted and the surrounding tiles was analyzed. This contrast differs for each obstacle and is dependent on the position of the obstacle, the viewing direction of the participant and (in a smaller amount) the height of the obstacles. Height is mainly related towards the visibility of the contrast in general, when an obstacle is hardly raised the contrast between the obstacle and the nearby obstacles is hardly visible which makes it more challenging to calculate this value. The variance in these contrast values could influence the obstacle detection rate of the participants and therefore their visual performance. The contrast value for all obstacles from both positions were determined with the formula that was explained in section 3.4.4. The analysis was conducted similarly as the height analysis but this time five different contrast ranges were added instead of height ranges. These different ranges are: < 0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8 and >0.8. From this, a boxplot and a graph were made where the x-axis

consists of different contrast value ranges and the y-axis is similar as the axis for the height of the obstacles. This makes it possible to compare the influence of height and contrast on the visual performance with each other.

Finally, the Pelli-Robson sign task as described in section 3.2.4 will be investigated in relation with the obstacle detection rate. These two tasks both measure visual performance but in a different manner. It is interesting to compare whether these two have the same outcome for the different luminaire types since this would make it possible to validate the reliability of the obstacle detection task with the Pelli-Robson sign task. This correlation between the obstacle detection task and the contrast sensitivity task will be tested by calculating the average rating for the contrast sensitivity task for each luminaire type per participant, which results in 7 ratings per participant. Afterwards, the average rating per luminaire type will be calculated. This will then be combined in a graph with the values of the obstacle detection rate that will be explained in the upcoming section.

Field study

The main aim of this research was to develop and validate a methodology. During the field-study, however, more data was collected: content-related data. These are results that are not necessarily relevant for the validation of the methodology but they are interesting findings to provide (potential) recommendations regarding the lighting conditions to create an accessible outdoor environment.

First, the facial expression recognition task will be analyzed in relation to the seven different luminaire types and the two different participant positions. This will enable to conclude whether there is a difference in facial expression recognition for different lighting conditions. It is expected that this variance will be small since the facial expression recognition task was purely a distraction task which should have been easy to execute. This analysis was conducted separately for the visually impaired people and the elderly/adolescents since the distraction task was different between these groups. First, the correct identification rate for the facial expressions per trial will be calculated for each participant. The three different emotions were given a number in the spreadsheet from [1] to [3]. With formula 8, the facial expression that was identified by the participant was compared with the facial expression that was raised. If the participant correctly identified the facial expression, this formula will give the answer '1'. Afterwards all, the correctly identified faces were ordered per luminaire type which results in 7 values per participant. From this, boxplots were created where the luminaire types are positioned on the x-axis and the average number of faces for each luminaire type that were correctly identified was positioned on the y-axis. Second, the same analysis was executed

but this time the correctly identified facial expressions were ordered by participant position instead of luminaire type, which results in 2 values per participant.

$$\frac{\text{Facial expression identified}}{\text{Facial expression raised}} \quad (8)$$

Next, the relation between the obstacle detection task and other variables will be analyzed in detail such as the luminaire type, participant position and discomfort glare. First, the difference in the obstacle detection rate between various luminaire types will be analyzed. When these results are linked with the photometric quantities of each light source, conclusion can be made regarding the most optimal light conditions for the visibility of obstacles. This analysis is similar to the previous analysis where the need for a practice trial was tested. The only difference is that the x-axis consists of the seven different luminaire types instead of the sequence of trials. The correct obstacle identification percentage was once again calculated for each luminaire type which results in 7 values per participant. Next, the two different positions will be analyzed to investigate the difference in obstacle detection rate between looking towards and looking away from the luminaire. This will all be combined in one boxplot to see the difference between the two different positions for each luminaire type. These two previously mentioned analyses will be done separately for people with different visual acuity levels to compare the visual performance of people with a good and a poor vision. Here five separate graphs for participants with different visual acuity levels will be combined to visualize the difference in obstacle detection rate for each visual acuity range (> 0.4, 0.4-0.8, 0.8-1.2, 1.2-1.6, > 1.6). In the final part of the analysis, the subjective ratings will be compared with the obstacle detection task to investigate whether there is a correlation. First, the environmental perception questions will be analyzed in relation to the obstacle detection task. If, for instance, people rate the light quality of a certain luminaire as optimal but their visual performance during the obstacle detection task is poor, it could be concluded that subjective questions regarding the light quality of the environment alone are not sufficient to make a space safe and accessible for everyone. This correlation between the obstacle detection task and the environmental perception questions will be tested by calculating the average rating for each of the five questions for all luminaire types per participant, which results in 7 (luminaire types) x 5 (questions) ratings per participant. Afterwards, the average rating per luminaire type will be calculated. Furthermore, the subjective perception of discomfort glare will be linked with the obstacle detection task to see whether people perform worse at the obstacle detection task if they experience more discomfort glare. This analysis will be executed similarly as the analysis related to environmental perception question.

3.6.3 Statistical analysis

Promising relations found during the previous analysis in MATLAB will be further tested in their significance in IBM SPSS Statistics 25. A significance value of $\alpha = 0.05$ and a power level of 0.80 was used for all tests (Hintze, 2008). Before starting the analysis, the assumptions of normality, independence of observations and homoscedasticity were checked. Furthermore, the data was analyzed and checked for outliers. Obstacles that were observed by participants but were actually not raised were considered outliers. The reasoning behind this will be discussed in subchapter 4.1.1. Besides this, all data was kept for further analysis since the variance is high between different participant groups which makes all data interesting for further analysis. Most relations will be tested with a one-way ANOVA, with this, for instance, it can be tested whether the obstacle detection rate is significantly different between luminaire types (categorical variable). Furthermore, the correlations which were visually analyzed using MATLAB will be tested again in SPSS to achieve statistical significance or not, for this, parametric tests will be used. Finally, a multi-factor analysis was conducted to be able to include all variables which have an influence on the obstacle detection task and investigate which factors are significant predictors of this task. This will be analyzed by testing correlations and a multiple linear regression. The variables that will be included for this analysis will be determined from the correlations found during the explorative analysis.

4 Results

In the upcoming chapter, the main findings from the field study will be highlighted, after which they will be discussed in detail in chapter 5. This chapter is subdivided into three separate sections. In the first section, an overview of the data is given, here all descriptive statistics of the field study are highlighted. The second section shows the findings for the validation of the developed methodology. In the third section, the additional findings from the field study are highlighted.

4.1 Descriptive statistics

During the five consecutive days that the study was executed a total of 32 participants participated in this study, with a mean age of 52.7 years old (range = 21-81, SD= 20.837). These participants were selected based on a wide variety in visual-acuity level with a range from 0.017-1.91 (mean = 0.97, SD=0.49). The 32 participants executed 1320 trials in total: 186 trials for luminaire A, 192 trials for luminaire B, 192 trials for luminaire C, 192 trials for luminaire D, 192 trials for luminaire E, 186 trials for luminaire F, 180 trials for luminaire G. The reason for this variety in number of trials is that three participants were not able to complete the study due to time constraints. The facial expression recognition task was correctly executed 77% of the total amount of trials. For the obstacle detection task, obstacle 1 was identified correctly 69 of the 309 times that the obstacle was raised (22%), obstacle 2 was correctly identified 112 of the 365 times that the obstacle was raised (31%), obstacle 3 was correctly identified 171 times of the total 393 (43%), for obstacle 4 the values are 116 times of the total 321 (36%), for obstacle 5 it is 116 of the 322 (36%) and obstacle 6 was correctly identified 158 of the 328 times the obstacle was lifted (48%). This results in an average correctly identified obstacle detection rate of 38%. When looking at the specific obstacles, the height of each obstacle differs. The average height that the obstacles were lifted is 10.9 mm (range = 0-25 mm, SD = 7.378). For the contrast level between the lifted obstacle and the surrounding tiles, the average contrast for all the obstacles combined is 0.49 (range = 0.08 – 0.88 mm, SD = 0.229). The descriptive statistics for each of the six obstacle numbers separately is visualized in table 4.

Table 4 - Descriptive statistics of the height and contrast values of the six obstacles

	Height				Contrast			
	Mean (mm)	Min (mm)	Max (mm)	SD	Mean	Min	Max	SD
Obstacle 1	11.15	4	20	5.446	0.55	0.10	0.85	0.238
Obstacle 2	10.36	0	25	7.743	0.48	0.13	0.83	0.222
Obstacle 3	12.63	2	22	6.623	0.46	0.08	0.074	0.197
Obstacle 4	12.86	4	20	5.075	0.51	0.12	0.88	0.221
Obstacle 5	8.37	2	20	5.111	0.48	0.14	0.78	0.208
Obstacle 6	10.32	0	22	7.497	0.49	0.13	0.86	0.229

These descriptive values give a first overview of the data. It is, however, important to determine whether all this data can be included during the upcoming statistical analysis. This will be discussed in the upcoming section. Afterwards, the properties of the seven different luminaire types will be discussed in the section ‘photometric properties’.

4.1.1 Outlier analysis

In the descriptive analysis, the number of correctly identified obstacles was discussed for each of the six obstacles. There were, however, also cases that a participant identified an obstacle that was not raised. This means that they saw an ‘invisible’ obstacle. Overall, an overview of all the obstacles that were wrongly identified can be seen in table 5. Some of these cases can (potentially) be explained by the fact that there were natural ‘obstacles’ present in the original pathway. An example of a natural ‘obstacle’ can be seen in Appendix XVI. In the table, the times participants (potentially) identified a natural ‘obstacle’ in the pathway are highlighted in grey. It is, however, hard to determine whether the participants actually saw the natural obstacle since this was not tested during the study. Furthermore, the natural ‘obstacles’ are randomly distributed throughout the pathway which results in unwanted differences between the luminaire types. Therefore, all the outliers presented in the table will be excluded from this dataset to create the most reliable outcome. Overall, this results in 44 outliers at luminaire A, 38 outliers for luminaire B, 25 outliers for luminaire C, 46 outliers for luminaire D, 44 outliers for luminaire E, 15 outliers for luminaire F and 19 outliers for luminaire G. Summarized, there are 231 outliers in total. The complete number of obstacles are the 1320 trials times 6 obstacles which is 7920. This means that 2.9% of the obstacle detection task data will be considered an outlier. Due to the three different target groups that were included in the study, the data consist of a high variance in answers this means that it is challenging to identify outliers so no other data was excluded from the data analysis.

Table 5 - Descriptive table with the number of false-alarm values for each obstacle per luminaire type. The values which are highlighted in grey are (potential) detected ‘natural’ obstacles

	Luminaire A	Luminaire B	Luminaire C	Luminaire D	Luminaire E	Luminaire F	Luminaire G
Obstacle 1	4	5	3	5	5	2	1
Obstacle 2	7	2	0	7	4	2	1
Obstacle 3	6	14	9	8	16	4	7
Obstacle 4	12	4	2	2	9	1	3
Obstacle 5	5	1	7	12	4	3	2
Obstacle 6	10	12	4	12	6	3	5
Total	44	38	25	46	44	15	19

4.1.2 Photometric properties

To investigate the difference in luminance distribution between the different luminaires, luminance photos were made with the HDR-camera. The photos were made during three different days at various times to get a sense of how the lighting changed throughout the evening. Overall, it can be concluded that during all days and times, the luminance distribution over the pathway was similar, with a maximum variation of 3%. This was determined by comparing the path luminance of six different points for each set of HDR-images (see Appendix IX). After this, it was decided that for the upcoming analysis, the HDR-images made on Thursday 10-03-2022 will be used since this was the only day that pictures were made both when the obstacles were raised and when the obstacles were lowered at each position. In table 6, the average luminance at the position of the obstacles and the average luminance at both participant positions are highlighted. These values were determined from the luminance profiles of which an example can be seen in Appendix XVII. From these profiles, the luminance values of each pixel were calculated which was averaged to determine the luminance at the different areas. The exact area that is used to compute the average path luminance at each position can be seen in Appendix XVIII. It should be noted that for this calculation the 50th percentile median line was used to minimize the effect of the chalk, that was used to mark the participant positions, on the luminance values. Furthermore, the luminance profiles are based on the HDR-images that were made at the side of position 2. The values for the HDR-images at position 1, however, are comparable to the values from the viewpoint of position 2. Overall, these values can be used during the upcoming data analysis to investigate the effect on the luminance distribution on the visual performance of the participants.

Table 6 - Average path luminance values for the area near the obstacles and on both participant positions for each luminaire type.

	Path luminance (cd/m ²) (obstacles)	Path luminance (cd/m ²) (Participant position 1)	Path luminance (cd/m ²) (Participant position 2)
Luminaire A	0.26	0.22	0.10
Luminaire B	0.25	0.28	0.09
Luminaire C	0.28	0.16	0.13
Luminaire D	0.17	0.18	0.12
Luminaire E	0.25	0.27	0.10
Luminaire F	0.24	0.29	0.09
Luminaire G	0.42	0.35	0.09

4.2 Method validation

To be able to provide feedback on the developed methodology, the field study was conducted. In this section, the results of different analyses to validate the method will be highlighted to be able to provide recommendations for further research in the next chapter. The main questions that were discussed are:

1. Are the number of trials appropriate?
2. Is there a need for a practice trial?
3. Are the positions of the obstacles rightly chosen?
4. What is the effect of obstacle height on the visual performance of people?
5. What is the effect of obstacle contrast on the visual performance of people?
6. Is there a relation between the Pelli-Robson signs and the obstacle detection rate?

After all these questions are discussed, the main predictors of the obstacle detection rate will be investigated with a multi-factor analysis.

4.2.1 Number of trials

In the developed methodology, three trials per positions are executed since this was manageable in the available timespan for the field study. It was assessed whether this number of trials is appropriate for this method. The three trials were separately investigated in relation to the visual performance during the obstacle detection task. This can be seen in figure 11. This figure illustrates the average percentage of the separate trials correctly identified during the obstacle detection task for each luminaire, averaged for all participants.

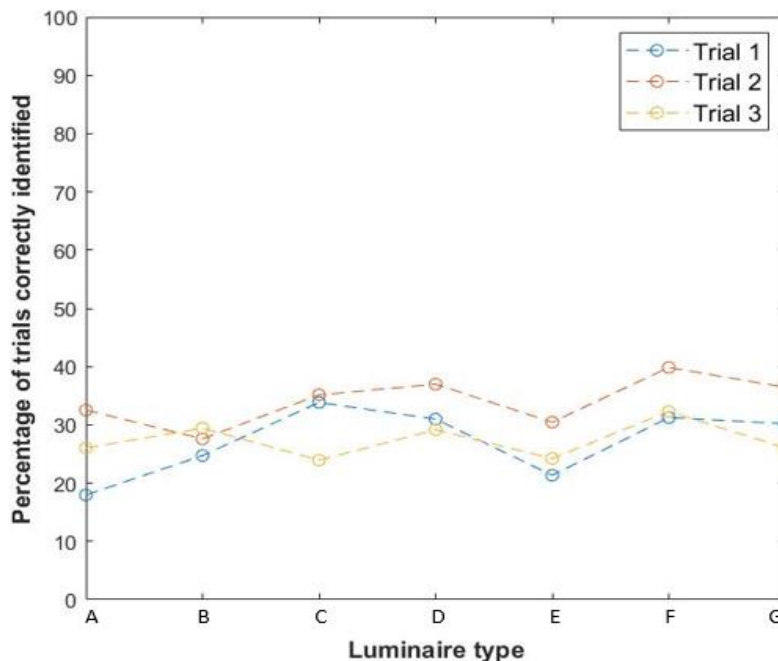


Figure 11 - Visualization of the percentage of trials correctly identified for the three separate trials per luminaire type.

Overall, the figure indicates that all trials are correctly identified between 18- 40% of the time. The lowest value is located at the first trial of luminaire A with a correct identification rate of 18 percent. There is variation between the three different trials but there is no clear increase in performance when people execute more trials at the same luminaire type. Summarized, for this methodology, three trials for each position are sufficient to gain a reliable dataset.

4.2.2 Need of a practice trial

During the field study, two or three participants participated simultaneously which means the participants started at various luminaire types. Specifically, 18 participants started at luminaire A, 12 participants started at luminaire B and 2 participants started at luminaire C. The participants were not given a practice trial to get acquainted with the task, to analyze whether this should be included in further research an analysis was conducted. In the boxplot in figure 12, the average number of trials correctly identified for each participant are compared for every sequence of luminaires. In the figure, sequence 1 (Nr1) performed (on average) two times worse than all other numbers. Another relation that can be visualized with a boxplot is whether people start to get tired after a certain number of trials. There is, however, no clear decrease in performance for the last number. Overall, the figure indicates that a practice trial should be included prior to the first luminaire.

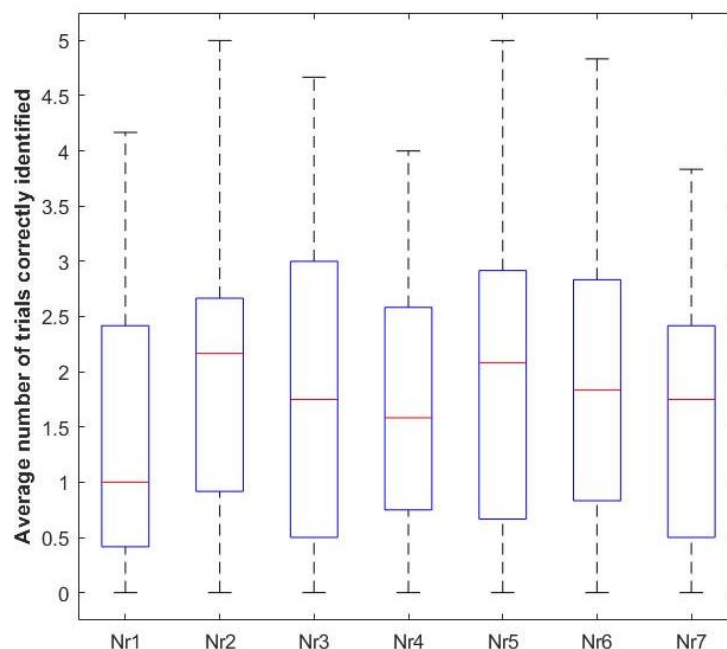


Figure 12 - Visualization of the trials correctly identified per sequence of luminaire type

4.2.3 Obstacles

Position of obstacles

For each luminaire, six obstacles were positioned at a distance from the participant to the obstacles between 2.5 and 4.0 meter (figure 13).



Figure 13 - Visualization of the different obstacle positions from the viewpoint of position 1.

These obstacles were located at the left, middle and right side. To investigate whether the obstacle positions were correctly chosen, the visual performance for all the separate obstacles is analyzed to see whether there is a clear difference between the obstacles. In figure 14, the average percentage correctly identified of that specific obstacle number can be seen for each of the three target groups (elderly, adolescents, and visually impaired people) for position 1. Here the distance between the obstacles and the participants goes from far away to nearby. In figure 15, the average percentage correctly identified can be seen for position 2. Here the distance between the participant and the obstacles goes from nearby to far away. At the x-axis of the graphs, the location of the individual obstacles can be seen. The specific obstacle is highlighted in red and the participant position is marked in blue. Overall, it can be concluded that the obstacles are identified correctly most often when the obstacles are positioned in the middle or on the right side of the participant. Another interesting conclusion is that elderly people can see a higher percentage of the obstacles at position 2 when the obstacles are positioned further away from them. Finally, obstacle number 1 is only correctly identified between 10-12% of the time at position 1 through both the elderly and the adolescents.

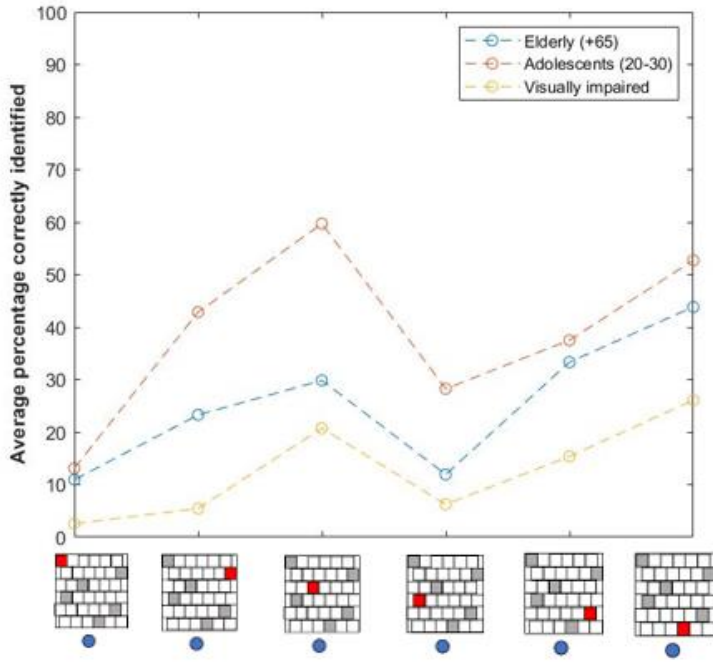


Figure 14 - Visualization of the difference in obstacle identification rate between the six obstacle positions (participant position 1)

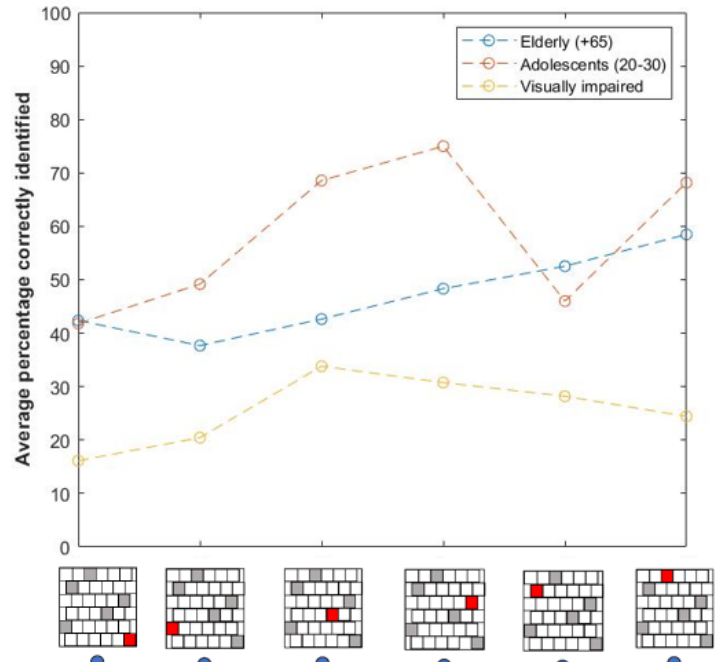


Figure 15 - Visualization of the difference in obstacle identification rate between the six obstacle positions (participant position 2)

To assess the difference between the obstacle detection rate for different obstacle positions even further an one-way ANOVA was conducted. This included the correctly identified obstacles for each individual obstacle as dependent variable for each luminaire type. Summarized, there was no significant effect ($p < .05$) for the obstacle detection rate of obstacle 1 ($p = .528$) between different luminaire types while there was a significant effect for the other five obstacles. The exact statistical values are: obstacle 2 ($F = 4.970$, $p = .000$), obstacle 3 ($F = 3.447$, $p = .002$), obstacle 4 ($F = 3.490$, $p = .002$), obstacle 5 ($F = 4.118$, $p = .000$), obstacle 6 ($F = 2.209$, $p = .040$).

