GLARE AND ENERGY FOR LIGHTING

PSO Project 348-009
Energy Efficient Lighting
Through Glare Control

COPENHAGEN SEPTEMBER 2017

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0. Executive Summary

This report has been prepared as one of the outputs from the project “348-009 Energy efficient lighting through glare control” supported by ELFORSK.

An abundance of light in a given environment causes the eye's pupils to constrict.

This project hypothesises that glary light causes the pupils to constrict excessively, thereby preventing part of the light from reaching the retina. The lighting becomes ineffective physiologically.

Through several pilot tests and a large experiment comprising 16 participants, the project has identified and disseminated a novel description of the relationship between the eye's reactions (pupil areas and gaze directions) in various office-like glare conditions. It has been shown, that indeed some excessive pupil constriction appears, and that up to 4% light may be saved in ordinary office environments alone through careful design.

Further, the project has produced some other unexpected, but important findings:

1) Pupil constriction is not (as hypothesized) governed by glare conditions as expressed in the UGR formula, but is strongly correlated simply to the vertical illuminance level measured at the eye. This leads to the conclusion that pupil constriction is just a minor part of the impact that glaring light produces in the visual system and that the mechannisms responsible for the perception of discomfort glare are likely to be be found in retinal reactions or in the nervous system including brain processes.
2) The use of wallwashers that reduced contrast in the field of vision greatly affected the pupil constriction stability, which may be an important visual comfort metric.
3) There are great individual differences in both pupil reactions and gaze reactions to the simple and rather ordinary lighting scenes presented to the participants.

It should be noted also that a former research program (ELFORSK346-046 – 2016) dealing with the exploration of preferences in energy efficient indoor lighting showed that wall luminance played a significant role in general brightness of a space. The electric power of new generations of wall washers, counting for about 0.3 to 1,0 W/m2 in typical rooms can often be compensated by reduction of the same power of general lighting, or even more for large spaces.

Dissemination

The results of the project at hand have been communicated in an article for the magazine LYS (to be published 1st December 2017), and through the newsletters of Danish Lighting Center and Danish Lighting Innovation Network. Further, the report will be accessible through the webpage of the Danish Lighting Center.

A scientific paper based on the present study will be presented to the international magazine Lighting Research and Technology in 2018.

A theme day on glare based on the project results and allowing for more expert input, as well as practical implementation guidelines, is planned for the autumn of 2017.

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1. Contents

1. Project Background and Prospects

1.1. What is Glare?

Glare is difficulty seeing in the presence of bright light such as direct or reflected daylight/sunlight or electric light such as car headlamps at night. Glare is caused by an excessive ratio of luminance between the visual task (that which is being looked at) and the glare source. Factors such as the angle between the task and the glare source and eye’s adaptation have significant impact on the experience of glare.

Glare can reduce visibility by:

- Saturating or bleaching photoreceptors in the retina.
- Reduction of brightness of the rest of the scene surrounding the glare source by constriction of the pupils – however, constricting pupils may also enhance visual function in terms of ability to focus (pin hole effect)
- Reduction in contrast of the rest of the scene by scattering of the bright light within the eye
- Reduction in contrast by scattering light through particles in the air, as when the headlights of a car illuminate the fog close to the vehicle, impeding vision at larger distance

Reduction in contrast by reflection of the light source in the task area, e.g. between print and paper (veiling glare).

Glare is a borderline case of contrast. Normally, a distinction between two types of glare is made:

- Disability glare caused by light that increases the adaption level in the eye so that the eye’s contrast sensitivity is reduced. Due to disability glare, a space may be perceived as darker than usual - and thereby increase the need for artificial lighting.
- Discomfort glare due to large luminance contrasts between, for example, a dark background and a light source with high luminance. Discomfort glare may not necessarily impede vision.

These two types are described in more detail in section 3.1. In practice discomfort glare often occurs indoors - and may be linked to both daylight and artificial light. Glare is one of the greatest occupational health problems. In office environments, excessive glare may cause fatigue and headaches, thus leading to tremendous productivity losses that may be hard to quantify precisely, but can clearly be documented through asking workers about their perceived productivity.

Because glare problems can cause reduced vision, there is also a link between glare and safety. Glare may cause everything from a mild discomfort to serious loss of vision, and thereby also potentially dangerous situations in for instance traffic or when working with machinery.

Glare problems (and other lighting problems) are very often neglected. Individuals tend to accept even very poor lighting conditions, and perform “work-arounds” like moving the computer screen instead of improving lighting conditions or solar shading.