Height

As mentioned, it was not possible to control the height of the obstacles completely. The variance in height that the obstacles were lifted could influence the obstacle detection rate since people probably see obstacles better if they are raised higher. In this section, it will be investigated which sides of the obstacles should be considered during further research. In the first analysis, only the front of the obstacle was considered for both position 1 and position 2 combined. In figure 16, the percentage of obstacles correctly identified for five different height levels are put together as an

average for each participant. Overall, 55% of the obstacles with a front height above 20 mm are correctly identified and 25% of the obstacles are correctly identified when the front height is lower than 5 mm. In the plot in figure 17, the averaged percentage of obstacles correctly identified can be seen for the three separate target groups. The percentage correctly identified is always highest for the adolescents but the trend is the same for all three target groups, more obstacles are correctly identified when the obstacle height is higher.

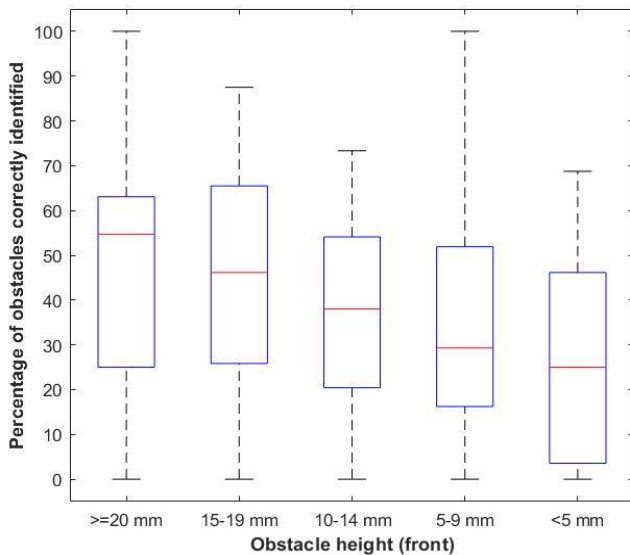


Figure 16 - Visualization of the percentage of obstacles correctly identified for different height levels (front side)

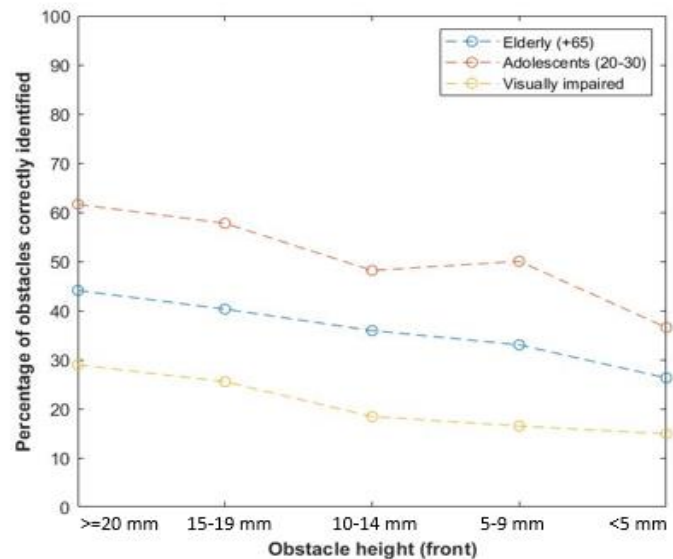


Figure 17 - Visualization of the average percentage of obstacle correctly identified for different height levels per target group (front side)

The previously conducted analysis was also conducted for both the left and the right of the obstacles, again respectively for both position 1 and position 2. When only the left side was considered, the left side from the obstacles from both the viewpoint of position 1 and position 2 are included in the analysis. In figure 18, the boxplot is visualized when only the left side of the obstacles is considered. Overall, 47% of the obstacles with a left height higher than 20 mm are correctly identified and 33% of the obstacles with a height lower than 5 mm are correctly identified. In the graph in figure 19, the percentage of obstacles correctly identified for each separate target group is highlighted again but this time for the left side. Overall, the trend is similar as the previous graph, more obstacles are detected when the height of the obstacle is higher. The slope of the trend is, however, less steep. Furthermore, from an obstacle height lower than 15 mm the obstacle detection rate becomes similar.

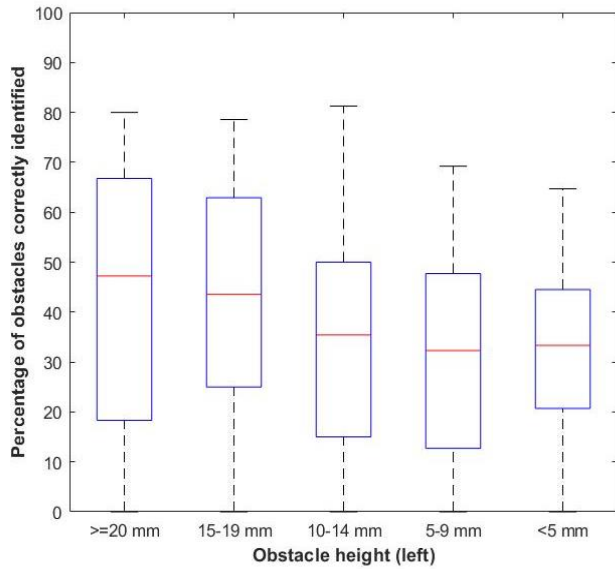


Figure 18 - Visualization of the percentage of obstacles correctly identified for different height levels (left side)

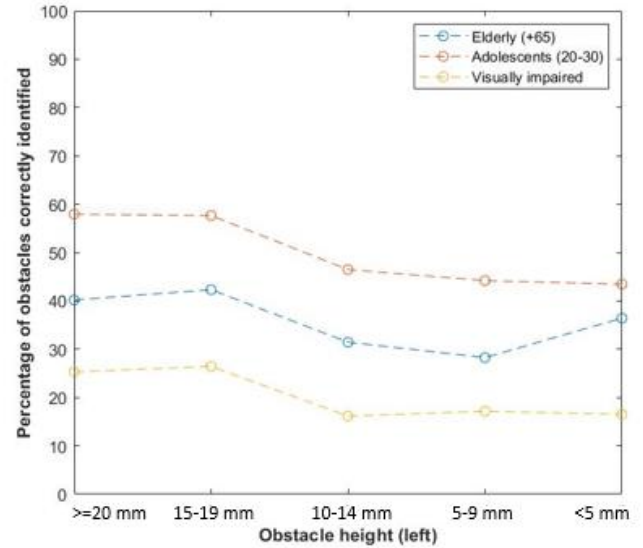


Figure 19 - Visualization of the average percentage of obstacle correctly identified for different height levels per target group (left side)

In figure 20, the boxplot is shown when only the right side of the obstacles is considered. The highest percentage of obstacles correctly identified is here at the height between 15 and 19 mm, with a value of 52%. When the obstacle height (right) is lower than 15 mm there is a steep drop to an average correct identification of 30.5%. In the graph in figure 21, the correctly identified obstacles are displayed per target group. Overall, the relation between the height of the obstacle and the correctly identification of obstacles is less clear than the previous sides. Once again there is a big drop for obstacles lower than 15 mm but thereafter the visual performance does not decline significantly.

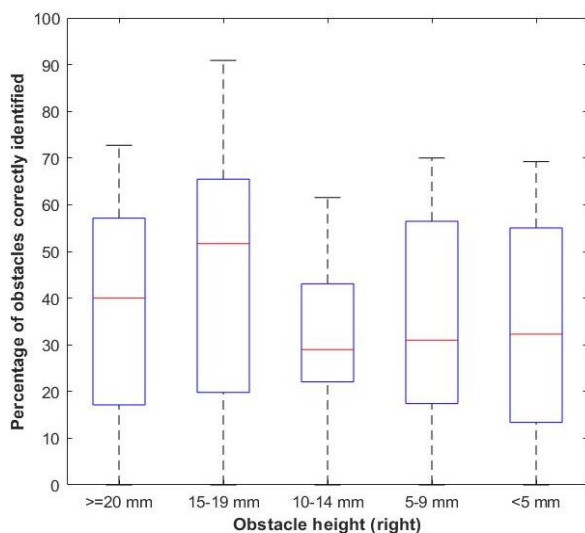


Figure 20 - Visualization of the percentage of obstacles correctly identified for different height levels (right side)

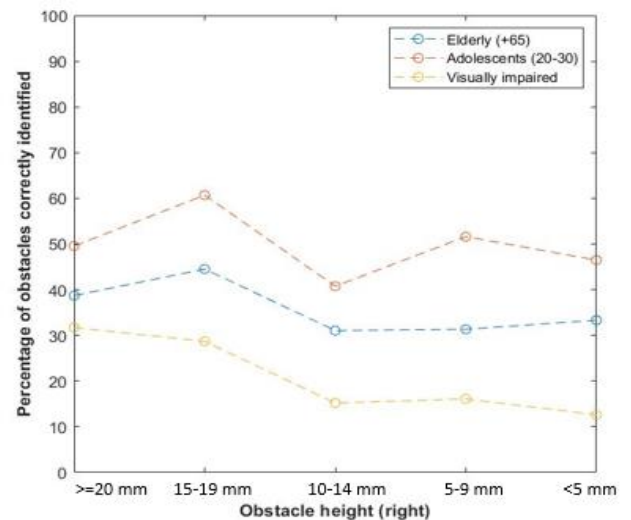


Figure 21 - Visualization of the average percentage of obstacle correctly identified for different height levels per target group (right side)

As a final part of the analysis regarding the height of the obstacles, all sides were considered combined. In figure 22, the graph with the percentage of obstacles correctly identified can be seen for all three target groups. Adolescents identify a higher percentage of obstacles than elderly and visually impaired people. For adolescents, the highest percentage identified is 60% at an obstacle height of 15-19 mm, the lowest percentage is 41% for obstacles with a height below 5 mm. For elderly people, the percentage of obstacles identified correctly is highest for obstacles with a height between 15-19 mm with a percentage of 43% and it is lowest for obstacles below 5 mm with a value of 31%. Finally, for people with visual impairment obstacles are correctly identified most often when the height is higher than 20 mm with a value of 29% and is lowest when the obstacles are below 5 mm with a value of 15%.

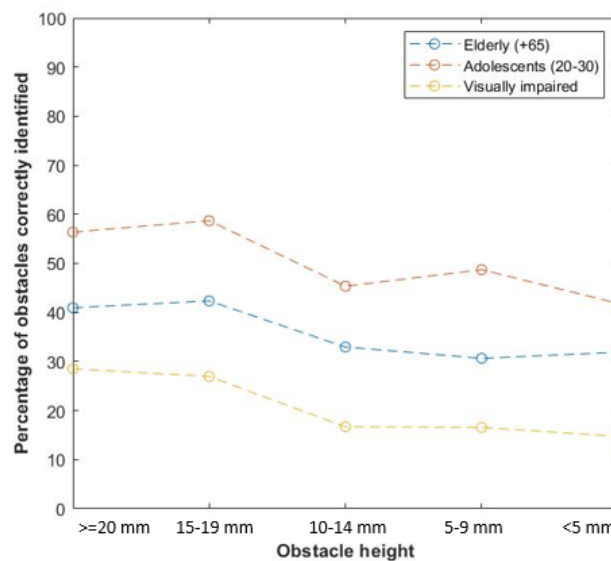


Figure 22 - Visualization of the average percentage of obstacle correctly identified for different height levels per target group (all sides)

To assess the effect of the obstacle height on the visibility of the obstacles even further the Pearson correlation was tested in SPSS between the visibility of each individual obstacle and the obstacle height of the front side for each obstacle. Overall, there was a significant correlation between the visibility of obstacle 3 ($r = 0.052$), obstacle 4 ($r = 0.065$), obstacle 5 ($r = 0.075$) and obstacle 6 ($r = 0.115$) and their corresponding height ($p < .05$). Obstacle 1 and obstacle 2 do not show a significant correlation with the obstacle front height with respective a value of $p = .438$ and $p = .835$. The left and right side were not tested since the correlation between the visibility of the obstacle and the height of the obstacle are less prominent. Overall, it can be concluded that the height of the front side of the obstacle is a significant predictor for the obstacle detection probability, but not for obstacle 1 and obstacle 2.

Contrast

Besides the variation in height of the obstacles, the contrast also differs for each obstacle. The variance in contrast values could influence the obstacle detection rate of the participants and therefore their visual performance. To investigate this, an analysis was conducted where the contrast values were compared with the percentage of accurately identified obstacles. In figure 23, the percentage of correctly identified obstacles with different contrast levels is displayed with an average value for each participant. Here '> 0.8' indicates the highest contrast value and '< 0.2' is the lowest contrast value. Overall, the median for detecting obstacles is 16% for a contrast value lower than 0.2 and the median for detecting obstacles is 65% for a contrast value higher than 0.8. In figure 24, the percentage of obstacles correctly identified can be seen for each separate target group for each contrast value range. Overall, the trend is that people detect obstacles better when the contrast is higher (independent on the path luminance) but visually impaired people are significantly inferior at the task compared to elderly people and adolescents.

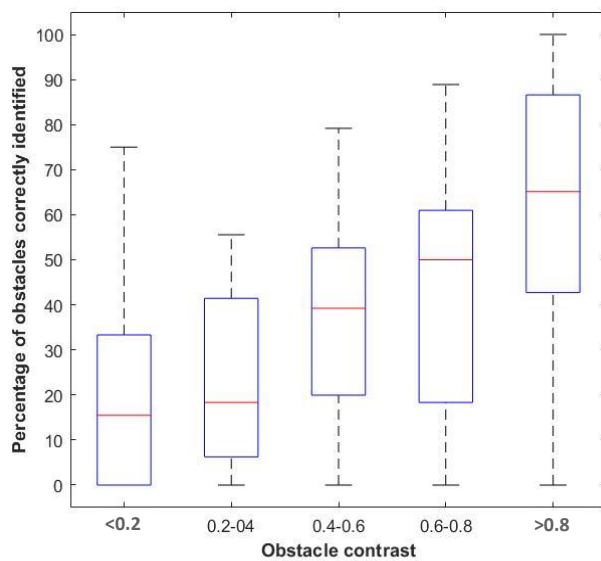


Figure 23 - Visualization of the percentage of obstacles correctly identified for different contrast levels

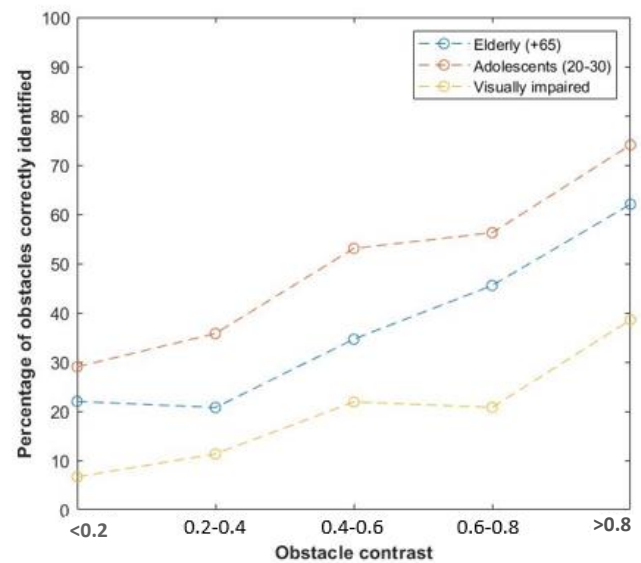


Figure 24 - Visualization of the average percentage of obstacle correctly identified for different contrast levels per target group

Like the analysis of the effect of height on the visibility of the obstacle, the bivariate Pearson correlation between the contrast of the individual obstacles and the visibility of the obstacles was also tested to see whether a significance value of $p < .05$ is met. There is a significant correlation between all the obstacle contrasts and the visibility of the individual obstacles ($p < .05$). The Pearson Correlation value for each obstacle are: obstacle 1 = 0.300, obstacle 2 = 0.244, obstacle 3 = 0.182, obstacle 4 = 0.215, obstacle 5 = 0.225 and obstacle 6 = 0.189.

Finally, the average rating of Pelli-Robson sign task for all participants were related to the obstacle detection task. As can be seen in the graph in figure 25, these two tasks seem highly correlated to each other. If participants perform better in the obstacle detection task, they also (on average) perform better at the contrast sensitivity task. To validate this result, the Pearson correlation was tested in SPSS. The results from this analysis were as expected, there is a highly significant relation between both visual performance tasks ($p=.000$, $r = 0.265$).

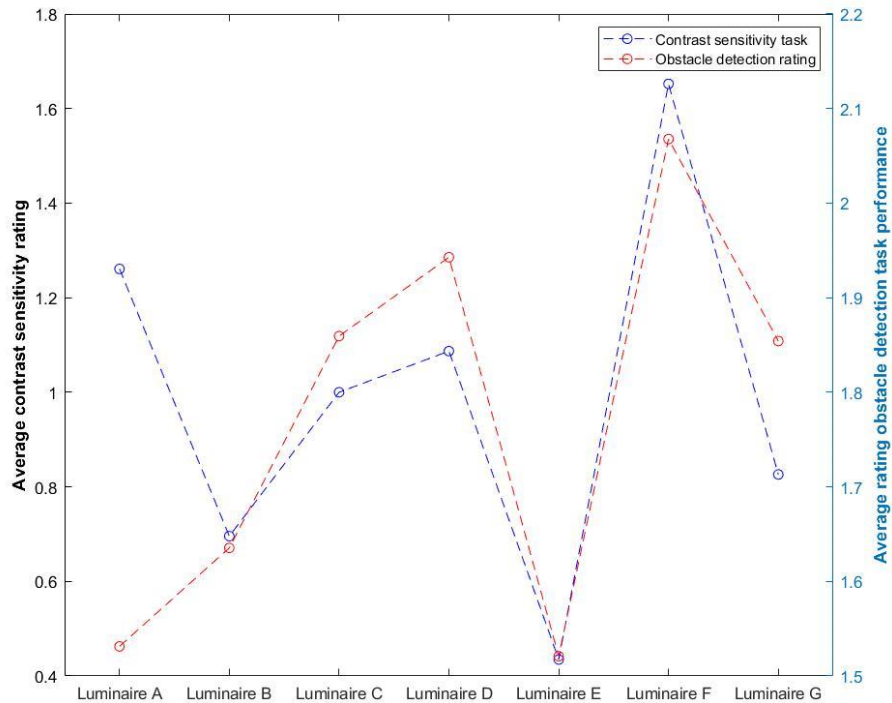


Figure 25 - Visualization of the correlation between the contrast sensitivity task and the obstacle detection rating

4.2.4 Multi-factor analysis

To test which variables are the main predictors for the obstacle detection rate, a multiple regression was conducted. The dependent variable is the average percentage of all the individual trials that is correctly identified for the obstacle detection task. The predictors that are included in this model were decided based on previous findings from other literature research and this study. The main potential predictors that were found are: age, visual acuity level, the average obstacle height for the obstacles that were lifted during the specific trial, the average contrast level for the obstacles that were lifted during the specific trial, the path luminance at the position of the obstacles, the path luminance near the observer and the difference in path luminance between the obstacles and the participant position. To identify the best predictors for the obstacle detection task, first, the correlation between the dependent variable and the independent variable was analyzed for each

variable separately (table 7). From this model it could be concluded that the obstacle detection rate is significantly correlated ($p = <.05$) with all independent variables except the luminance at the position of the obstacles ($p = .590$). This variable was excluded from the further analysis.

Table 7 - Pearson Correlation between the obstacle detection rate and the dependent variables

	Obstacle detection rate	
	r-value	p-value
Age	0.192	.000
Visual acuity	0.333	.000
Obstacle contrast	0.284	.000
Obstacle height	0.091	.003
Luminance participant position	-0.226	.000
Luminance obstacle position	-0.017	.590
Luminance difference (uniformity)	0.169	.000

To select the best predictor, a multiple linear regression was executed where all independent variables except the luminance at the position of the obstacles were included. The R-squared which represents the proportion of variance for the dependent variable that can be explained by all the independent variables is 0.315. This indicates that these variables are not an optimal fit for this model. The variable that has the highest p-value is 'age' with a value of .558. However, the R-squared does not increase when this variable is excluded from the model, so all variables are kept in the model. The significance of all variables that are included in the model can be seen in table 8. Furthermore, their share in the overall R-squared value was calculated and added in the same table. Overall, we can see that the main predictor of the obstacle detection task is the visual acuity of the participants with a value of 0.111. Followed by the contrast of the obstacles which has a value of 0.081.

Table 8 - Overview of the p-value and R-squared of different variables for the obstacle detection probability

	p-value	R-squared
Age	.558	0.036
Visual acuity	.000	0.111
Obstacle contrast	.000	0.081
Obstacle height	.047	0.008
Luminance participant position	.017	0.051
Luminance difference (uniformity)	.267	0.028
Total R-squared		0.315

4.3 Field study

In this section, the additional data that was acquired during the study will be highlighted, this is specifically content related data. The main questions that will be analyzed here are:

1. Are there differences in facial expression recognition rate between different luminaire types?
2. Are there differences in facial expression recognition rate between the two positions?
3. Are there differences in obstacle detection probability between different luminaire types?
4. Are there differences in obstacle detection probability between the two positions?
5. What is the effect of visual acuity on the obstacle detection probability?
6. Is there a relation between the subjective evaluation of the outdoor environment and the obstacle detection rate?
7. Is there a relation between the subjective rating of discomfort glare and the obstacle detection rate?

4.3.1 Facial expression recognition

The facial expression recognition task was added as a distraction task to make sure people do not focus on the pathway. The design of this task, however, was in such way that it is also possible to analyze this data. During this analysis, the visually impaired people were analyzed separately from the elderly and adolescents since the distraction task was different between these groups. The first analysis that was conducted was the relation between the luminaire type and the facial expression recognition, this can be seen in figure 26 for the elderly people and the adolescents and in figure 27 for the people with a visual impairment.

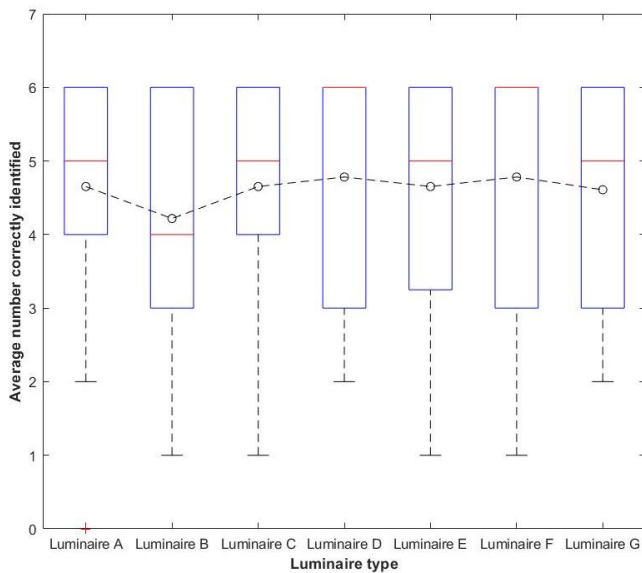


Figure 26 - Visualization of the average number of correctly identified facial expression for different luminaire types. Furthermore, the range and median are displayed in a boxplot (adolescents & elderly people).

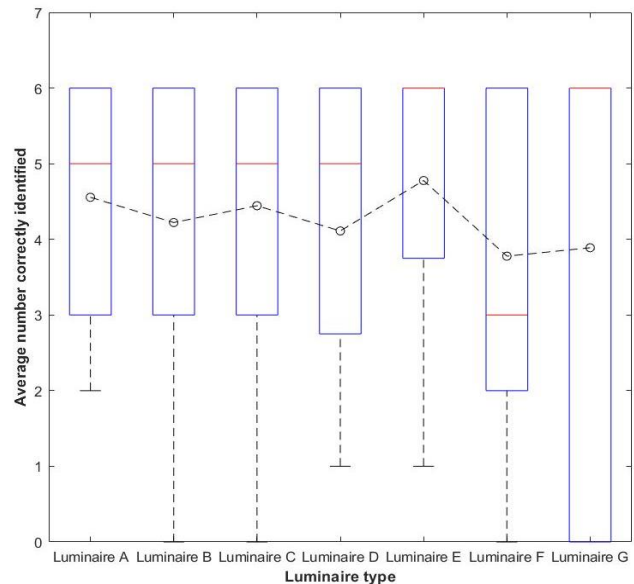


Figure 27 - Visualization of the average number of correctly identified facial expressions for different luminaire types. Furthermore, the range and median are displayed in a boxplot (for visually impaired people).

Besides the boxplot, a black line is displayed which is the average number of facial expressions correctly identified for both groups. Overall, there is a low variance for elderly people and adolescents in facial expression recognition. The average range of correctly identified facial expression for different luminaire types is between 4.1 and 4.8, where the poorest performance is for luminaire B. The variance between the different luminaires is slightly larger for people with a visual impairment, the range goes from 3.7 till 4.9.

To assess the difference between the facial expression recognition between different luminaires further a one-way ANOVA was conducted. This included the correctly identified facial expressions as dependent variable for each luminaire type. There was no significant effect ($p < .05$) for the facial expression recognition between the different luminaire types ($F = 0.962$, $p = .449$).

The facial expression recognition task was executed at two different positions. In figure 28 & figure 29, the relation can be seen between the facial expression recognition task and the different positions for either adolescents and elderly people or visually impaired people. The average facial expressions correctly identified is the sum for all luminaires per position which indicates a maximum number of 21 faces correctly identified. From the boxplots it can be concluded that position 1 results in a higher number of correctly identified faces compared to position 2 with a median of 20 versus 15 for elderly people and adolescents. For visually impaired people, the difference is even more prominent with a value of 20 for position 1 and 12 for position 2.

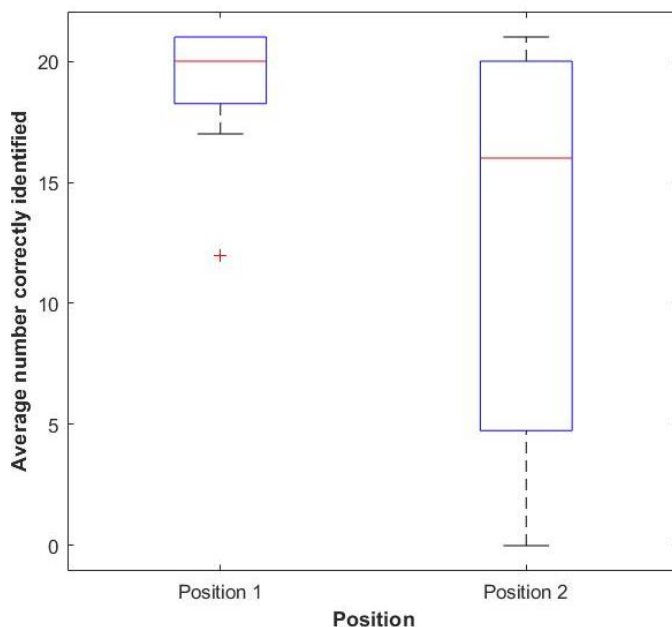


Figure 28 - Visualization of the average number of correctly identified facial expression for the two different positions. Furthermore, the range and median are displayed in a boxplot (adolescents & elderly people).

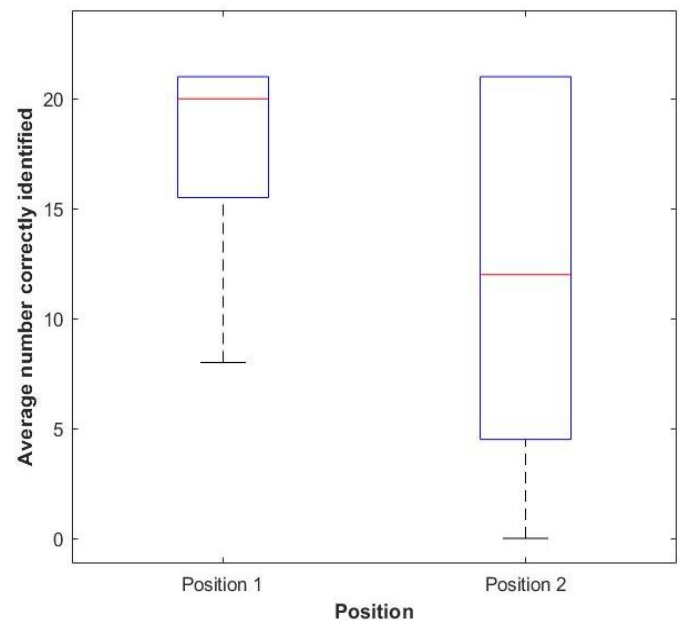


Figure 29 - Visualization of the average number of correctly identified facial expressions for two different positions. Furthermore, the range and median are displayed in a boxplot (for visually impaired people).

Furthermore, the variance between participants is higher for position 2. In figure 28, for instance, the range for position 1 goes from 17 till 21 while the range for position 2 goes from 0 to 21. The reason for this can be seen in figure 30, here the number of correctly identified faces for each position are visualized for all participants separately. The boxes display the three separate target groups. Especially, the elderly people and the people with a visually impairment have a diverse visual performance at position 2. Some participants correctly identified more than 15 faces while other identified 0 faces correctly.

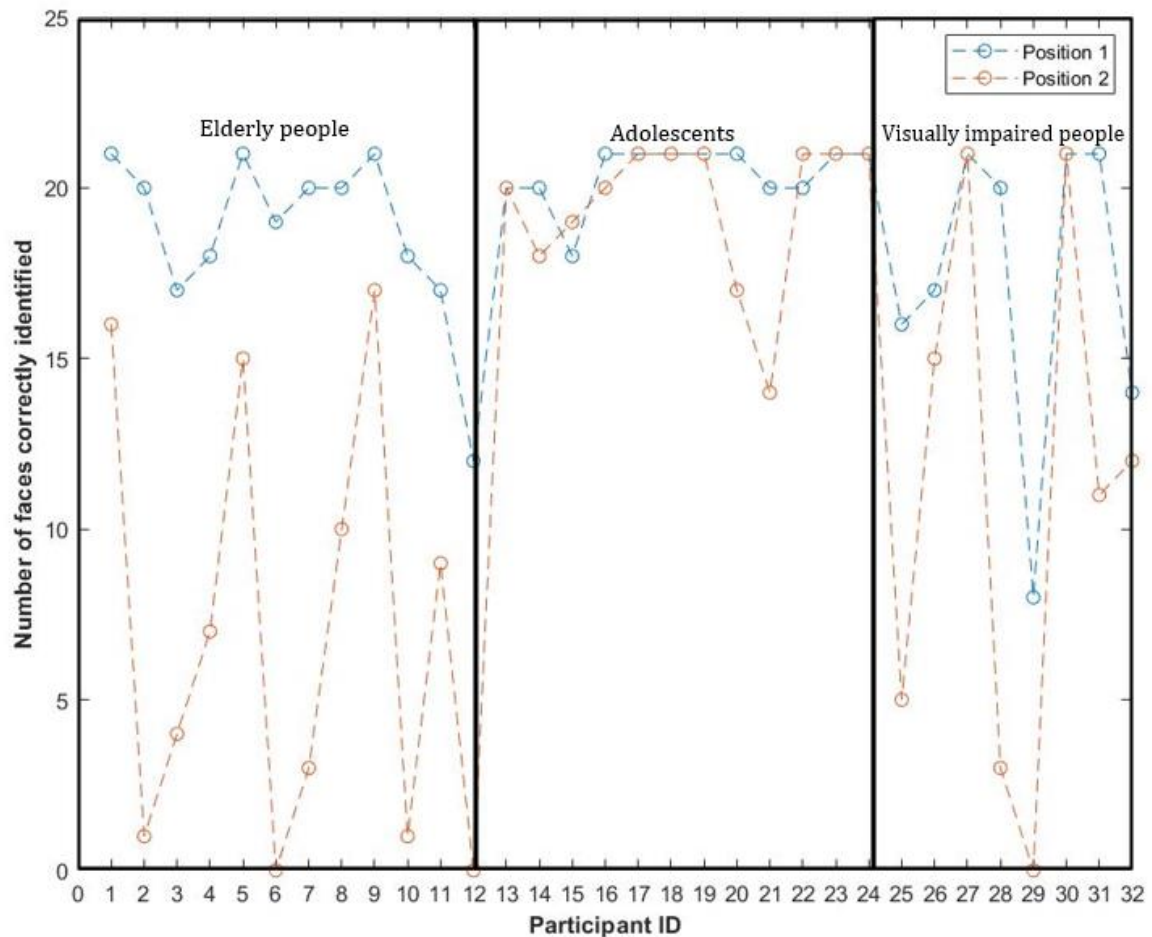


Figure 30 - Visualization of the average number of correctly identified facial expressions for each participant for both position 1 & position 2

The difference between the two positions was also tested with a small statistical analysis. An ANOVA was conducted where the dependent variable was (once again) the facial expression recognition and this was compared for the two different positions. There was a highly significant effect ($F = 198.5$, $p < .05$) for the facial expression recognition task between the two different positions.

4.3.2 Obstacle detection task

The primary task during the study was the obstacle detection task. For this analysis, the control trials (when no obstacles were raised) were excluded from the study. The number of obstacles that were raised during each trial was, however, randomized which means it should be tested whether the number of trials is still similar for all luminaire types when the control trials are excluded from the dataset. Overall, the total sum of trials where obstacles are raised for all participants combined is in the range of 143 till 158 for the separate luminaires. This is a small range but will be considered during the upcoming analysis.

The first analysis that was conducted was the relation between the obstacle detection task and the luminaire type. In figure 31, the average number of correctly identified trials for each participant is displayed for every luminaire type. Overall, the median obstacle detection rate is highest for luminaire C with a value of 2.25 trials. Other luminaires that score high are luminaire D with a value of 2.0833 and luminaire F and G with values of 2. The luminaire that performance most poorly is luminaire A with a median of 1.0833. Other luminaires that perform lower are luminaire B and luminaire F with value of 1.5883 and 1.5. It should be noted that during this analysis, all trials are included in the analysis which means the first trial where participants perform more poorly are still included. To test the difference in obstacle detection probability when the first trial is excluded, the same analysis is conducted again but this time without the first trial for each participant (see figure 32).

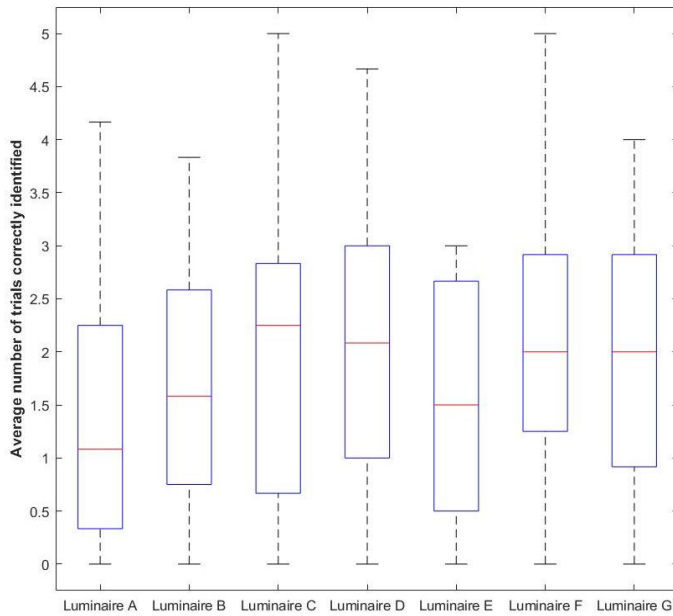


Figure 31 - Visualization of the average number of trials correctly identified for the obstacle detection task for each luminaire type (N = 1054)

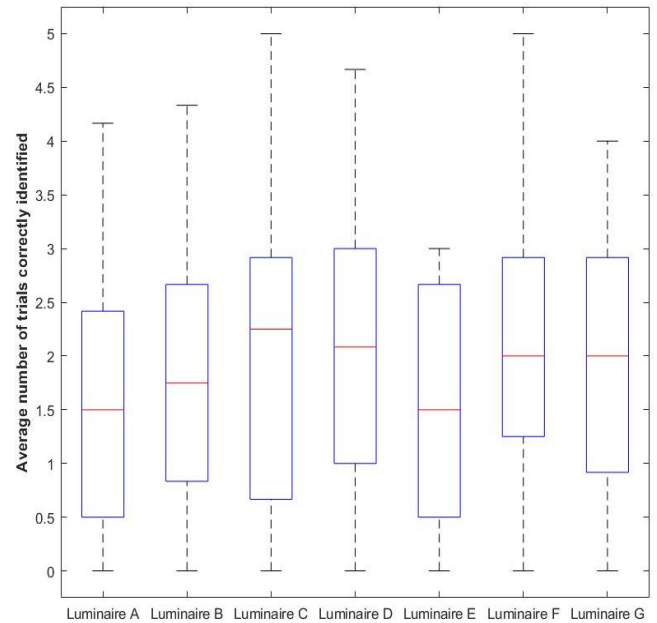


Figure 32 - Visualization of the average number of trials correctly identified for the obstacle detection task for each luminaire type when the first trial executed is removed for each participant (N = 1022)

Overall, the average number of trials correctly identified increases for luminaire A with 0.4 trial and the average number of trials correctly identified for luminaire B increases with 0.2 trial. The trend, however, remains similar. Luminaire A still performs worse than most other luminaire types combined with luminaire E. For the upcoming analysis, it is decided that the data of the first trial of each participant is not removed. One main reason for this is that the remaining data for luminaire A and luminaire B for position 1 is reduced significantly which results in too little data to give a reliable outcome. Therefore, in the upcoming analysis all the trials will be kept in the model.

In the previous analysis, both positions were added together for each luminaire. To be able to see the difference between the two participant positions for each luminaire, however, the analysis should be conducted for the positions separately, this is visualized in figure 33. Position 2 on average scores better than position 1 with an average median of 0.5 trials correctly identified compared to 1.0833 at position 2. The difference between the two position differs, however, per luminaire type. At luminaire D, the average median for all participants is 0.833 trials at position 1 and 1 trials at position 2 which creates a difference of 0.1667. For luminaire F, however, the average median at position 1 is 0.5 and at position 2 is 1.5 which creates a difference of a one complete trial that is correctly identified at position 2.

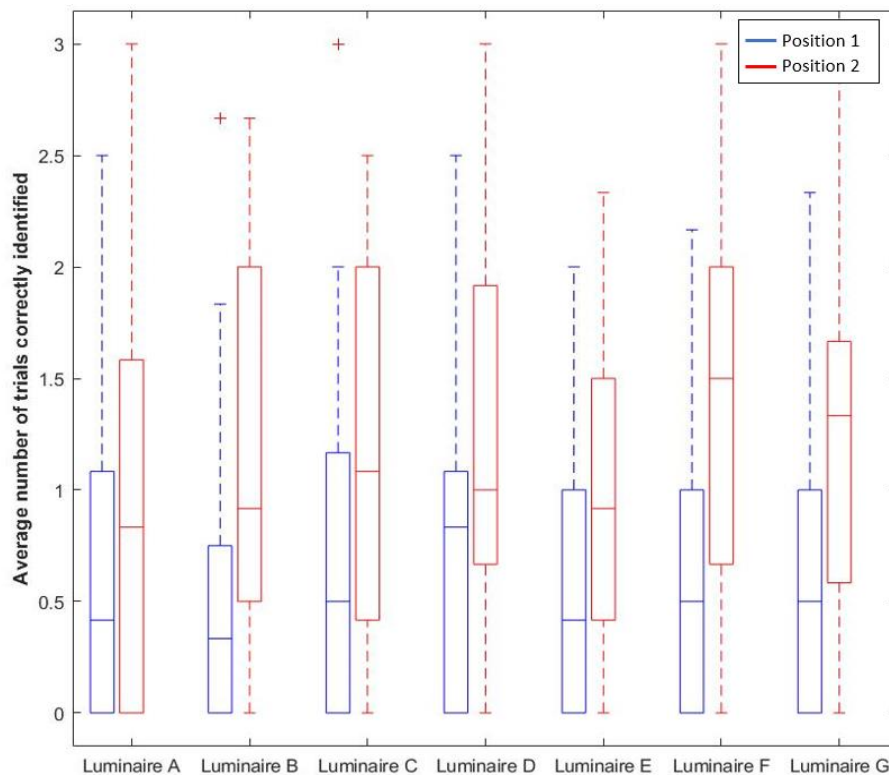


Figure 33 - Visualization of the average number of trials correctly identified for the obstacle detection task for each luminaire type at two different positions.

With an ANOVA, the effect on the obstacle detection rate on both the luminaire type and the different positions was tested. The obstacle detection rate per luminaire type is significant related with a value $p=.021$ ($F = 2.50$). Furthermore, the obstacle detection rate per position is highly significant with a value $p=.010$ ($F = 68.37$).

Up to this point, the obstacle detection task was analyzed for all participants combined. It is, however, possible that there is a large variance between the participants since there were three different target groups with a wide range of visual acuity levels. In the next analysis, the average number of trials correctly identified were analyzed for 5 different visual acuity (VA) ranges: <0.4 , $0.4-0.8$, $0.8-1.2$, $1.2-1.6$ and > 1.6 . It should be noted that not all ranges consist of the same number of participants, the first group (VA <0.4) includes 4 participants. The second group (VA of $0.4-0.8$) includes 6 participants. The third group (VA of $0.8-1.2$) has 3 participants, the fourth group (VA of $1.2-1.6$) has 9 participants and finally group 5 (VA > 1.6) includes 10 participants. Despite this variance, the analysis is still interesting to see the main difference between people with a different visual acuity level. In figure 34, the results from the analysis are visualized. The main thing that can be concluded is that participants with a visual acuity lower than 0.4 correctly identified an average of 0.25 trials during the obstacle detection task while the maximum number that they could score was 6 (there are six trials per luminaire type). Furthermore, the participants with a visual acuity higher than 1.6 have an average of 4 trials correctly at luminaire A which is higher than any other value displayed in the graph.

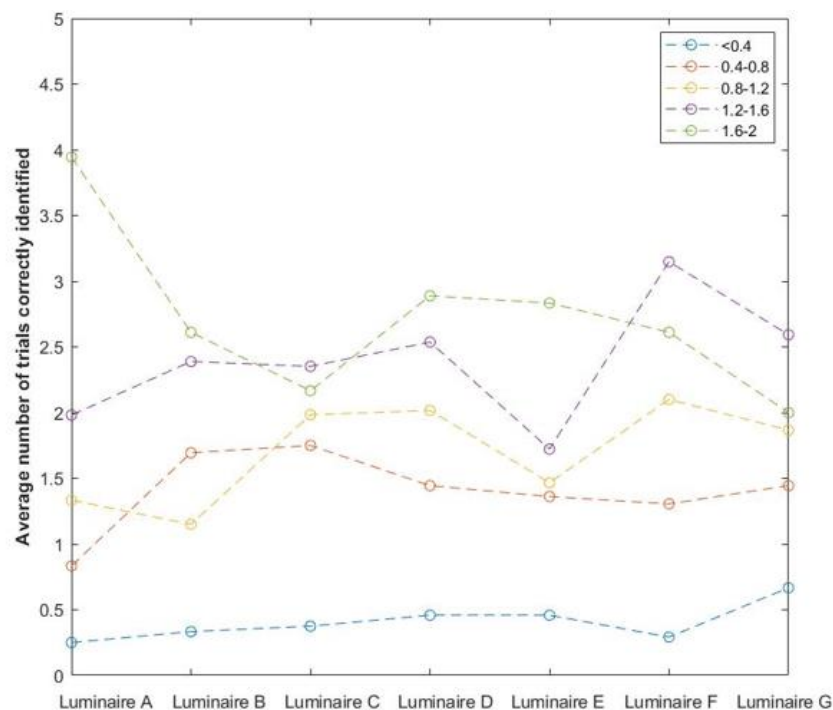


Figure 34 - Visualization of the average number of trials correctly identified during the obstacle detection task for different luminaire types for different visual acuity ranges

To validate the high variance between the obstacle detection rate for different visual acuity ranges, a bivariate Pearson correlation was executed in SPSS to see whether a significant value of $p < .05$ is met. The variables included in this model were the visual acuity for each of the participants and the percentage of obstacles that were correctly identified for each trial. Overall, there is a highly significant correlation between these two variables ($p = .000$, $r = 0.333$).

Besides the obstacle detection task and the facial expression recognition task, other questions were asked which were related to the environmental perception of the participants and the subjective experience of the level of discomfort glare. In this upcoming section, each of these elements will be discussed briefly in relation to the obstacle detection task.