1.2. Project Prospects

Glare will inevitably force the human eye to adapt by squinting and/or decreasing the pupil aperture thus also decreasing the total amount of light reaching the retina. In essence: The more glare, the less useful light. Consequently, glare-free lighting is more effective for visual tasks.

$$\left.\begin{array}{c}\text{Possible Squinting}\\ \text{Pupil Constriction}\\ \text{Decreased sensitivity of retinal cells}\end{array}\right] \rightarrow \text{Less light is perceived}$$

It can be argued that there is a direct link between visual comfort and energy efficient lighting.

Because glare will reduce the effective amount of light affecting the retinal cells by one or more of the factors above, we may also assume that absence of glare may allow for better use of the light present. A more advanced understanding of how minimizing glare affects the ability to gain full effect of a light in a space may be used to find an optimal balance between lighting levels and lighting comfort, and minimize the energy consumption related to lighting.

In luminaires, shading components or appropriate optics are necessary to provide lighting with sufficient visual comfort. However, luminaire optics affect efficiency: The more advanced the optics, the more surfaces the light must interact with, bounce off or pass through on its way from the light source to the surrounding space, the more light is absorbed and lost (converted into heat). As a rule of thumb, well-shaded luminaires for e.g. office spaces will absorb minimum 20-30% of the light in their optics.

Disregarding light losses and glare properties of the space, a budget for the light available for the visual systems in a glaring and a not-glaring situation could be illustrated as in Figure 1-1.

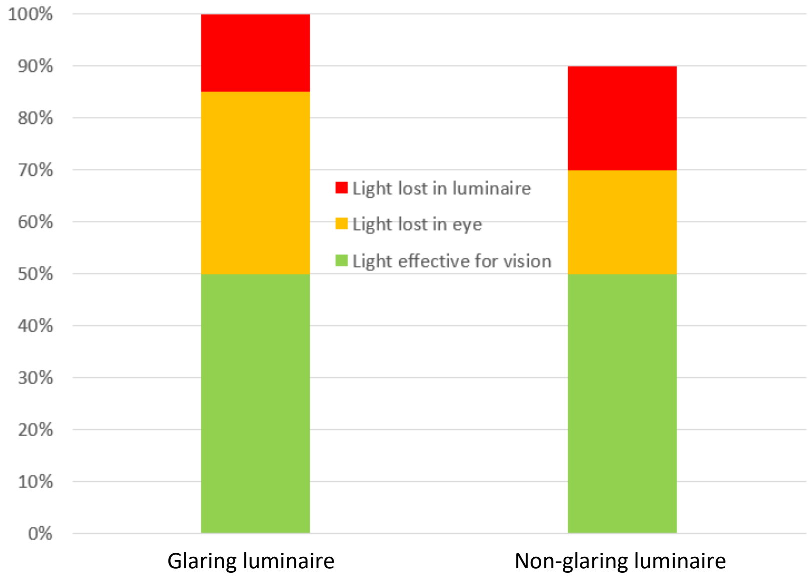

Figure 1-1 1 Schematic light and energy budget

Hence, the hypothesis of this project is, that a delicate balance between energy consumption and visual comfort exists: We propose that with the right lighting comfort settings in a space, energy for lighting can be saved without compromising the amount of light effective for visual tasks.

This project seeks to establish a direct coupling between glare and pupil size, which is the most easily measured of the factors above.

Photo-pigmentation can also be monitored with photopigment densitometry, which is a measure of retinal bleaching status that can be implemented in a reflectance imaging system and has been used to study the retina for over 60 years. However, light absorption by the retinal cells is a much more complicated to study. Light travels through several cell layers (in the fovea working more or less like optical fibres), before being detected. In the direction that light travels into the eye, these layers are: the inner limiting membrane, the nerve fibre layer, the ganglion cell layer, the inner plexiform layer, the inner nuclear layer, the outer plexiform layer, the outer nuclear layer, the external limiting membrane, finally the photoreceptor layer, and the retinal pigment epithelium [Masella]. All though the intensity of photo-pigmentation can be monitored by studying the fundal reflectance, it is not clear how this affects the light loss and efficacy in the full retinal depth. Further, flashing the retina several times in sequel (as is necessary for such images) will actually change the pigmentation of the retina.

Consequently, this project limits itself to studying glare and effect on pupil sizes, because the area of the pupil opening is assumed directly proportional to the amount being available to the retina. Further, this project seeks to investigate the hypothesis mentioned above by seeking a coupling between glare, pupil area and energy consumption.