There were five questions asked for each luminaire type in relation to the subjective perception of the environment, these questions were related to: the visibility of the environment, the perception of safety, the light quality, the visibility of the surrounding environment and finally the perceived walkability of the environment. In the graph in figure 35, the average ratings for all participants combined are visualized to show the relation with the obstacle detection tasks (black bold line). The trend of all five questions are quite similar with a lower rating for luminaire A, B, E, F and G. The highest rating is given at luminaire type C and luminaire type D. The obstacle detection task, as previously discussed, is performed most optimal at luminaire type C, D and F which indicates that the trend for obstacle detection is quite similar for all luminaires except luminaire F.

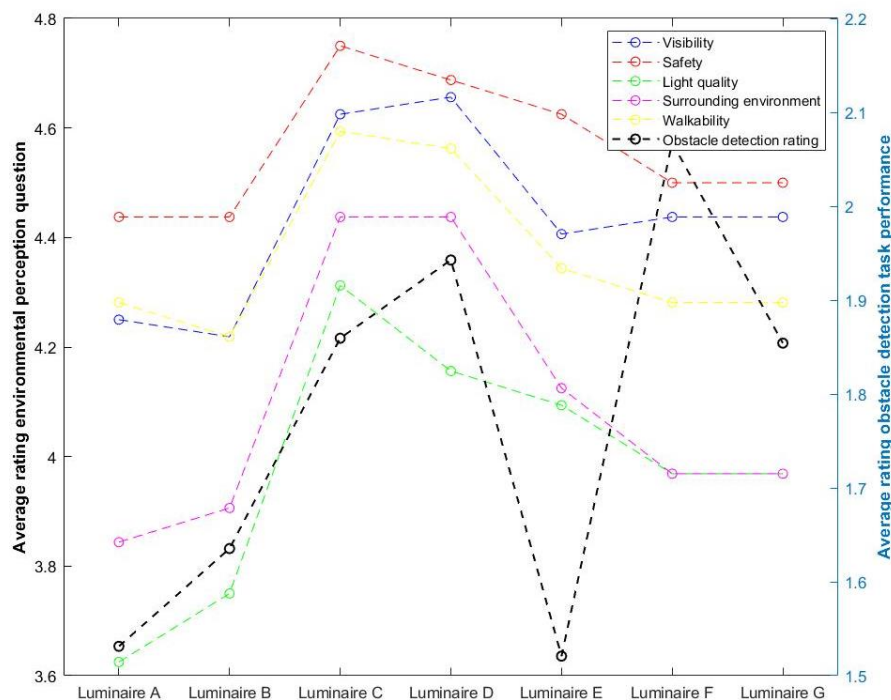


Figure 35 - Visualization of the correlation between the environmental perception rating and the obstacle detection rating.

When the Pearson correlation for each of the questions and the obstacle detection rate is analyzed in SPSS. Three questions are significantly correlated with the obstacle detection task ($p < .05$): the visibility of the environment ($r = 0.135$), the light quality ($r = 0.099$), and the perceived walkability of the environment ($r = 0.079$). However, the questions related towards the perception of safety and the question related to the surrounding environment are not statistically significant with values of respectively $p = .204$ and $p = .175$.

The next analysis is the analysis of the subjective rating of discomfort glare for all participants compared to the obstacle detection task. In the graph (figure 36), when the discomfort glare rating is higher, the participants experienced on average more discomfort glare. Overall, the participants seemed to experience most discomfort glare at luminaire type C, D and F which is interesting cause the obstacle detection performance is also best at luminaire type C, D and F.

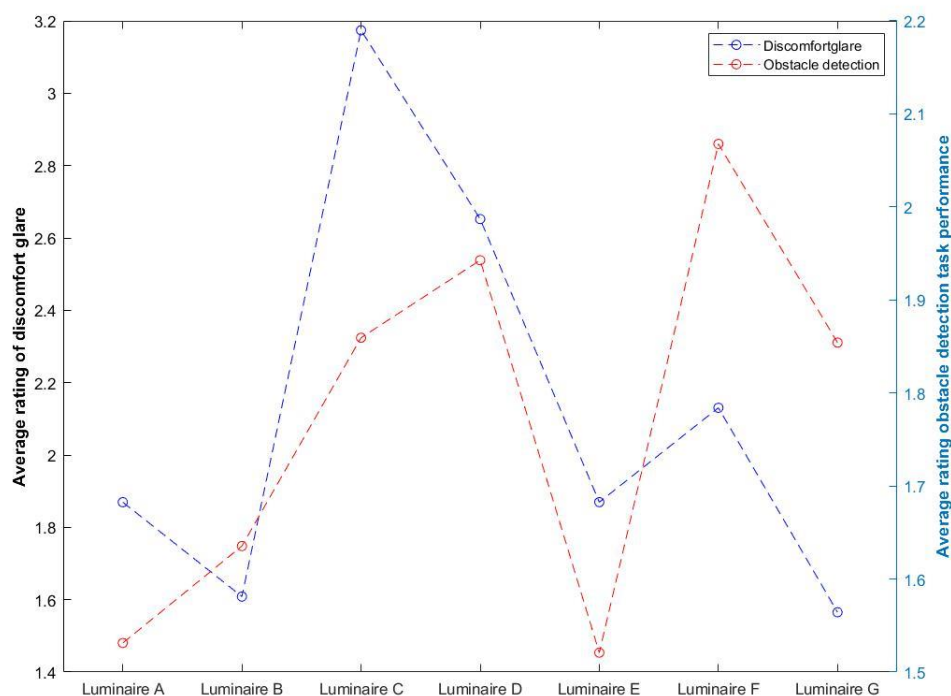


Figure 36 - Visualization of the correlation between the subjective rating of discomfort glare and the obstacle detection rating

The bivariate Pearson correlation was once again executed for this relation, where the obstacle detection percentage for each trial was correlated with the discomfort glare rating from each participant for each luminaire type. Summarized, there is a significant correlation between these two variables with a p-value of .003 ($r = -0.091$).

5 Discussion

The aim of this chapter is to discuss the findings and limitations found during the development and execution of this methodology for validation purposes. Besides validating the method, this study can give additional insights regarding the optimal lighting conditions to make the outdoor environment as accessible and safe as possible for everyone. In the first section of this chapter, the key findings of the field study will be discussed. Next, the limitations of the study will be described. Finally, in the last two sections the implications for theory and practice will be discussed.

5.1 Key findings

5.1.1 Methodology validation

In this part of the discussion section, the key findings from the data analysis regarding the method validation will be discussed. The findings will be separate into five different sections: trials, obstacle positions, the obstacle height & obstacle contrast, visual acuity and the Pelli-Robson signs.

Trials

The first conducted analysis investigated whether three trials per position was sufficient. There is variation between the three separate trials per luminaire type, with a maximum difference between the obstacle detection rate of two trials of 15% (averaged for all participant combined). During the first trial of each luminaire, participants (in general) did not perform worse than during the other two trials. However, when looking at the first trial that was performed during the complete field study, participants perform more than two times worse than during all the other trials. There is a learning effect during the first few trials of the participants. This indicates that a practice trial should be included in the study or the data from the first trial should be excluded from the data analysis for all participants. There is, however, no clear decrease in performance during the three trials per luminaire which indicates that the participants remained alert during the experiment. Overall, it can be concluded that three trials are not excessive but it is possible that even more trials would give a more reliable result without adding too much burden to the participants. More trials, however, means that the complete study takes more time which could result in a reduction in their alertness for the last luminaire types. During this field study participants did not perform worse at the end of the study so they were not getting tired and less alert. However, five participants did complain regarding the duration of the study so it should not be lengthened too excessively.

Obstacle positions

There were six obstacles positioned near each luminaire type. Whether the obstacles were identified from the left or right shifted when the position of the participant changed, the obstacles in the middle remained (almost) similar. In general, the obstacles in the center of the pathway were

detected most often by the three target groups. This detection rate was mostly independent on the whether the middle obstacle was located 'far away' or 'nearby'. There is, however, a relation between the distance of the obstacles and the obstacle detection rate for elderly people at position 2. Elderly people detect obstacles better when they are located further away. Reason for both findings could be the small viewing angle compared to the facial expression recognition task. The participants look towards the front to identify a facial expression, the obstacles in the center of the pathway and the obstacles which are located further away from the participants are closer to the facial expression recognition task which makes it easier to glance towards these locations. This is visualized in figure 37, here the angle A is between the facial expression recognition task and the furthest obstacle and the angle B is between the facial expression recognition task and the nearest obstacle. This relation is not visible for the adolescents, a reason could be that adolescents are better at the facial expression recognition task which gives them more time to scan the environment for obstacles at all the different locations.

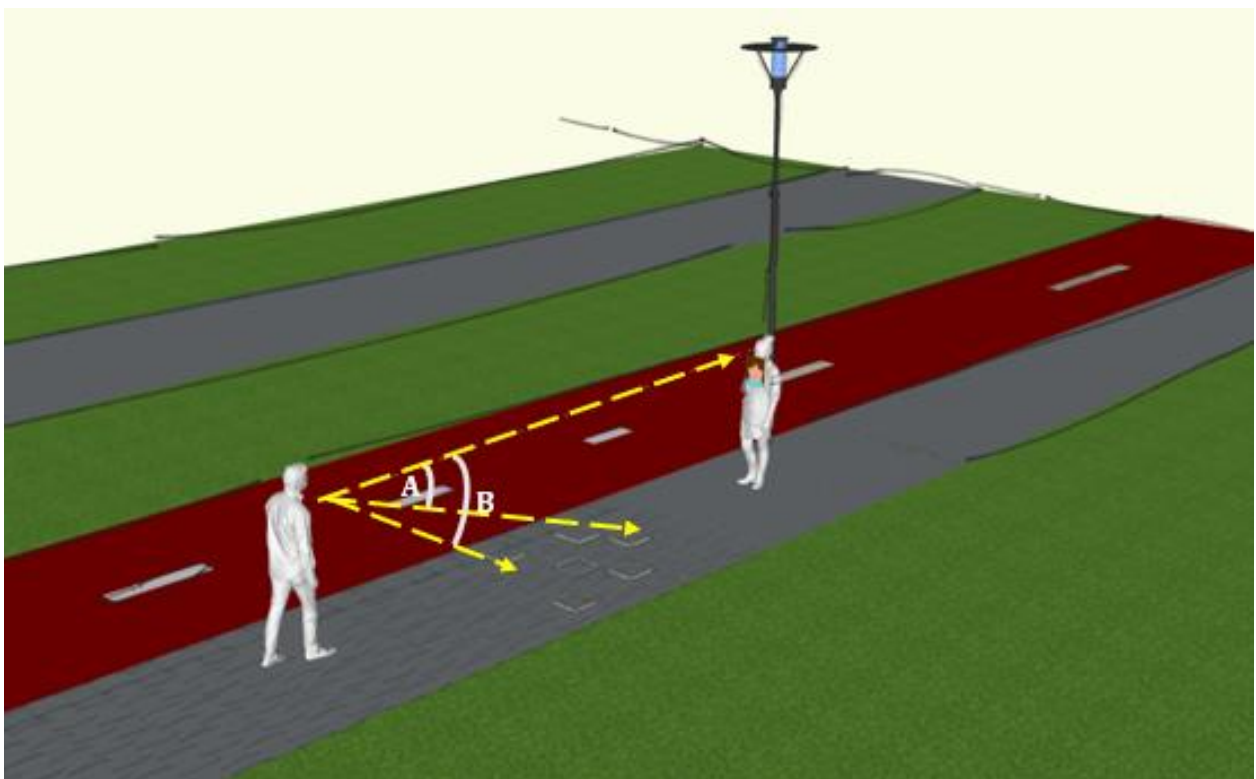


Figure 37 - Visualization of the different angles between the facial expression recognition task and the obstacle detection task.

Another interesting finding is that the obstacles located at the left-hand side of the participants have a lower detection rate than the obstacle located at the center and right of the participants. This finding is most likely related to the effect of the eye dominance. About 75% of the

world population is right-handed which indicates they prefer to write and perform other task with their right hand (McManus, Porac, Bryden, & Boucher, 1999). Right-handers, however, also prefer to use their right eye for monocular eye tasks and are thus right eye dominant. One theory for the relation between right-handers and right-eye dominance is the fact that right-handers use their right-hand more often for actions than their left hand which makes the space around the right hand their dominant space (Le Bigot & Grosjean, 2012). There is more visual processing required around the dominant side which indicates that the eye becomes dominant towards the right-hand side. A study from Fotios et al. (2020) studied the effect of the obstacle location on the obstacle detection rate. They, however, did not find a significant difference when the obstacle was located either on the left or right. There was, however, in their study a difference between the obstacles located 'far away' or 'nearby'. Independent of where the obstacles were located (left, right or middle), the obstacles that were located nearby or in the middle were detected correctly most often. This is a different finding than the result that was found in this field study which found that elderly detect obstacles most often when they are located further away.

Obstacle height & obstacle contrast

The method that was developed during this study was applied in a real setting which means that it is challenging to control all variables completely. The height of the obstacles is one of these variables that has a slight variation between all 42 obstacles. In the result section, all sides of the obstacles were evaluated to investigate which sides of the obstacles are relevant to consider during further research. There is a clear relation between the front of the obstacle and the obstacle detection rate. When the obstacle is raised more, the obstacle is detected more frequently than when the obstacle is hardly raised. This relation is almost linearly from a high height towards a low height. When looking at the left side of the obstacle, the relation is present but less prominent. From a height of 14 mm and lower, the obstacle detection rate stays similar independent of the obstacle height. A similar conclusion can be drawn when looking at the right obstacle side. From this, it can be concluded that the left and right side of the obstacles are less relevant when predicting the obstacle detection rate compared to the front of the obstacle. Furthermore, the height of obstacle 1 & 2 was not a significant predictor for the obstacle detection probability. A reason for this is that these two obstacles are correctly identified the least of all the six obstacles with a correct identification rate of 22.3% and 30.7% respectively. In previously conducted laboratory studies, the effect on the obstacle detection rate was tested with several different height levels (Fotios et al., 2020; Uttley et al., 2017) These obstacles were, however, a circular shape and all sides were raised equally. All studies, however, do conclude that obstacle height is a significant predictor for the obstacle detection rate. A

study from Fotios & Cheal (2013) identified an obstacle height of 1.5 mm to have a 50% detection probability at 1 lux (± 0.1 cd/m²). Another study found an 50% detection probability at 0.2 lux (0.04 cd/m²) for an obstacle height of 2 mm (Uttley et al., 2017). During the field study conducted for this thesis, a height of 15-19 mm was needed to have a detection probability of 50% at around 0.2 cd/m² (2 lux with a reflectance of 0.1) which indicates that a field study creates a more challenging task than in a laboratory setting. One reason why the task is more challenging is the difference in contrast values between a laboratory study and a field study. All laboratory studies used a similar set-up with a luminance contrast of the target obstacle against its surrounding area of approximately 0.82 (Mao & Fotios, 2021). During the field study, however, the contrast level could not be controlled and was dependent on the height that the obstacles were raised but also on the luminance near the obstacle and the position of the participant. Overall, there was a big variance between contrast values of different obstacles with a range from 0.08 – 0.88 (SD = 0.2291). During this study, the contrast level was (in general) higher at position 2 than position 1. The reason for this is the difference between a positive or a negative contrast from the observer position. When the contrast between the obstacle and the adjacent surfaces is higher, the obstacle detection rate is higher. The difference between the lowest contrast value range (<0.2) and the highest contrast value range (>0.8) is a detection probability of 40%. From the statistical analysis that was conducted, it could be concluded that the contrast levels were a much better predictor for the obstacle detection task than the height of the obstacle. Which is different than previously conducted studies that mainly focused on the height of the obstacle instead of the contrast values.

Visual acuity

Another important predictor of the obstacle detection probability is the visual acuity of the participants. During this field study, the variance between the visual acuity of different participants was high (range = 0.0167 – 1.91). This also resulted in a high variance for the obstacle detection probability, with a difference in detection probability of 90% between the highest and lowest visual acuity levels. Especially for the people with a visual impairment, the obstacle detection task appeared to be a challenging task. People with a visual acuity lower than 0.4 only identified 0.25 trials correctly of the total of 6 per luminaire type.

The Pelli-Robson signs

The final analysis that will be discussed in this section is the correlation between the Pelli-Robson sign task and the obstacle detection task. These two tasks are highly related with each other. In general, when people were good at detecting obstacles under a certain luminaire, they are also good at the contrast sensitivity task. This is a very interesting outcome because this indicates that there

are two very different tasks which give similar results per luminaire type. This means that these two tasks can validate each other's results and can make the individual results more reliable. For instance, if the Pelli-Robson task was already executed at a setting and had reliable results, an obstacle detection task at that location will most likely also result in reliable results. The obstacle detection task is, however, a more realistic task to perform by participants but it is very helpful that this task can easily be validated by the contrast sensitivity task. Comparable results were found in a study from Rahm & Johansson (2018). This study investigated both a sign reading task and an obstacle detection task under three different lighting conditions. The performance of both tasks was similar under the different lighting conditions. It should, however, be noted that the sign reading task used in this experiment was different compared to the one used during the current study.

5.1.2 Content-related results

The other findings from the field study will be discussed in detail in this section. First, the facial expression recognition task will be discussed briefly followed by the obstacle detection task.

Facial expression recognition task

During the facial expression recognition task, the participants needed to identify three different emotional expressions from 6-meter distance. Overall, the variance in facial expression recognition between different luminaires is low. The reason for this is that it was an additional distraction task which was created in such way that the participants were able to execute it with ease at every luminaire. There was, however, an unexpected large difference between the two different positions. At position 2, the participants needed to look towards the luminaire while identifying a facial expression. Especially elderly people found this task challenging and were not able to properly identify all expressions. This results in a high variance in the performance for the facial expression recognition task at position 2 while the variance is low at position 1.

Obstacle detection task

The primary task during the field study was the obstacle detection task. The difference in visual performance between the different luminaire types is much more prominent when looking at the obstacle detection task. Participants were always better at the obstacle detection task when they were located at position 2, as discussed earlier the higher contrast values compared to position 1 between the obstacles and the adjacent surface are a prominent reason for this. A similar conclusion was drawn in the study from Fotios et al. (2020) where the best obstacle detection rate resulted when the luminaire was positioned either behind or on top of the obstacles. For this study, however, the difference between the obstacle detection at position 1 and position 2 varies between the seven different luminaire types. At luminaire D, the variance between the two positions is small while the

variance is high for luminaire F. This difference can be explained by looking at the path luminance profiles of the different luminaires (Appendix XVII) and the average luminance value which were discussed in table 6. For luminaire D, the average luminance at the obstacles is 0.17 cd/m^2 and the average luminance at position 1 for the participant is 0.18 cd/m^2 . Which indicates that the light at the pathway is uniformly distributed throughout the pathway. For luminaire F, however, the average luminance at the obstacles is 0.24 cd/m^2 and the luminance at the participant position is 0.29 cd/m^2 . At this luminaire, participants are standing in a brighter environment than where the obstacles are located which results in a very low contrast value which makes it harder to detect the obstacles. This finding was also found in the study of Jenness & Singer (2008). When the participants are located at position 2, however, the participants are standing at a location with a low path luminance for all luminaire types. Luminaire F, however, has a high average luminance at the obstacles (as mentioned) which makes the obstacles better visible than for luminaire D where the luminance at the obstacles is 0.07 cd/m^2 lower. The lowest obstacle detection rate is for luminaire A, luminaire B and luminaire E. These luminaire types all have a brightly lit area near the luminaire which results in high luminance values at participant position 1 which has negative consequences for the obstacle detection rate at position 1. The poor performance at position 2 is hard to quantify when looking at the luminance values since these are for luminaire B and luminaire E quite similar compared to luminaire F but the visual performance is much worse. The difference in obstacle detection rate was also evaluated in previously conducted studies. In general, it can be concluded that a higher luminance level at the obstacle position results in a higher obstacle detection rate (Fotios & Cheal, 2013). A study from Rahm & Johansson (2018) identified that the most optimal lighting conditions for an obstacle detection task was an LED light source with a CCT of 3810 K and an obstacle illuminance range between 10-21 lux ($\pm 0.5-1 \text{ cd/m}^2$). The obstacle detection rate was poorest under low CCT values and an obstacle illuminance range of 4-8 lux ($\pm 0.2-0.4 \text{ cd/m}^2$). It is, however, challenging to compare results from laboratory studies with the current field study. During this study especially the relation between the path luminance at the participant position and the path luminance at the obstacle position is a relevant predictor for the obstacle detection probability. This, however, has not been thoroughly investigated during previously conducted studies.

There were also questions asked related to the environmental perception of the participants. These five questions were asked for each luminaire type and related to: the visibility of the environment, the perception of safety, the light quality, the visibility of the surrounding environment and the perceived walkability of the environment. The ratings of all these questions were compared with the obstacle detection task to see whether we can predict visual performance by subjective

questions regarding the light in the environment. Overall, there seemed to be a correlation between the environmental perception rating and the obstacle detection task. Two of the five questions were not significantly correlated with the obstacle detection task. First, the question related to the perception of safety was not significantly correlated with the obstacle detection probability. A potential reason for this was already mentioned throughout the study by seven different participants. All participants felt quite safe during the field study but the participants mentioned that this was only because they were guided by two experimenters. It was challenging for them to imagine a situation where no experimenter was present and they were walking alone on that pathway without any raised obstacles. Another question that was not related to the obstacle detection task was the visibility of the surrounding environment. Participants often had some difficulties answering this question because they did not understand what the surrounding environment was. One side of the pathway was blocked with a large black screen while the other side were some bushes, both were not identified as being relevant to be lit properly. The other three questions, however, were significantly positively correlated with the obstacle detection task which implies that you can (partly) predict the obstacle detection performance under different luminaire types by asking questions related to the visibility of the environment, the light quality, and the walkability of the environment.

Another measure that was rated by participants is the subjective rating of discomfort glare. When this rating was compared with the obstacle detection task for each luminaire, it could be concluded that there was a significant correlation between the subjective rating of discomfort glare and the obstacle detection rate. When the visual performance of people is higher, they experience a higher level of discomfort glare. Luminaire C, D and F are identified as the most promising luminaires with regards to obstacle detection and these are also the luminaires where people experience the most discomfort glare. A reason why people experience more discomfort glare at these luminaires could be that the light is directed more downwards compared to the other luminaire types. This is especially prominent for luminaire D and F, for luminaire C this is less clearly visible.

5.2 Limitations & further research

The research discussed in this thesis represents the first version of a methodology to investigate obstacle detection for pedestrians in a real environment. There are, however, five limitations that were found while executing this method. These will be discussed in the upcoming paragraph.

The first limitation of this study is related to correct use of the peripheral vision during the obstacle detection task. People were supposed to fixate on the facial expression task and use only their peripheral vision to detect obstacles on the pathway. A study from Fotios, Uttley, & Cheal (2016)

investigated whether people maintained their gaze on the foveal fixation point during the experiment. They found, by using an eye-tracking device, that less than 0.9% of the eye fixations was directed towards the obstacles. During the current field study, however, no eye tracking device was used so there is no certainty that people did not fixate on the obstacles during this study. Furthermore, as previously mentioned, the obstacle detection task seemed to be more challenging compared to the previously executed laboratory studies which could give participants more reason to use their foveal instead of their peripheral vision. Due to this uncertainty regarding the participants gaze behavior, it is possible that some participants detected obstacles with their foveal vision while others used their peripheral vision. As investigated by Fotios et al. (2016) this could influence the results, reaction times are shorter when looking directly at a peripheral target than when looking at the fixation point. For further research, it would be interesting to repeat the developed methodology but include the use of an eye tracking device during the study. This will make it possible to investigate whether the 0.9% that was found in a laboratory setting is accurate in a real environment. Another factor that can be tested with the eye-tracking device is the theory that people are (in general) right eye-dominant, since 75% of the world-population is right-handed. As previously mentioned, this means that participants notice the obstacles in the center and on the right more often than the obstacles on the left. If the eye movements of the participants are monitored and they are questioned whether they are right- or left-handed, conclusion can be made regarding this theory.

The second limitation is the lack of knowledge regarding the 'invisible' obstacles that were detected during the obstacle detection task. This means that participants state that an obstacle is present while no obstacles are raised. There were 7920 obstacles in total that could have been raised during the study. In total, participants detected an obstacle that was not raised 231 times. In laboratory studies, these values were included in the analysis and they concluded that the number of false alarms increases when the illuminance increases (Fotios & Cheal, 2009). Conducting such an analysis on the outliers found during this field study is, however, not reliable since there were 'natural' obstacles present in the pathway prior to the study. During the data analysis, the 'invisible' obstacles that were identified near a natural obstacle were (at first) excluded from the outliers since it is expected that people identified a 'natural' obstacle. It is, however, impossible to know whether this is indeed the case. It would be optimal to level the pathway completely before conducting an obstacle detection experiment to exclude the possibility that participants detect 'natural' obstacles. This, however, would almost create a laboratory environment while the aim is to create a

methodology that is able to deal with the variability of the outdoor environment. Overall, more research towards this issue should be conducted.

The third limitation is related to the analysis regarding the determination of the contrast levels between the obstacle and the adjacent surface. The formula that was used during this research was simplified and calculated the average luminance of the raised area divided by the average luminance of the top of the obstacle. The results showed the trend between the obstacle detection rate and the contrast level adequately. As can be concluded from this study, however, the difference in contrast levels for different obstacles is one of the main predictors for the obstacle detection task. For future research it would, therefore, be interesting to investigate further how to calculate the contrast levels between the obstacle and the pathway to see whether this clear trend continues to exist when more complex calculation methods are used. During this study it was, for instance, uncertain which surface needed to be included as the background area. It would be optimal if a formula was developed that can be used when calculating the contrast between an obstacle and the nearby area.

The fourth limitation is related to the individual target groups that were investigated during the field study. For both the adolescents and the elderly people, the results from the obstacle detection task and the facial recognition task were diverse and interesting. Furthermore, in the analysis differences in visual performance could be found between the different luminaire types. For people with a visual impairment ($VA < 0.4$), however, the obstacle detection task appeared to be too challenging since they only identified on average 0.25 of the 6 trials correctly per luminaire type. This also indicates that no clear differences between the different luminaire types could be found since they were not able to perform the task under all lighting conditions. It would be interesting to repeat the developed methodology under daylight conditions to see whether people with a visual impairment are able to identify obstacles in bright lighting conditions. If participants are still unable to detect obstacles it can be concluded that it is not possible to make raised pavement slabs visible for people with a visual impairment.

Another task that was too challenging for the participants with a visual impairment was the Pelli-Robson sign task. This contrast sensitivity task was already located at the location of the field study prior the start of the study. During the field study, however, it became clear that the distance between the sign and the participant was too large (7 m) for participants with a lower visual acuity (< 1.0). The adolescents were often able to read one till four of the total six rules, the elderly people were sometimes able to read one or two rules of the signs but the people with a visual impairment

were not able to read any of the six rules on the sign. It was, however, tested during the study whether the people with a visual impairment would have been able to execute the task if the distance between the participant and the sign would have been reduced. Three of the four participants were not even able to read the sign from a distance < 1 meter. The data from the subjective questions and the subjective perception of discomfort glare consisted, however, of a much bigger variance for people with a visual impairment than the other target groups. Especially, the rating of discomfort glare was much higher (in general) for people with a visual impairment. A larger focus on the influence of glare on the visual performance and visual comfort of people with a visual impairment would be interesting to include in further research. Overall, more research should be conducted to investigate the creation of an accessible and safe environment for people with a visual impairment. These studies should be designed specifically for this target group to be able to give more valid conclusions regarding their lighting needs.

5.3 Implications for theory

In this thesis a first version of a methodology was developed and proposed to investigate obstacle detection for pedestrians in a real setting. The main advantage compared to previously conducted studies is the inclusion of the variability of a real environment. Due to the conducted field study, it was possible to create the most optimal version of the methodology which was discussed in the previous paragraphs. In table 9, all the variables that were discussed in chapter 3 are highlighted. Furthermore, how they were used during this field study and the recommendations for further research are summarized.

With this methodology, the difference between various lighting conditions can be investigated which can be used to develop the optimal luminaire for the creation of an accessible and safe outdoor environment at nighttime. It is, however, currently not possible (yet) to give an answer to this aim due to high number of still unanswered questions. To give more concrete conclusions regarding the validity of the methodology and the creation of an accessible public space, the developed methodology should be applied on a larger scale. More participants should be recruited during follow-up studies, it is especially vital to pay more attention regarding the needs for people with a visual impairment. When including this target group, however, the current methodology should be adjusted to ease the assigned tasks. Another area of interest would be to include a higher variance in luminaire types, the luminous flux of the light sources was quite similar during this study. Furthermore, it would be optimal to replicate the study (on a larger scale) during daylight conditions to create a baseline reference. This can be compared with the visual performance under different luminaire types during nighttime.

Table 9 - All the included variables in the methodology and their current characteristics

Variable	Used for the field study	Recommendations
Distraction task	A facial expression recognition task for elderly & adolescents and a E-hook was used for visually impaired people.	Test whether they focus on this task with an eye-tracking device.
Distance participant - distraction task	6 meters	This distance is appropriate for people with a visual acuity > 0.6.
Distance participant – obstacles	Between 2.5-4.0 meters	This is a good distance between the obstacle and the participant.
Participant position	2 different participant positions (negative and positive contrast)	The two different positions are very relevant to include in follow-up studies.
Luminaire type	7 LED luminaires with different diffusers	More variation between the different luminaire types would be optimal.
Target group	11 adolescents with a visual acuity > 0.6 12 elderly people with a visual acuity > 0.6 9 visually impaired people with a visual acuity < 0.6	More focus on the demands for the visually impaired people since this is a prominent predictor for the obstacle detection rate.
Obstacle height	+/- 10 mm	There is a relation between obstacle height and the obstacle identification but this does not need to be measured during further research (can be ignored)
Obstacle contrast	$\frac{\text{Average luminance of the (visible)sides of the obstacle}}{\text{Average luminance of the top of the obstacle}}$ → should be above 0.3 for a decent visibility.	Obstacle contrast is a prominent predictor for the obstacle detection rate and needs to be taken into account during further research
Obstacle positions	6 different obstacle positions (left, right and in the center)	In total 231 outliers were seen during this research, how to take these into account needs more research.
Number of obstacles raised per trial	Between 0-3 raised during each trial	More research should be conducted regarding the inclusion of the control trials in the data analysis (these were now often excluded from the analysis)
Number of trials	3 trials per participant position	Include a practice trial during further research

Overall, this thesis is an important step to create a bridge between the creation of a safe public space at night and different light conditions. By connecting the visual performance of pedestrians to the outdoor lighting conditions, the impact of different lighting types on the mobility of pedestrians is assessed. Hopefully, in the future, there will be more focus on the pedestrian perspective of the outdoor environment to create a safer and more accessible space for everybody.

5.4 Implications for practice

The field study that was conducted in this thesis investigated obstacle detection for pedestrians in a real-life setting. From this study, it is possible to create some first guidelines regarding the lighting needs to create an accessible space for everybody. The guidelines will be discussed with several different relevant parties such as CROW, VISIO, signify and the municipality of Utrecht. The results are especially relevant for 'het Afwegingskadar: Goede verlichting voor een toegankelijke openbare ruimte' that will be created by CROW and other parties. In their report, several variables are discussed that have an effect on the accessibility of an outdoor space: minimum path luminance, discomfort glare, adaptation, guidance through light and contrast. Some conclusions can be made regarding the minimum path luminance, contrast, and discomfort glare but it should be noted that more extensive research is needed to create valid conclusions. A first understanding regarding the optimal lighting conditions, however, was found during this study.

When a pedestrian that is walking along a footpath encounters an obstacle, the most important predictors as to whether he detects the obstacle are: the obstacle contrast and the visual acuity of the pedestrian. The obstacle contrast between the obstacle and the path should be 0.55 to have a detection rate of 50% which indicates that the contrast value should be at least higher than this value. For the visual acuity, especially pedestrians with a visual acuity < 0.4 were not able to identify any obstacles. If we wish to create an accessible outdoor environment for everybody, more studies should focus on this target group and the lighting requirements should be adjusted towards their needs. When looking more towards the lighting conditions to detect obstacles by pedestrians, both the luminance at the position of the obstacle and the luminance at the location of the pedestrian are relevant for the detection probability of the obstacle. When the luminaire is located behind the pedestrian, the most optimal lighting condition is when the path luminance is uniformly distributed from the pedestrian up until the obstacle. The best visual performance found during this field study was when the average path luminance was 0.18 cd/m^2 near the participants and 0.17 cd/m^2 near the obstacles. This light source had the lowest path luminance near the obstacles compared to all the other luminaire types but still performed best due to the uniform distribution of the light. All the other light sources had a high luminance value at the participant position and a low luminance value at the obstacle position which results in a low contrast between the obstacle and the adjacent surface. This reduces the visibility of the obstacle. When the luminaire is in front of the pedestrian, the most optimal lighting condition is when the path luminance at the position of the obstacles is high. The visual performance of pedestrians, however, does not increase when the average path luminance is higher than 0.30 cd/m^2 . This value is, as mentioned, only relevant for adolescents and elderly people,

because for people with a visual impairment no concrete conclusions regarding the optimal lighting conditions can be made. Overall, however, from the subjective questions it can be concluded that this target group preferred the same luminaire types as the other target groups that were included in the study. It should, however, be noted that for the luminaires with the highest visual performance, the discomfort glare rating was also highest which indicates that they experience a 'blinding effect' but this does not have an effect on their visual performance. It can be concluded that it is challenging to create a lighting scheme between two luminaires where the obstacle is visible throughout the entire route. The most important variable is not the path luminance but the uniform distribution of the lighting to create an appropriate contrast level at all positions throughout the path.

6 Conclusion

This paper describes the development and validation of a methodology to investigate obstacle detection under different lighting conditions for pedestrians in a real-life setting. The study was conducted as an addition to the previously conducted laboratory studies. The main research question that was answered during this study was: *“How to design a valid methodology to study obstacle detection for pedestrians under different lighting conditions in a real-life setting?”*. After the execution of the field study, it was found that a methodology to investigate obstacle detection probability should include the following parameters. First, a distraction task should be included besides the obstacle detection task. Second, these tasks should be investigated under various lighting conditions and participant positions relative to the luminaire. Third, the study should be repeated at least three times per position and a practice trial should be included prior to the study. Finally, the obstacles should be located at 3.4-meter distance of the participant at various positions. The sub-research questions that were formulated in subchapter 1.1, can be answered with the findings from the field study. The first sub-question was: *“What is the effect of different contrast levels of the obstacles on the visual performance of pedestrians?”*. During the data analysis it was found that the contrast between the obstacle and the nearby environment is a strong predictor for the obstacle detection probability. When the contrast between the obstacle and the nearby area is high, the obstacle detection rate increases. The difference between a low contrast level (<0.2) or high contrast level (>0.8) was over 40%. The other strong predictor for the obstacle detection probability, visual acuity, can answer the second sub-question which was: *“How does visual performance change with age and a visual impairment?”*. Overall, the visual performance increases with a higher visual acuity level independent of the age of people. From the data, it can be concluded, that elderly people often have a lower visual acuity than adolescents. It should be noted that specifically people with a visual acuity lower than 0.4 were not able to identify any of the obstacles. This indicates that there should be more focus on people with a visual impairment since the current lighting standards are not sufficient to create a safe environment for this target group. The final sub-question was: *“How does the path luminance affect the visual performance of pedestrians during an obstacle detection task?”*. When looking specifically towards the path luminance at either the participant position or the obstacle position, it was found that especially the absolute luminance difference between the two positions seems to be an important predictor. It was found that the exact luminance value is almost negligible but the uniformity along the entire path should be high. Overall, this study has provided a starting point for more research that focuses on the pedestrian perspective of the outdoor environment. And hopefully, in the future, everybody will be able to walk safely outside during nighttime.

7 Bibliography

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Appendix

Appendix I

Ethical review research proposal

Ms. Anneloes de Lange
a.a.j.d.lange@student.tue.nl



Date
January 28, 2022

Reference
ERB2022BE4

Ethical Review Board TU/e

T +31 (0)40 247 6239
ethics@tue.nl

intranet.tue.nl/ethics

Ethical review research proposal

Dear Ms. De Lange,

It is a pleasure to inform you that the Ethical Review Board (ERB) has discussed and approved your application "Design a valid methodology which investigates obstacle detection for pedestrians under different street lighting conditions in a real-life setting".

The Board wants to draw your attention to the terms and conditions in the appendix.

Success with your research!

Sincerely,

A handwritten signature in black ink, appearing to read 'D. Lakens'.

Dr. D. Lakens
Chair Ethical Review Board TU/e

Enclosures
1

The ERB retains the right to revise its decision regarding the implementation and the WMO¹/WMH² status of any research study in response to changing regulations, research activities, or other unforeseen circumstances that are relevant to reviewing any such study.

The ERB shall notify the principal researcher of its revised decision and of the reasons for having revised its decision.

¹WMO: Law on Medical Scientific Research Involving Human Beings (in Dutch: Wet medisch-wetenschappelijk onderzoek met mensen)

²WMH: Medical Device Directive (in Dutch: Wet op de medische hulpmiddelen)

Figure 38 - Ethical review research proposal approval

Appendix II

Visualization luminaires

Luminaire A - Rechlanternen:



Figure 39 - Visualization of luminaire A



Luminaire B – Philips Citysphere:



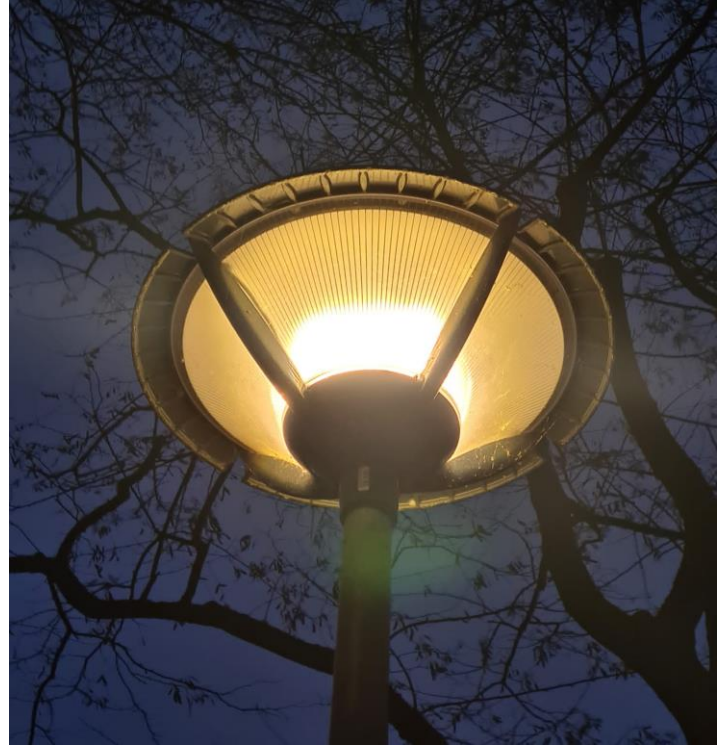
Figure 40 - Visualization of luminaire B



Luminaire C – Schreder Alura:



Figure 41 - Visualization of luminaire C



Luminaire D – Innolumis Ariane Area Clear:



Figure 42 - Visualization of luminaire D



Luminaire E – Innolumis Ariane Area Frosted:



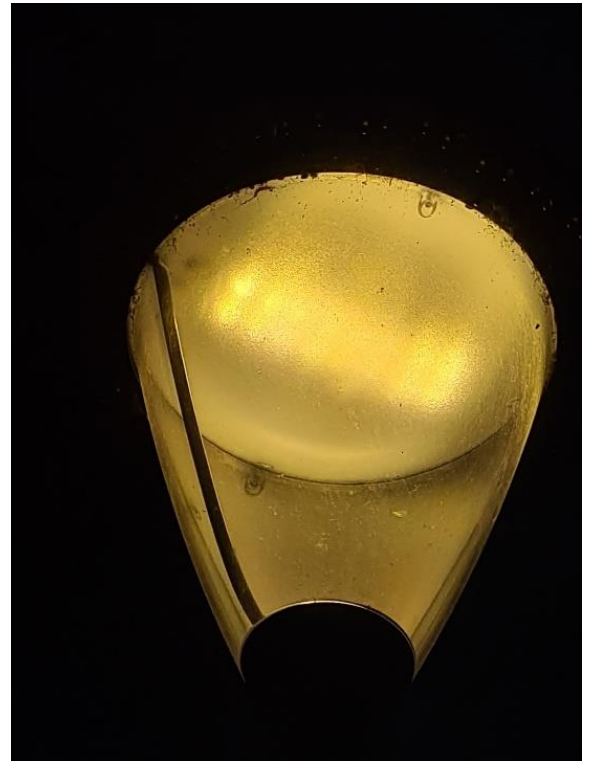
Figure 43 - Visualization of luminaire E



Luminaire F – Lightronics Prunus:



Figure 44 - Visualization of luminaire F



Luminaire G – Disano Polar:



Figure 45 - Visualization of luminaire G

naam: pp-nr:.....
 datum:/...../ 2022 tijd: : uur plaats:.....
 Leeftijd: jaar oogaandoening:
 naam onderzoeker:

[illegible]

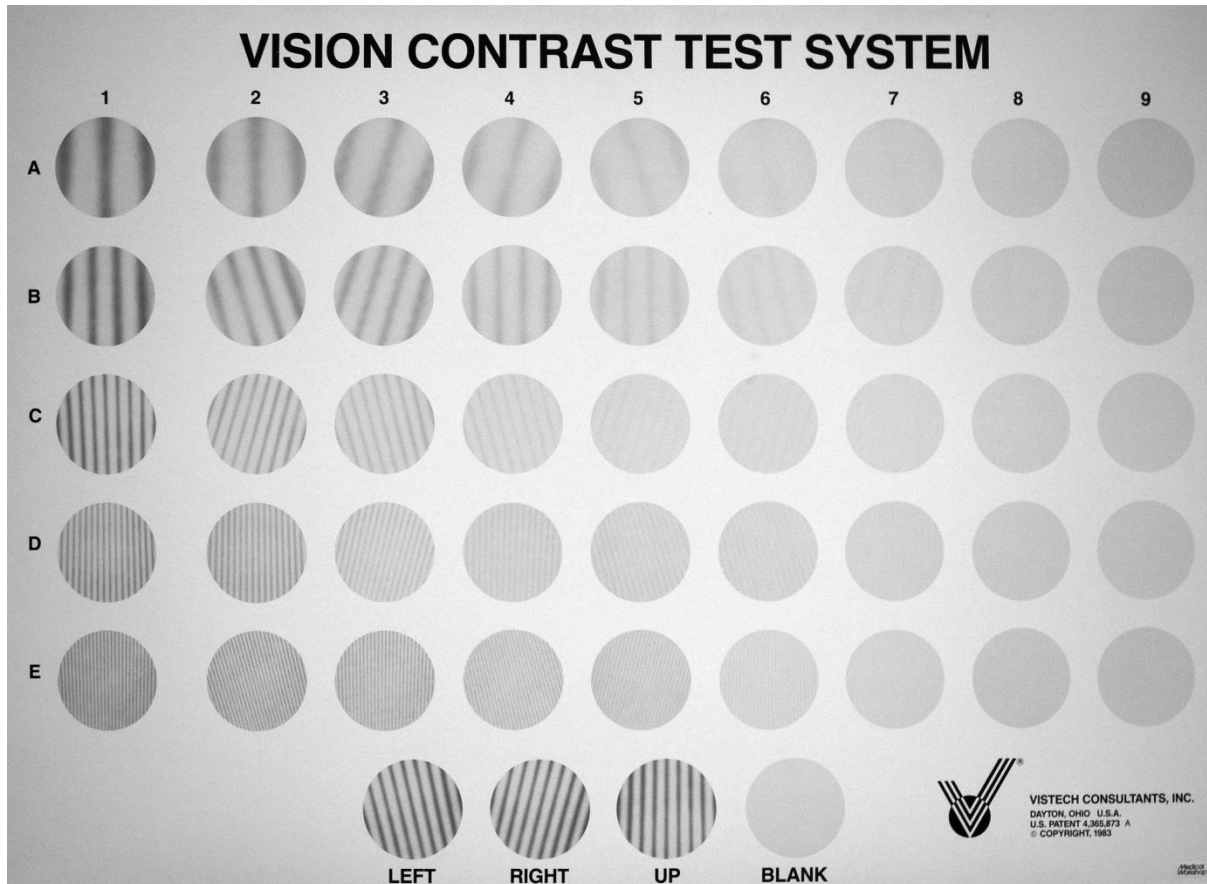
Afstand: 4 meter

Verlichting: 500 lux

Meting: binoculair

Streep alle letters door die niet of niet correct gelezen werden

VODS =



Afstand: 3 meter

Verlichting: 500 lux

Meting: binoculair

Streep alle rondjes door die niet of niet correct gelezen werden

Vistech-score: patch: 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9

A = (bij 1,5 cycles/degree; VODS ~0,05; 03 / 07 / 12 / 20 / **35** / **70** / 120 / 170 / x)