Further, this project also studies vertical illumination as a means of reducing contrast (i.e. the minimizing luminance harsh differences in the field of vision) and thereby minimizing glare.

The total electricity consumption for lighting in 2011 represented 19% (Brown, 2010) of the world's total electricity consumption of 20,407 TWh/year (IEA, 2013). If just a single percent of this could be saved by optimizing use of light for visual tasks through intelligent light design (and eliminating unwanted side effects of lighting such as glare), such a reduction would amount to 39 TWh/year, or around 6 billion EUR/year (given an EU- average 2012 retail electricity price of around 0.15 EUR/kWh) (European Commision, 2014).

Reduced illumination levels can be obtained primarily for lighting of work environments (e.g. offices) and in street lighting. The authors of this report estimate that the savings potential may be in the range of 3-7%. In some street lighting applications the savings potential may be considerably higher and maybe up to 30%, depending on prevailing local standards and lighting traditions.

1.3.Solid State Lighting – Dealing with New Glare Issues

LED street luminaires are often considered to increase glare in comparison with, for instance, metal halide or high-pressure sodium sources. This is mainly related to the reduction of size of the light sources, and the associated increase of luminance for the observer. New optical design, reflectors and transmission lenses have been proposed which significantly reduce glare.

Contemporary luminaires for both indoor and outdoor lighting are often based on Solid State Lighting (contain LEDs). In many cases, and particularly in street lighting products, users may look directly into batches of maybe 30-100 non-diffused LEDs (sometimes with small primary optics).

Modern LED components (primary light sources) typically have a very high luminous intensity.

Figure 1-2 Cree XLamp CXB3590, 4,000 K, CRI 70, Light emitting area Ø28.5 mm. This component provides approximately 13,000 lumen @85°C – or more than 16 traditional incandescent 60W lamps (Photo: Cree)

Just 10 years ago, almost all downlight luminaires contained 1 or 2 compact fluorescent tubes – a light source far bulkier than LEDs and with a large light-emitting surface. Such solutions would require fairly large reflectors, and consequently the luminance both directly from the light source as well as indirectly from the reflector and other internal surfaces would be spread across a rather big surface, thus making the luminance tolerable and luminance transitions from light source to background moderately smooth.

Prevalent glare evaluation models were not developed to take full account of such compact, high luminance optics.

In production of electronics, smaller is usually better and more cost effective. Another important advantage is that precision optics can be much easier made to fit compact light sources. But as argued, precision optics and high outputs are not always comfortable on the eye and may contribute to significant glare problems. In lighting design, it is also necessary to avoid dramatic changes between lit and unlit areas that are difficult to handle for elderly citizen and may increase the risk of falls and fall-related accidents (e.g. broken hips which are a major “killer” in the older population).

The only way of effectively preventing such counter-productive development is to have proper glare metrics that enable product developers and lighting designers to predict glare more accurately.

1.4.Danish/Nordic Lighting Traditions

In general, there are large regional differences in requirements for illumination levels. In Denmark, there is a tradition of rather dim lighting in streets and offices compared to other countries, but also a cultural preference for low-glare luminaires. Varying natural lighting conditions in different parts of the world and seasonal changes seem to be responsible for these preferences. Much in correlation with Danish/Nordic lighting traditions an American study (Miller, 2013) concludes, that:

“Not every neighbourhood is suited for pedestrian-friendly approaches, but where communities are receptive, the following may help mitigate glare, improve visual comfort and visibility, and make outdoor spaces more inviting:

- *Lower lumen output luminaires and lower illuminances, if luminaire brightness can be controlled*
- *Luminaires that spread luminance (“brightness”) over a larger area, including luminaires that use indirect optics*
- *Luminaires with less optical punch and less sharp cut-off in candlepower [=0.981 candela]*
- *Luminaires delivering warmer colour light, usually lower than 4,000 K, and often below 3,000 K CCT.*

The problems of pedestrian lighting occur with all technologies, but LEDs offer optical options and opportunities the industry has never had before.”

City lighting in Denmark is actually famous for being subtle, almost dark. Still, citizens rarely complain about feeling unsafe and the number of road fatalities per 100,000 inhabitants is one of the smallest in the world. Usually this is explained by the fact, that traditional Danish road light engineering tends to favour glare reducing solutions – including luminaires that restrict light in low angles and including solutions that reduce glare by “spilling” light to surroundings.