B = (bij 3 cycles/degree; VODS ~0,1; 04 / 09 / 15 / 24 / **44** / **85** / **170** / 220 / x)

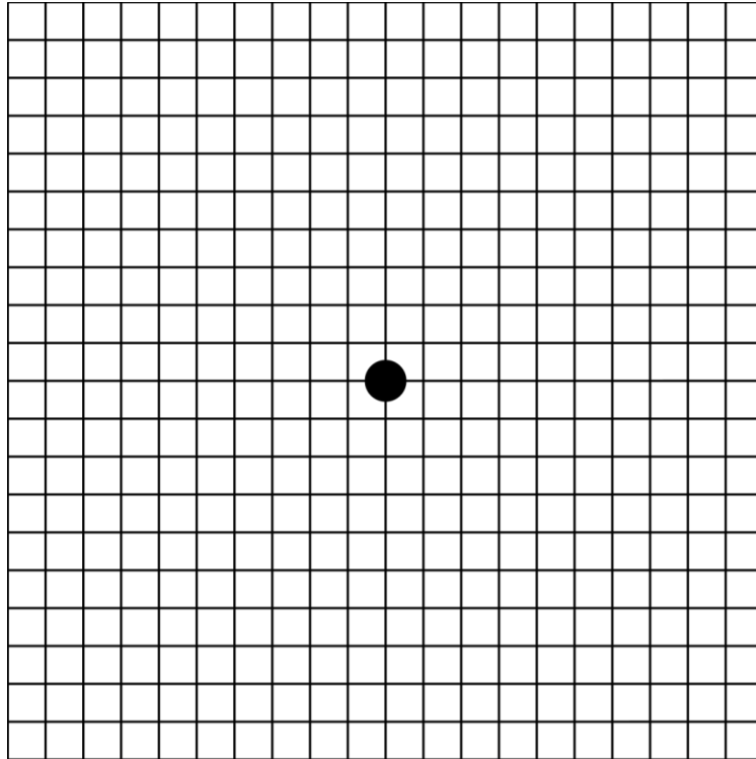
C = (bij 6 cycles/degree; VODS ~0,2; 05 / 11 / 21 / 45 / **70** / **125** / **185** / 260 / x)

D = (bij 12 cycles/degree; VODS ~0,4; 05 / 08 / **15** / **32** / **55** / **88** / **125** / 170 / x)

E = (bij 18 cycles/degree; VODS ~0,6; 04 / **07** / **10** / **15** / **26** / **40** / **65** / 90 / x)

Normaalwaarden zijn hier **vet**-gedrukt

Amsler test



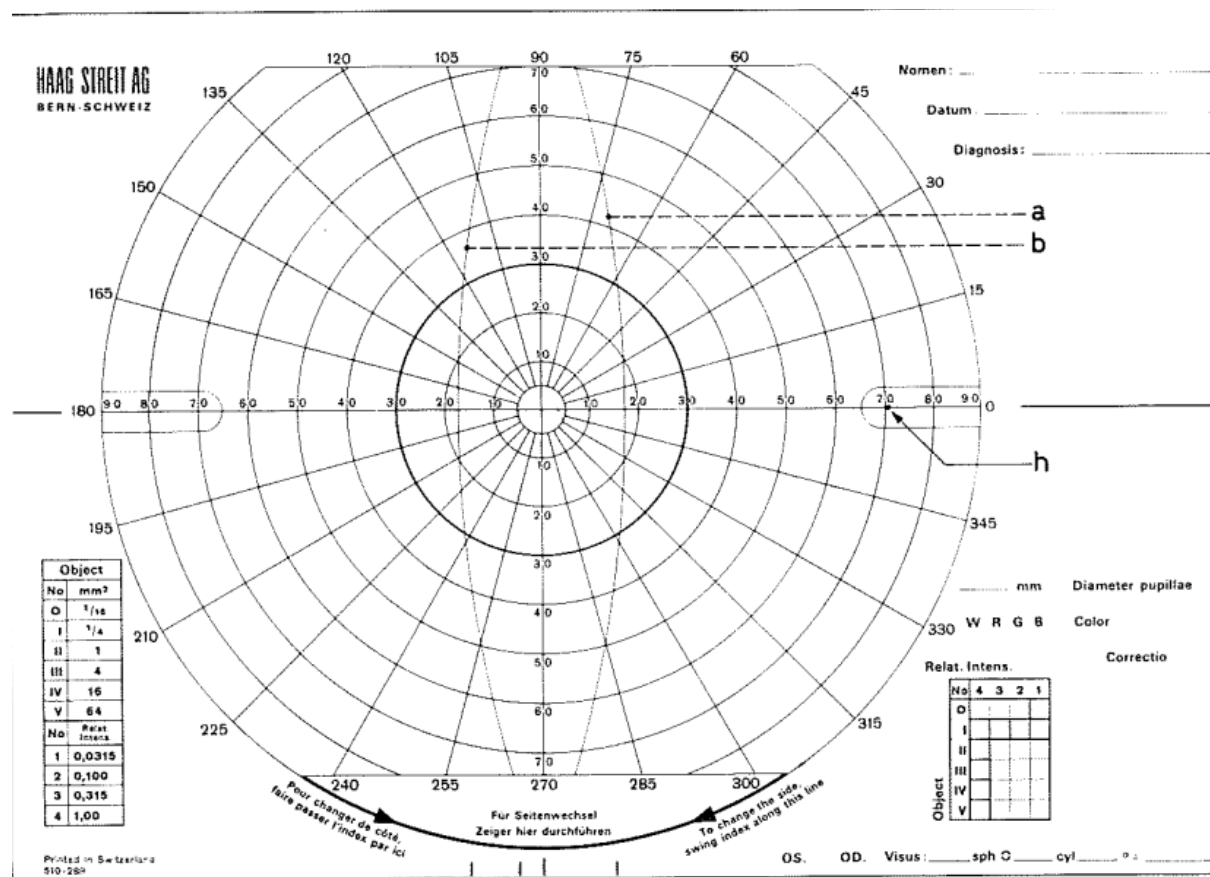
Afstand: 30 cm

Verlichting: 500 lux, of anders:

Meting: binoculair

Laat fixeren op de stip. Teken de aangegeven uitval in. Noteer waar deelnemer aangeeft de lijnen als niet-recht waar te nemen.

Gezichtsvelde confrontatief



Strooilicht: C-quant

	Rechter oog:	Linker oog:
log(s):
Esd:
Q:
Kleur iris:	bruin / blauw / groen	

Pupilgrootte: rechter oog:mm bij lux, gemeten op het oog
linker oog:mm

Appendix IV Visualization of mechanical device



Figure 46 - Visualization of the mechanical devices used to raise the pavement tiles

Appendix V

Obstacle height

Table 10 - The height of all the sides of the raised obstacles per luminaire type (A-G) per obstacle (OB1-OB6)

Luminaire	Direction	OB 1 (mm)	OB 2 (mm)	OB3 (mm)	OB4 (mm)	OB 5 (mm)	OB 6 (mm)
A	Up	10	10	5	5	10	22
A	Right	10	10	9	10	2	22
A	Down	10	10	9	12	15	2
A	Left	0	0	9	12	5	20
B	Up	18	0	15	4	11	20
B	Right	18	22	10	11	8	18
B	Down	18	25	22	20	4	2
B	Left	4	22	20	18	8	18
C	Up	5	2	20	15	12	10
C	Right	8	14	18	3	4	7
C	Down	11	16	2	15	20	1
C	Left	11	11	20	15	20	7
D	Up	8	15	6	7	3	16
D	Right	2	15	15	4	4	16
D	Down	8	3	10	10	3	14
D	Left	12	15	12	8	7	16
E	Up	4	2	22	14	12	0
E	Right	5	14	20	20	4	5
E	Down	10	13	16	10	4	10
E	Left	15	7	17	5	15	13
F	Up	20	20	17	20	6	2
F	Right	2	20	20	4	6	10
F	Down	20	18	18	14	6	19
F	Left	20	4	4	20	6	18
G	Up	10	11	10	15	9	16
G	Right	12	12	15	0	10	10
G	Down	4	0	4	20	2	11
G	Left	12	4	10	17	2	15

Appendix VI
Facial expression selected from the FACES database

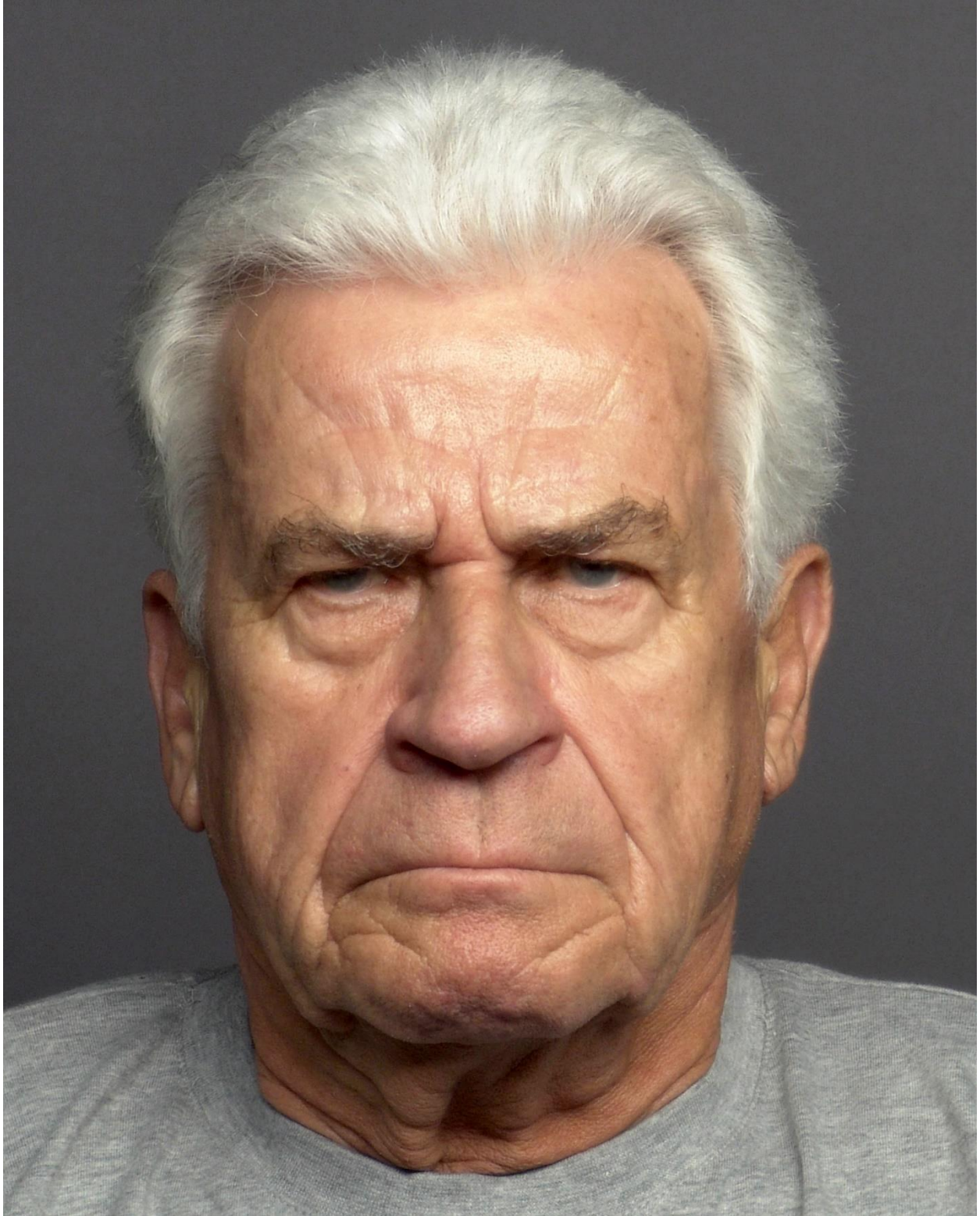


Figure 47 - Facial expression: elderly man & angry

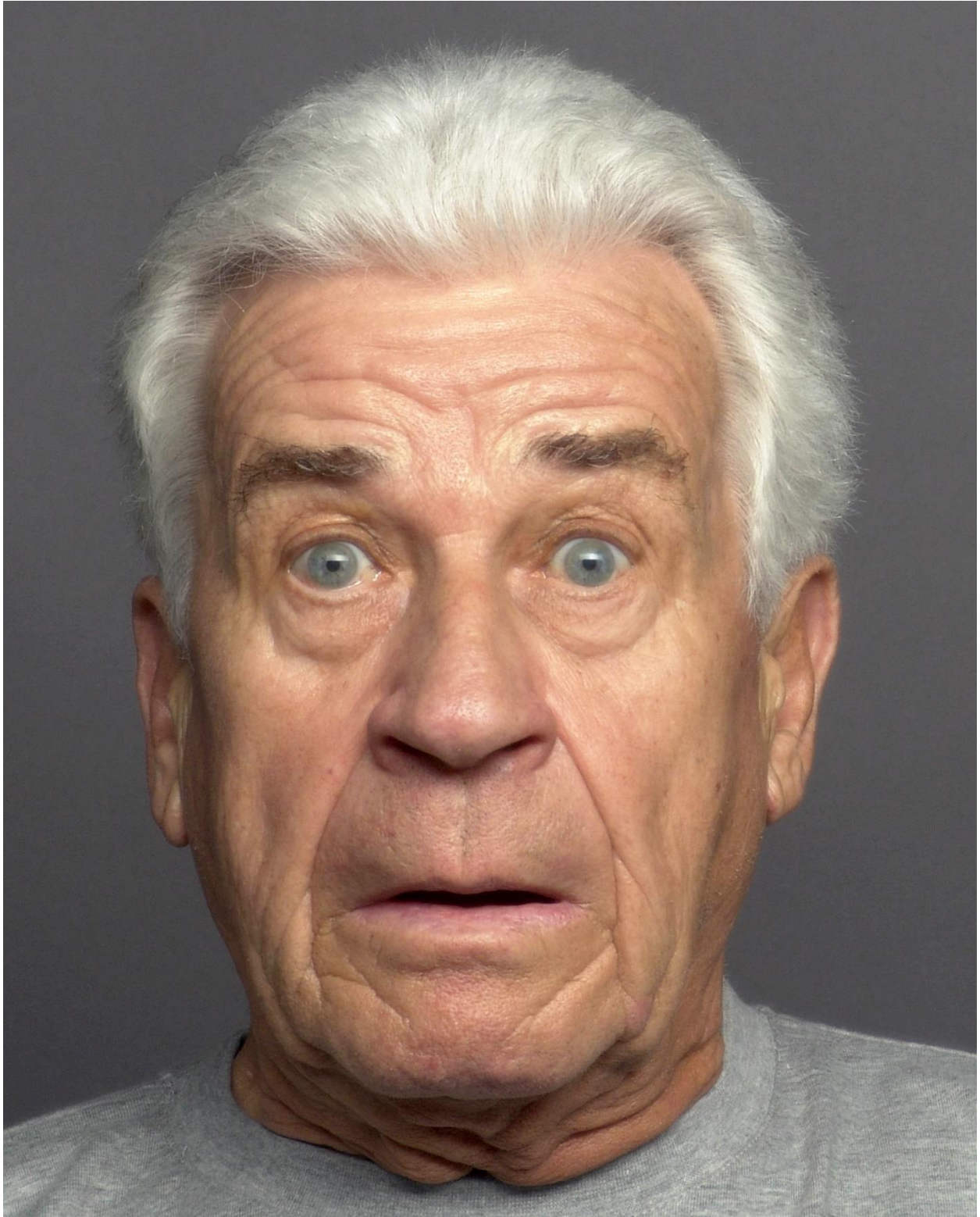


Figure 48 - Facial expression: elderly man & fear

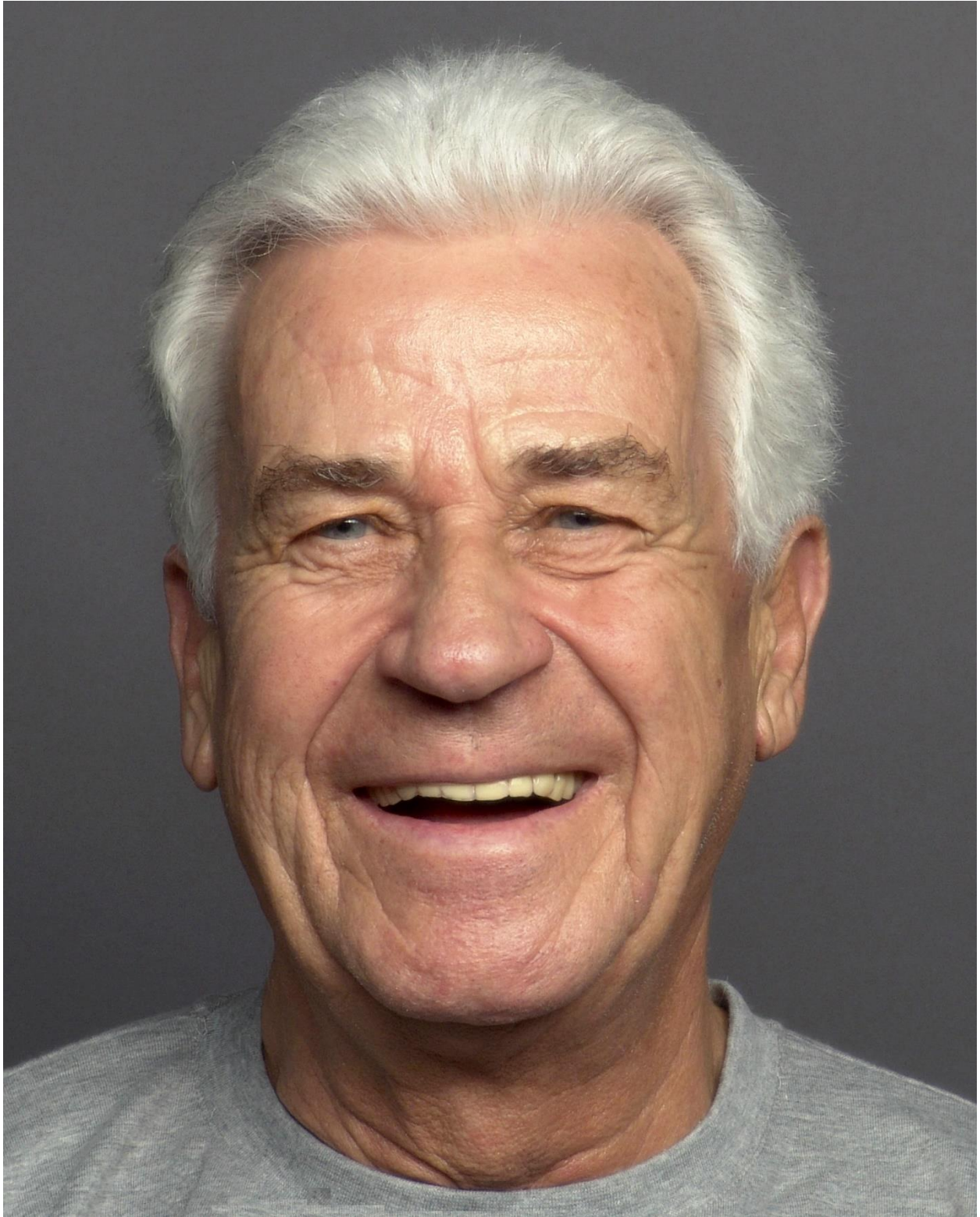


Figure 49 - Facial expression: elderly man & happiness

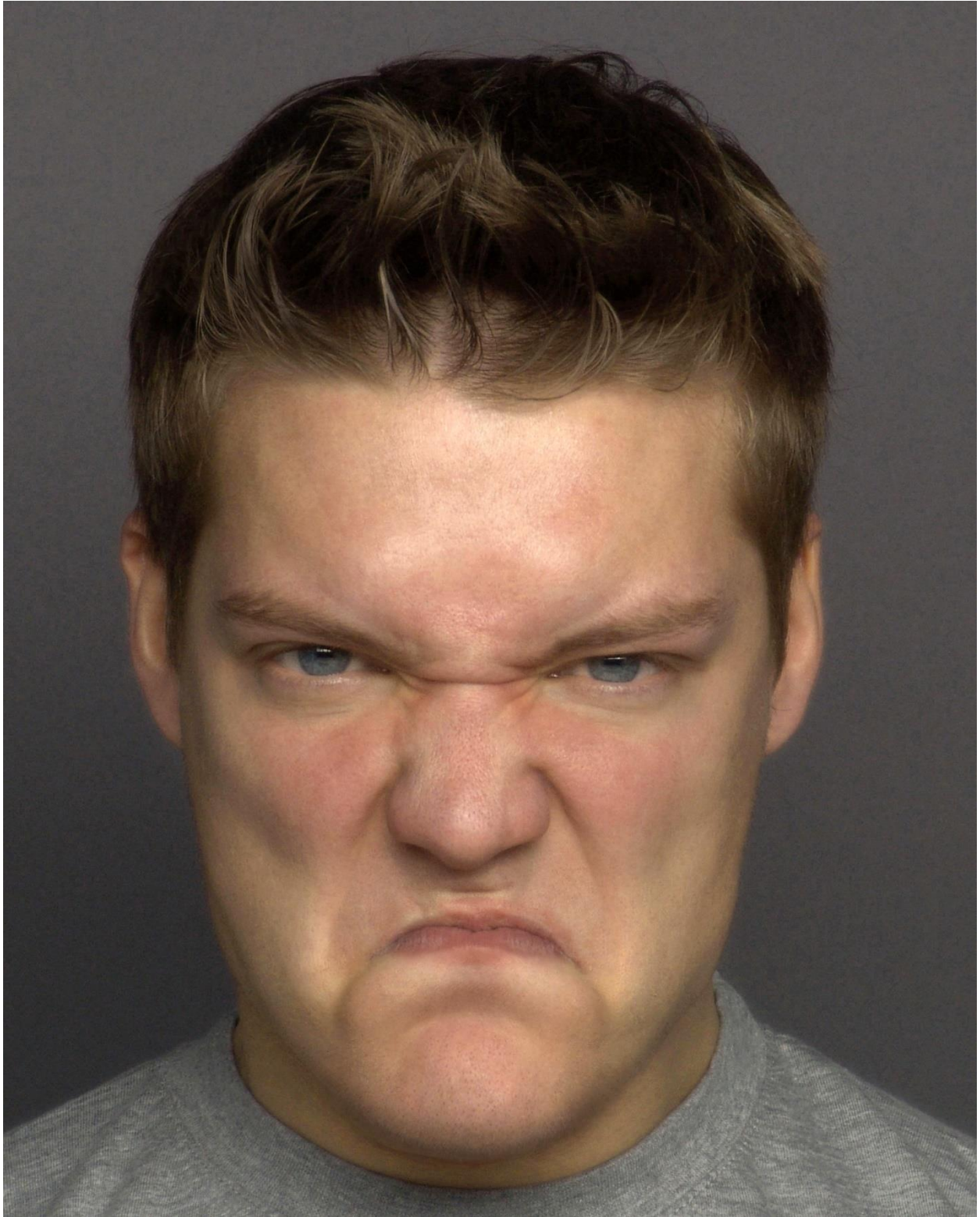


Figure 50 - Facial expression: young man & angry

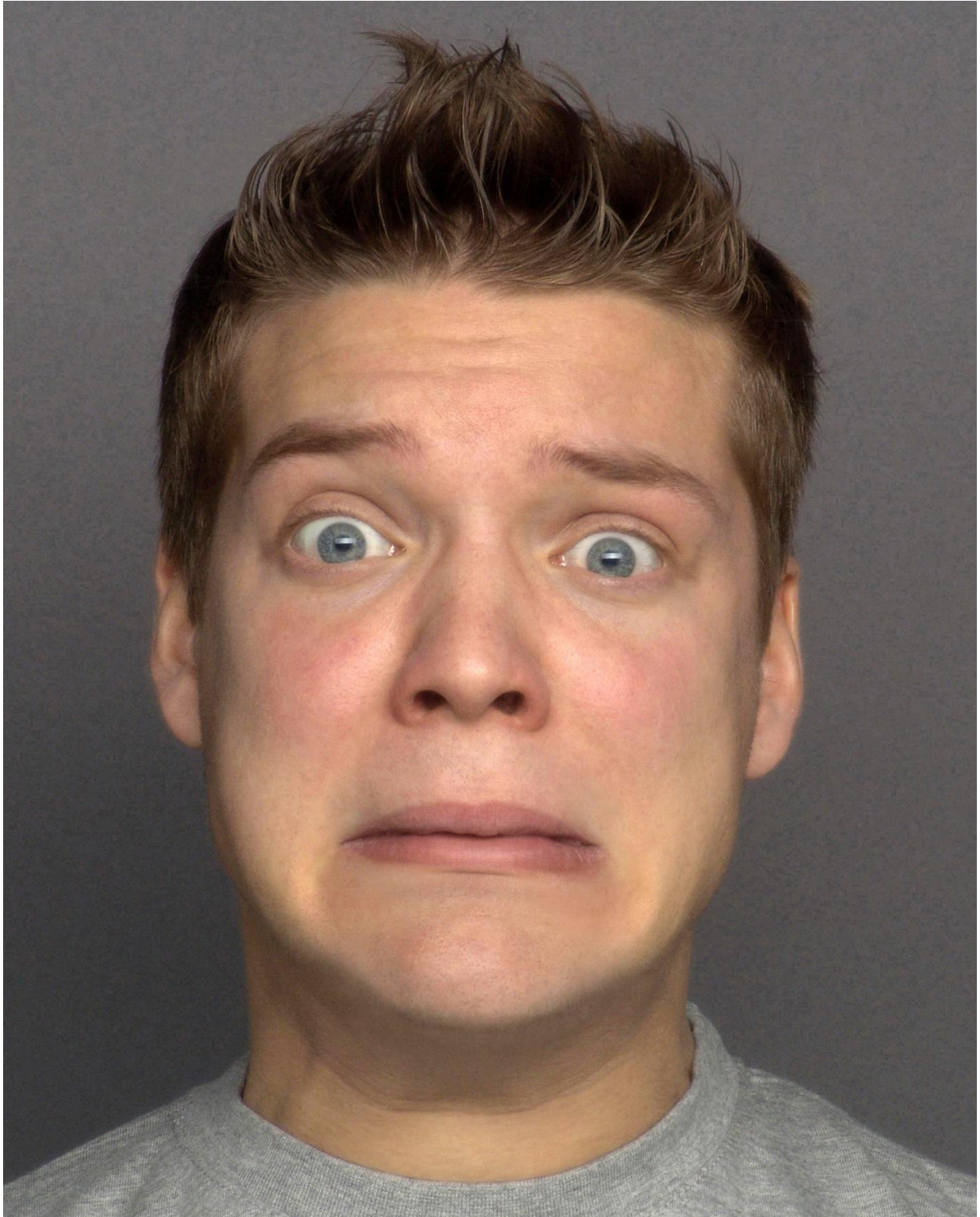


Figure 51 - Facial expression: young man & fear



Figure 52 - Facial expression: young man & happiness

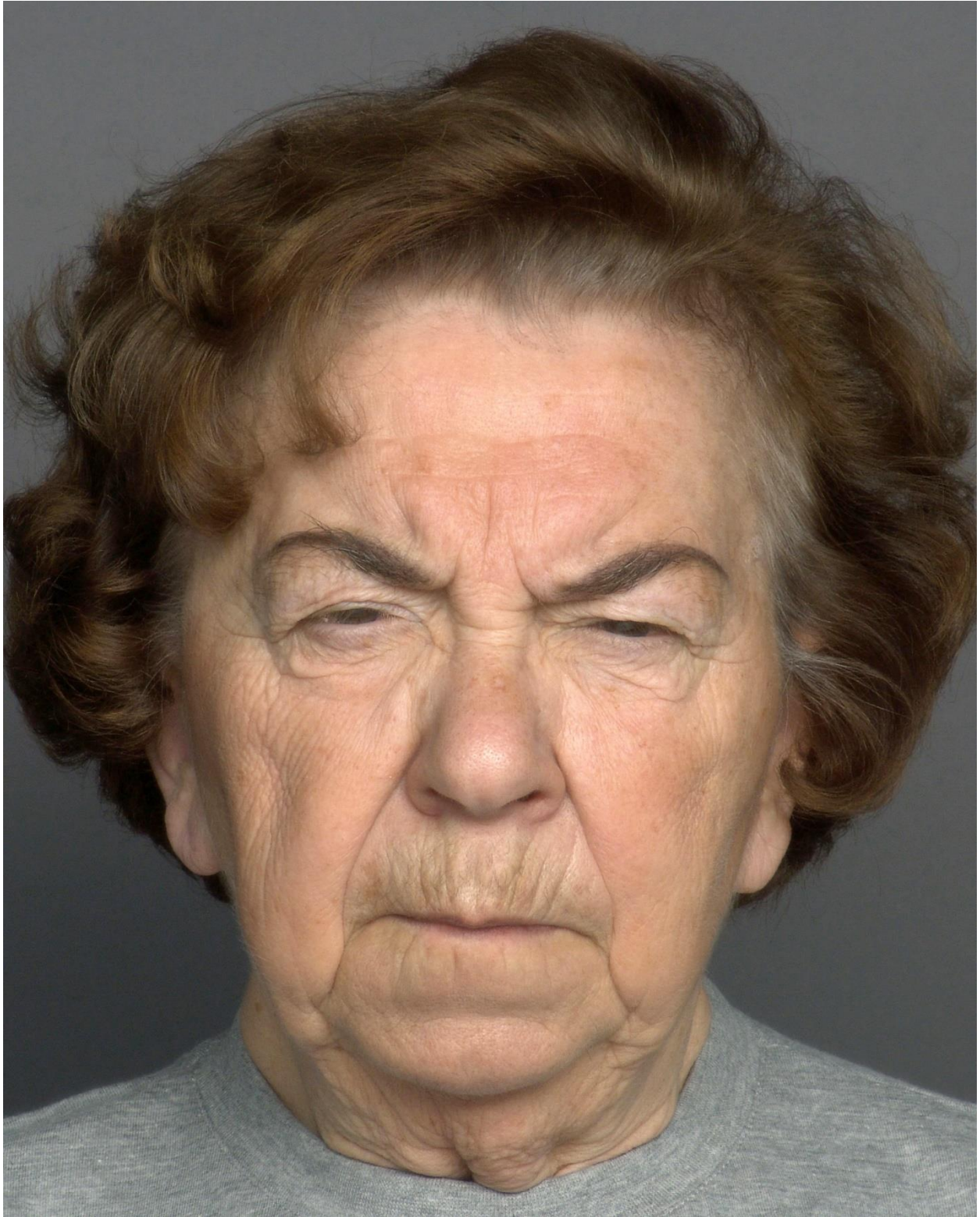


Figure 53 - Facial expression: elderly woman & angry

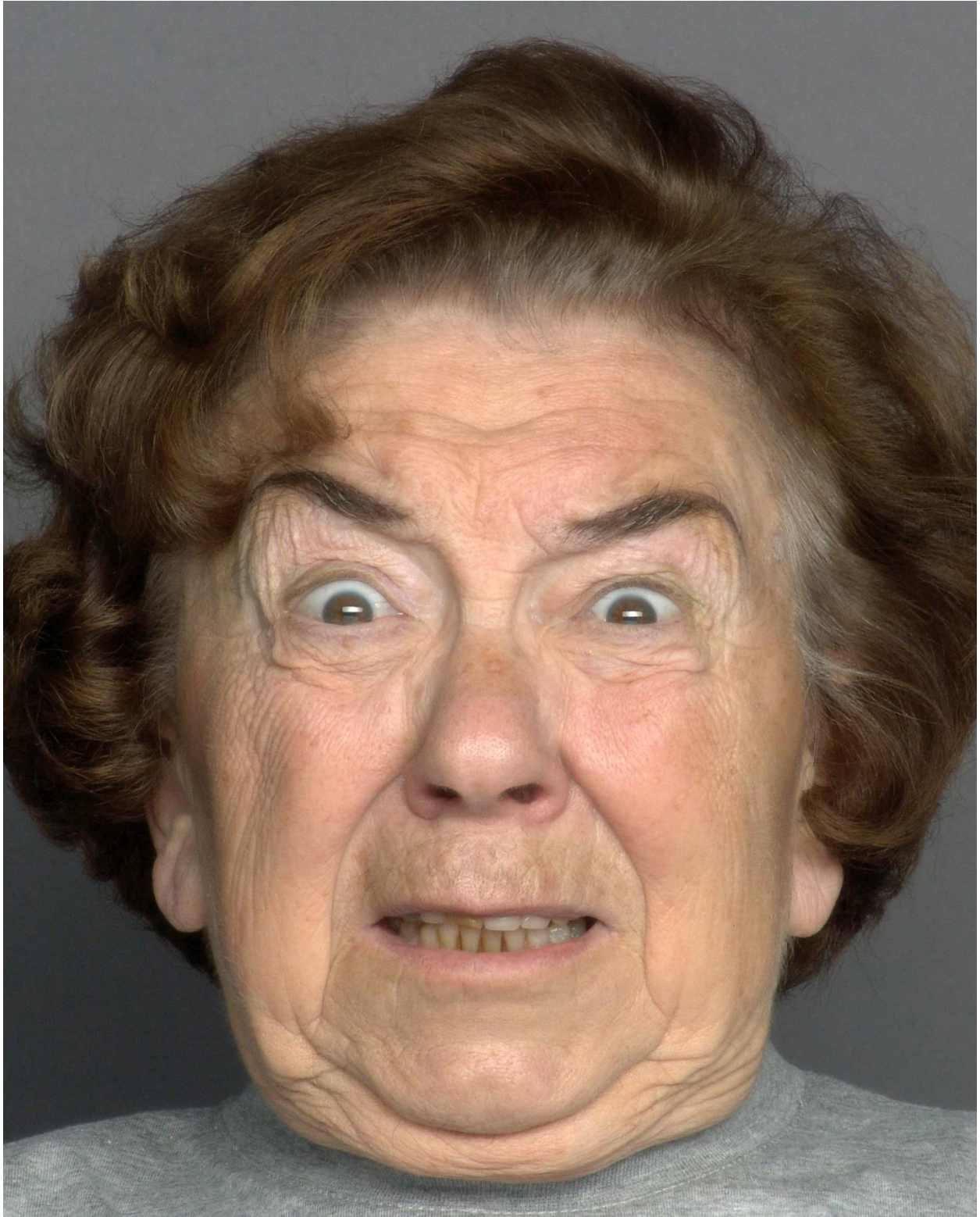


Figure 54 - Facial expression: elderly woman & fear



Figure 55 - Facial expression: elderly woman & happiness

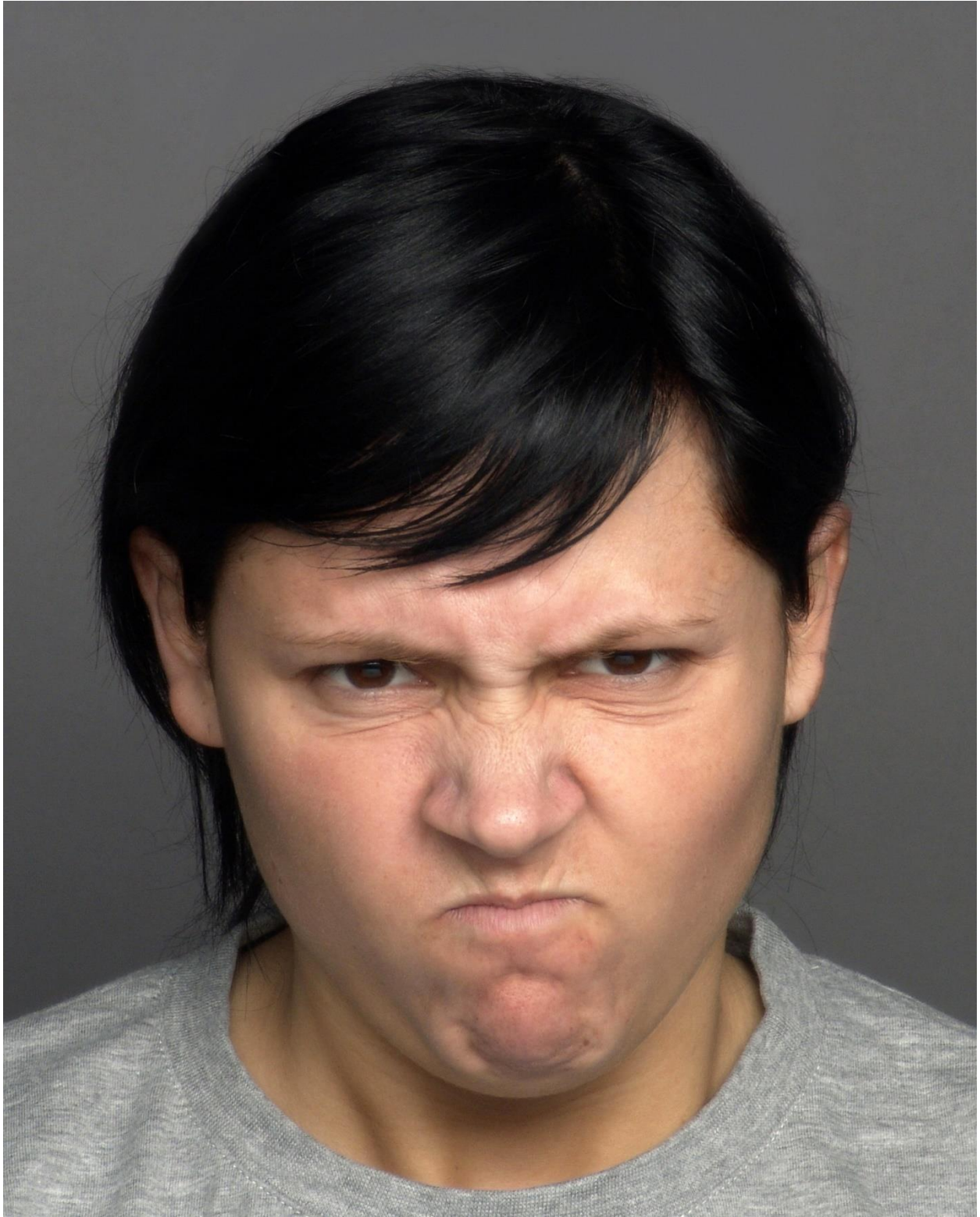


Figure 56 - Facial expression: young woman & angry

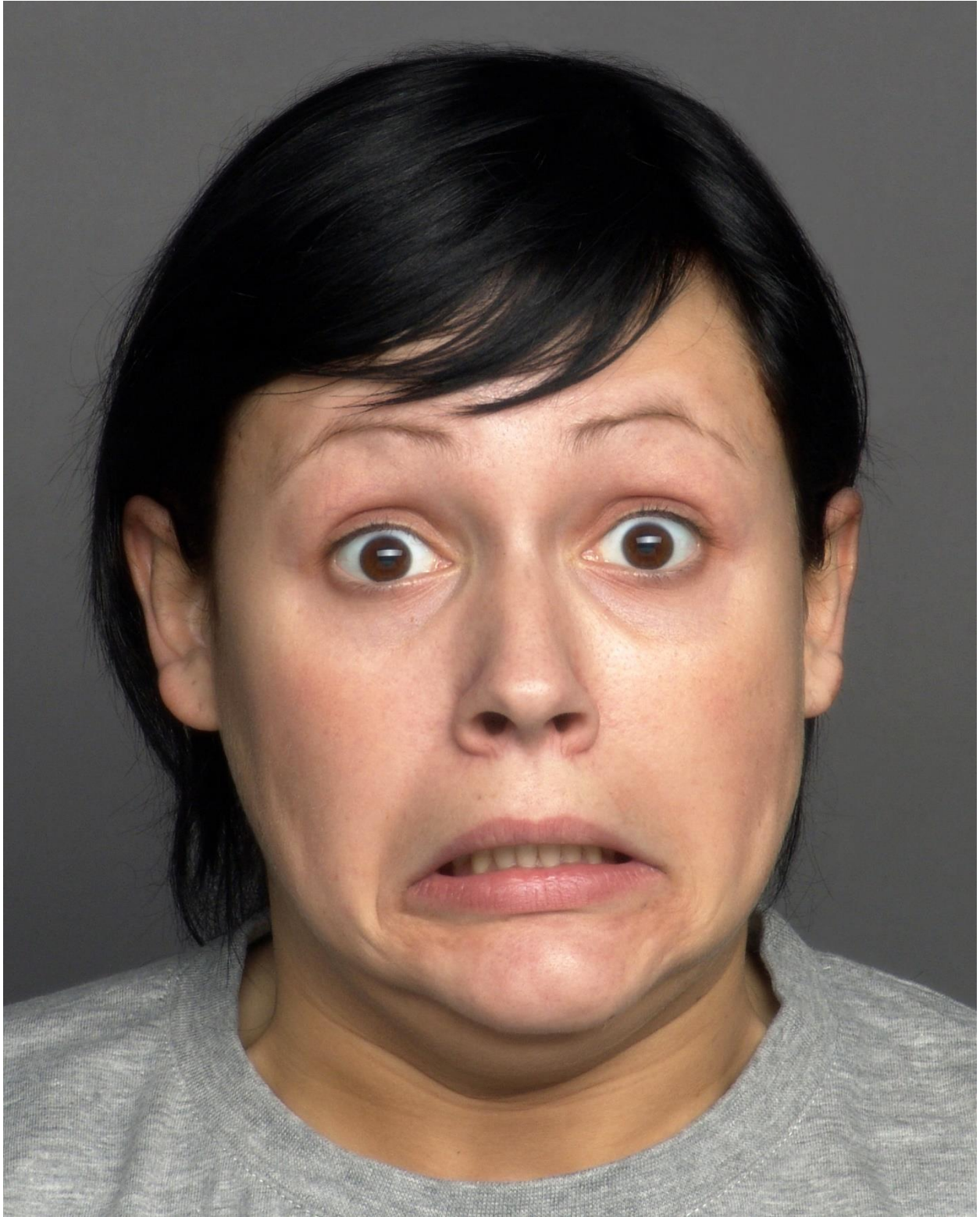


Figure 57 - Facial expression: young woman & fear

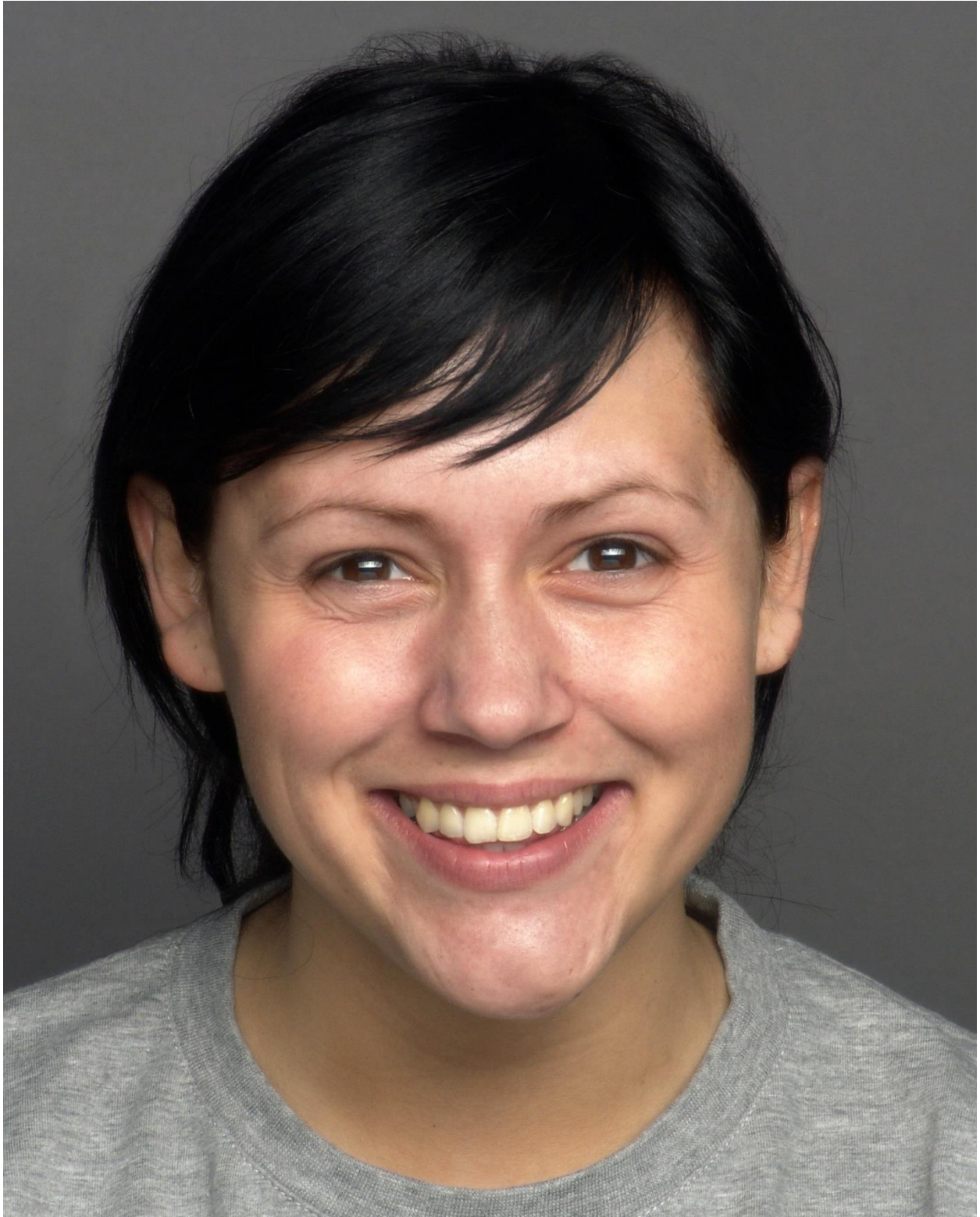


Figure 58 - Facial expression: young woman & happiness

Appendix VII

Visualization of E-hooks

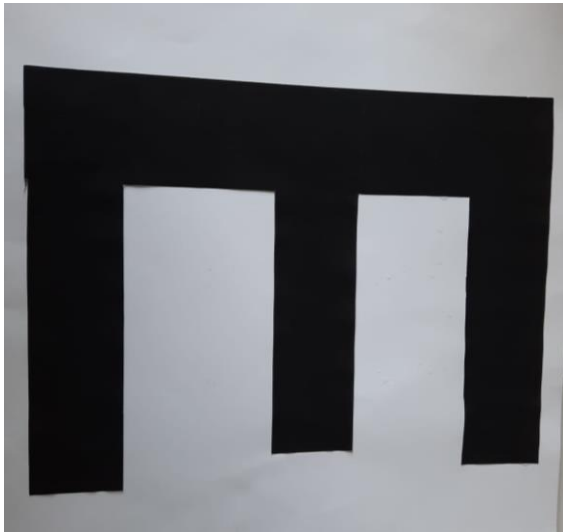


Figure 59 - E-hooks: down



Figure 60 - E-hooks: up



Figure 61 - E-hooks: right



Figure 62 - E-hooks: left

Appendix VIII

Contrast sensitivity measurement



Figure 63 - Visualization of Pelli-Robson sign task

Appendix IX

Reference points used to calibrate the HDR-images



Figure 64 - Visualization of the points used to compare the HDR-images made during different evenings throughout the field study.

Appendix X

Informed consent form

Informatieblad voor onderzoek “Verlichting aan de Carnegiedreef”

1. Inleiding

U bent gevraagd om deel te nemen aan het onderzoek “Verlichting aan de Carnegiedreef”.

Deelname aan dit onderzoek is vrijwillig: u besluit zelf of u mee wilt doen. Voordat u besluit tot deelname, willen wij u vragen de volgende informatie door te lezen, zodat u weet waar het onderzoek over gaat, wat er van u verwacht wordt en hoe wij omgaan met de verwerking van uw gegevens. Op basis van die informatie kunt u middels de toestemmingsverklaring aangeven of u toestemt met deelname aan het onderzoek en met de verwerking van uw persoonsgegevens.

U bent natuurlijk altijd vrij om vragen te stellen aan de onderzoeksleider via a.a.j.d.lange@student.tue.nl, of deze informatie te bespreken met voor u bekenden.

2. Doel van het onderzoek

Dit onderzoek wordt geleid door Anneloes de Lange, een student werkend aan haar afstudeerproject binnen de opleiding bouwkunde aan de Technische Universiteit Eindhoven (TU/e). Ze wordt tijdens dit project begeleid door dr. ir. Juliëtte van Duijnhoven en dr. ir. Rianne Valkenburg. Het onderzoek betreft een samenwerking tussen de TU/e, VISIO, CROW en de gemeente Utrecht.

Het doel van dit onderzoek is om de verschillende verlichtingsarmaturen op de Carnegiedreef te testen door middel van een gezichtsherkenning experiment en een obstakeldetectie taak. Hierdoor kunnen er conclusies worden gemaakt over de werking van verschillende lichtbronnen en kan hopelijk een norm worden ontwikkeld voor buitenverlichting om zo de openbare leefomgeving voor iedereen veiliger en toegankelijker te maken. De resultaten van deze studie kunnen worden gebruikt voor een publicatie in een professioneel of wetenschappelijk tijdschrift.

3. Wat houdt deelname aan de studie in?

- Wij vragen u om een studie bij te wonen aan de Carnegiedreef waar u 90 minuten lang een aantal experimenten uitvoert.
- De experimenten betreffen een aantal vragenlijsten, een gezichtsherkenning experiment en obstakel detectie taak met als doel de openbare verlichting te optimaliseren.
- De vragenlijsten zullen door iemand anders worden ingevuld dus u hoeft alleen maar verbaal antwoord te geven op de gestelde vragen.
- Tevens zal uw oogkwaliteit getest worden met een korte test om de verschillende lichtbehoeftes voor mensen met goed en beperkt zicht in kaart te brengen.

4. Potentiële risico's en ongemakken

Er zijn geen fysieke, juridische of economische risico's verbonden aan uw deelname aan deze studie. U hoeft geen vragen te beantwoorden die u niet wilt beantwoorden. Uw deelname is vrijwillig. Dit betekent dat u uw deelname op elk gewenst moment mag stoppen door dit te melden bij de onderzoeker. U hoeft niet uit te leggen waarom u wilt stoppen met deelname aan het onderzoek.

5. Vergoeding

U ontvangt voor deelname aan dit onderzoek een vergoeding van **30 euro** als waardering voor uw deelname. Hiernaast krijgt u de nodige reiskostenvergoeding om naar de onderzoek locatie te reizen.

6. Vertrouwelijkheid van gegevens

Wij doen er alles aan uw privacy zo goed mogelijk te beschermen. De onderzoeksresultaten die gepubliceerd worden zullen op geen enkele wijze vertrouwelijke informatie of persoonsgegevens van of over u bevatten.

De onderzoeksgegevens worden indien nodig (bijvoorbeeld voor een controle op wetenschappelijke integriteit) en alleen in anonieme vorm ter beschikking gesteld aan personen buiten de onderzoeksgroep.

Tot slot is dit onderzoek beoordeeld en goedgekeurd door de ethische commissie van de Technische Universiteit Eindhoven.

7. Vrijwilligheid

Deelname aan dit onderzoek is geheel vrijwillig. U kunt als deelnemer uw medewerking aan het onderzoek te allen tijde stoppen, of weigeren dat uw gegevens voor het onderzoek mogen worden gebruikt, zonder opgaaf van redenen.

Als u tijdens het onderzoek besluit om uw medewerking te staken, zullen de gegevens die u reeds hebt verstrekt tot het moment van intrekking van de toestemming in het onderzoek gebruikt worden als hier geen bezwaar tegen is. Wilt u stoppen met het onderzoek, of heeft u vragen en/of klachten? Neem dan contact op met de onderzoeksleider of haar leidinggevende dr. ir. Juliëtte van Duijnhoven.

Anneloes de lange – a.a.j.d.lange@student.tue.nl
Juliëtte van Duijnhoven – j.v.duijnhoven1@tue.nl

Dit onderzoek wordt uitgevoerd vanuit de Technische Universiteit Eindhoven en is de verwerkingsverantwoordelijke in de zin van de AVG. Indien u specifieke vragen hebt over de omgang met persoonsgegevens kun u deze ook richten aan de functionaris gegevensbescherming van de TU/e door een mail te sturen naar functionarisgegevensbescherming@tue.nl. U hebt daarnaast het recht om een klacht in te dienen bij de Autoriteit Persoonsgegevens.

Tot slot heeft u het recht een verzoek tot inzage, wijziging, verwijdering of aanpassing van uw gegevens te doen. Ga voor meer informatie naar <https://www.tue.nl/storage/privacy/>. Dien uw verzoek daartoe in via privacy@tue.nl.

***** Scrol naar beneden voor het toestemmingsformulier *****

Toestemmingsformulier voor deelname volwassene

Door dit toestemmingsformulier te ondertekenen erken ik het volgende:

1. Ik ben voldoende geïnformeerd over het onderzoek door middel van voorafgaand informatieblad. Ik heb het informatieblad gelezen en heb daarna de mogelijkheid gehad vragen te kunnen stellen. Deze vragen zijn voldoende beantwoord.

JA ☐ NEE ☐

2. Ik geef toestemming om mijn antwoorden te gebruiken in de onderzoek publicaties – zonder dat daarbij mijn naam wordt gepubliceerd.

JA ☐ NEE ☐

3. Ik neem vrijwillig deel aan dit onderzoek. Er is geen expliciete of impliciete dwang voor mij om aan dit onderzoek deel te nemen. Het is mij duidelijk dat ik deelname aan het onderzoek op elk moment, zonder opgaaf van reden, kan beëindigen. Ik hoef een vraag niet te beantwoorden als ik dat niet wil.

JA ☐ NEE ☐

Naam Deelnemer:

Handtekening:

Datum:

Appendix XI
Example of the trials

Participant 1 – Begeleider 2

Armatuur 1:

Positie	Trial	Obstakels		
1	1	-	-	-
	2	4	-	-
	3	6	1	4
2	1	2	5	-
	2	-	-	-
	3	1	-	-

Positie	Trial	Gezichtsemotie
1	1	Jonge vrouw – Angst
	2	Oude vrouw – Woede
	3	Oude man – Geluk
2	1	Oude vrouw – Woede
	2	Oude man – Woede
	3	Oude man – Woede

	1								
							2		
				3					
	4								
								5	
				6					

Appendix XII
Answer sheet example

Algemeen

Vragen	Antwoorden
Leeftijd	
Geslacht	
Lichaamslengte	
Draagt u nu een bril?	Ja Nee
Heeft u last van nachtblindheid?	Ja Nee

Armatuurtype 1 (straatlantaarn 1)

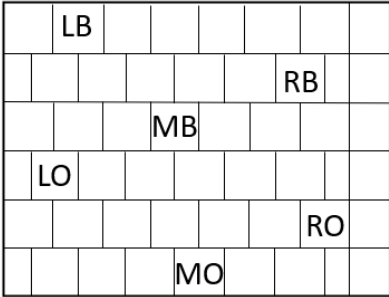
Positie	Trial	Gezichtsuitdrukking
1	1	
	2	
	3	
2	1	
	2	
	3	

Gezichtsuitdrukkingen
Angst (A)
Woede (W)
Geluk (G)

* Noteer 'A' voor emotie 'Angst', noteer 'W' voor emotie 'Woede' en noteer 'G' voor emotie 'Geluk'

Positie	Trial	Obstakeldetectie
1	1	
	2	
	3	
2	1	
	2	
	3	

* Noteer 'LB' voor links ver weg, noteer 'RB' voor rechts ver weg, noteer 'MB' voor midden ver weg, noteer 'LO' voor links dichtbij, noteer 'RO' voor rechts dichtbij en noteer 'MO' voor midden dichtbij.

Obstakel detectie	Benaming
	Links ver weg/boven = LB
	Rechts ver weg/boven = RB
	Midden ver weg/boven = MB
	Links dichtbij/onder = LO
	Rechts dichtbij/onder = RO
	Midden dichtbij/onder = MO

Vragenlijst armatuur 1

1. Kunt u aangeven welke stelling van toepassing is?

	Volledig oneens	Beetje oneens	Neutraal	Beetje eens	Volledig eens
Ik kan voldoende waarnemen van mijn directe omgeving					
Ik voel me veilig					
Ik heb last van lichthinder of verblinding					
De omgeving naast het pad is voldoende verlicht					
Het deze verlichting kan ik prettig over het trottoir lopen					

* Aankruisen welke van toepassing is

2. Kunt u een waardering geven voor de lichtkwaliteit die u ervaart?

- ☐ Slecht
- ☐ Onvoldoende
- ☐ Matig
- ☐ Voldoende
- ☐ Ruimvoldoende
- ☐ Goed
- ☐ Uitstekend

3. Acht meter voor u ziet u een bord met letters. Het contrast van de letters neemt per regel af. Hoeveel regels kunt u goed lezen?

- ☐ Geen enkele regel
- ☐ 1 regel
- ☐ 2 regels
- ☐ 3 regels
- ☐ 4 regels
- ☐ 5 regels
- ☐ 6 regels
- ☐ Meer dan 6 regels

Appendix XIII
Example of trials for a participant with a visual acuity < 0.6

Participant 31 – Begeleider 2

Armatuur 1:

Positie	Trial	Obstakels		
1	1	3	1	-
	2	-	-	-
	3	5	-	-
2	1	3	2	6
	2	5	-	-
	3	2	-	-

Positie	Trial	E-haken
1	1	Omlaag
	2	Rechts
	3	Omhoog
2	1	Omhoog
	2	Omhoog
	3	Omhoog

	1							
						2		
			3					
4								
						5		
			6					

Appendix XIV

Visualization calculation contrast

$$\frac{\text{Average luminance of the (visible) sides of the obstacle}}{\text{Average luminance of the top of the obstacle}}$$

(1)



Figure 65 - Visualization of the areas used to calculate the contrast values for each obstacle

Appendix XV

Contrast values

Table 11 - The contrast value of each of the six obstacles per luminaire type per participant position

Luminaire	Direction	OB 1	OB 2	OB 3	OB 4	OB 5	OB 6
A	Position 1	0.41	0.29	0.53	0.48	0.54	0.60
A	Position 2	0.80	0.69	0.50	0.53	0.73	0.87
B	Position 1	0.35	0.25	0.34	0.34	0.22	0.17
B	Position 2	0.90	0.54	0.57	0.48	0.86	0.87
C	Position 1	0.31	0.56	0.53	0.53	0.69	0.26
C	Position 2	0.48	0.62	0.91	0.50	0.80	0.74
D	Position 1	0.37	0.39	0.36	0.42	0.23	0.44
D	Position 2	0.15	0.87	0.82	0.40	0.33	0.57
E	Position 1	0.35	0.58	0.40	0.14	0.45	0.53
E	Position 2	0.25	0.36	0.92	0.79	0.42	0.14
F	Position 1	0.24	0.17	0.26	0.13	0.29	0.43
F	Position 2	0.73	0.88	0.50	0.88	0.55	0.33
G	Position 1	0.18	0.30	0.43	0.41	0.43	0.53
G	Position 2	0.75	0.79	0.54	0.88	0.74	0.75

Appendix XVI

Example of a 'natural' obstacle



Figure 66 - Visualization of a 'natural' obstacle that was present during the field study

Appendix XVII

Example of a luminance profile (luminaire A)

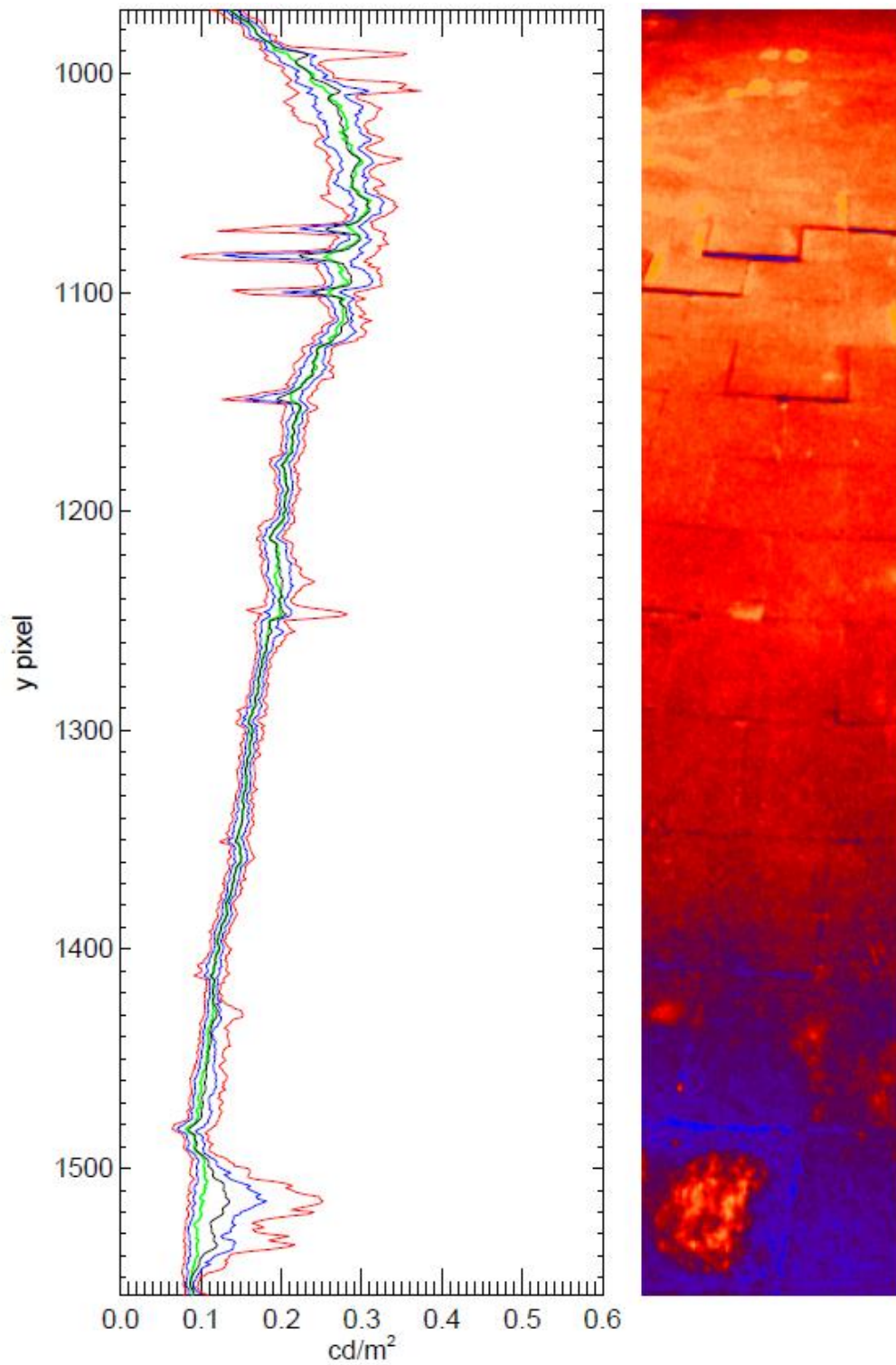


Figure 67 - Example of a luminance profile between the two participant positions (luminaire A). At the top, position 1 of the participant is located and at the bottom position 2 of the participant is located. In the graph on the left the luminance value for each pixel is visualized.

Appendix XVIII Visualization calculation area path luminance (luminaire A)

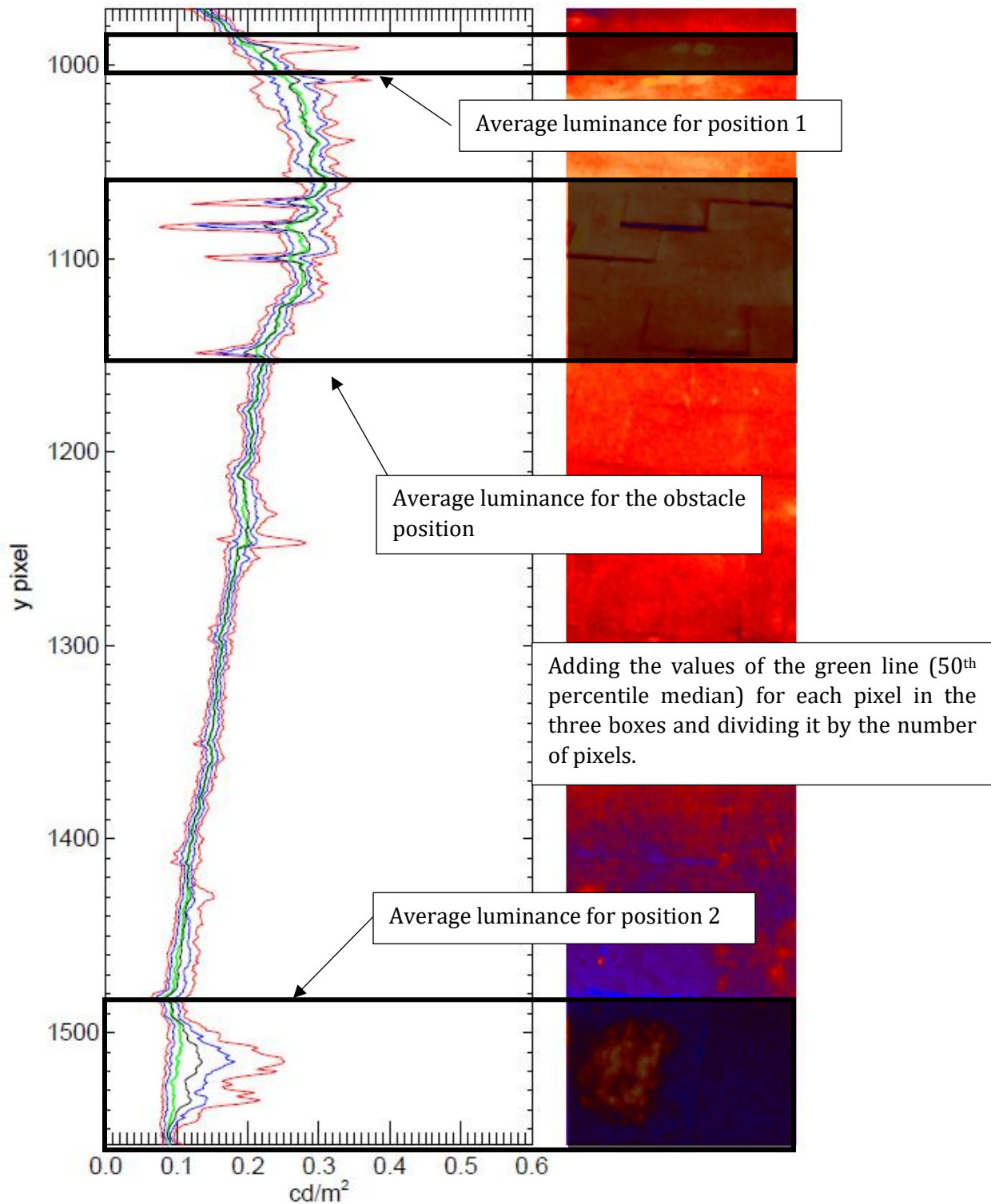


Figure 68 - Visualization of the calculation of the path luminance for either the participant positions or the position of the obstacles. During the calculation the average of the green line in the graph is used, this is the 50th percentile median line.