A similar approach is rooted in Danish indoor lighting design traditions. When studying light and comfort, architects all over the world turn to the works of Poul Henningsen, who almost singlehandedly embedded an extra sense of lighting comfort into Danish design traditions and every Danish person’s perception of what good lighting should be.

1.5.Glare and Occupational Health and Safety Issues

Glare is one of the main lighting problems in working environments. Glare reduces visual performance and at worst could lead to accidents. Any abrupt transition from small to large luminance or vice versa, and large luminance contrasts in the visual field can cause glare or reduced visibility. As a rule, a gradual luminance changes, both on surfaces in the space and on the work area would be preferable.

Glare may occur in several ways; for instance, when powerful, insufficiently shaded light sources or direct sunlight at low angles are in the field of vision. Just as importantly, glare may occur when direct light is reflected in bright or glossy materials in indoor spaces. Particularly reflections in computer screens may be very disturbing. Originally, computer screens where slightly convex and thereby more likely to mirror many light sources. For a period of time, PC screens were plane and matte, but nowadays most computer screens, laptops as well as stationary, are relatively glossy, so the risk of glare through reflection persists.

Figure 1-3 Photo of a glossy display showing reflective properties, source: www.tftcentral.co.uk

But glare will also occur in bright or glossy surfaces such as window frames, white or glossy paper, glossy furniture or the like.

Eye fatigue or eye strain is a common and annoying condition. The symptoms include tired, itching, and burning eyes. Eye fatigue is rarely a serious condition. Common sense precautions at home, work, and outdoors may help prevent or reduce eye fatigue. Eye fatigue is associated with uncomfortable and annoying symptoms, such as[1]:

- Sore or irritated eyes
- Difficulty focusing
- Dry or watery eyes
- Blurred or double vision
- Increased sensitivity to light

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[1] One paper describes a very high prevalence (2/3) of eye fatigue related to computer problems (in Sri Lanka) BMC Res Notes. 2016 Mar 9;9:150. doi: 10.1186/s13104-016-1962-1. Computer vision syndrome among computer office workers in a developing country: an evaluation of prevalence and risk factors.
Ranasinghe P[1], Wathurapatha WS[2], Perera YS[3], Lamabadusuriya DA[4], Kulatunga S[5], Jayawardana N[6], Katulanda P[7].)
The following paper is a review describing the same problems related to computer use
Ophthalmic Physiol Opt. 2011 Sep;31(5):502-15. doi: 10.1111/j.1475-1313.2011.00834.x. Epub 2011 Apr 12.
Computer vision syndrome: a review of ocular causes and potential treatments.Rosenfield M1.

- Pain in the neck, shoulders, or back
- Headaches

These symptoms can decrease productivity. They may be intensified by sleep deprivation. Lack of sleep may result in persistent eye irritation. (WebMD). As an example, 9% of all interviewed persons in the Danish Ministry of Education reported in an occupational health survey in 2013 (“Arbejdspladsvurderinger”) that they often or always experienced glare in their workplace (Undervisningsministeriets Departement, Kvalitets- og Tilsynsstyrelsen, 2013).

Glare problems in the manufacturing industry may cause both decreased productivity and hazardous situations. Direct view of glaring light sources as well as reflections in the task area may reduce visual function in terms of ability to see details and moving objects. Also after-images (local disadaptation usually accompanied by the continued image of a bright spot, coloured or not, which produces a veil or masking effect) may prevent proper vision and lead to potentially dangerous situations.

It can be concluded that reducing glare in working environments has a large potential to reduce work related health and safety problems. Eye fatigue and headaches are probably the most overlooked problems and hence reducing glare in office and other working environments may have the largest potential in terms of both minimising health problems and productivity losses.

1.6. Project Prospect Conclusions

Understanding glare well enough to be able to quantify this sensation proves to have many potential benefits for both individuals and society:

- Finding the perfect balance between glare/visual comfort and illumination levels may lead to better understanding of the illumination levels actually needed, and thus optimisation of the energy consumption and enormous savings are within reach.
- Reduced glare in working areas can result in better performance and higher productivity per capita, and fewer work related accidents, and individuals may experience less fatigue, headaches and eye strain.
- Simple glare reduction methods such as the right choice of colour/reflectance and glossiness of furniture may get more attention if glare can more easily be quantified. As a result, both daylighting and electric lighting in buildings and outdoors can be improved in design and provide better visual environments for individuals.
- Better visual environments can influence on performance and safety in traffic and lead to less accidents as well as making outdoor spaces more inviting or feeling safe.
- The proportion of elderly citizens rises, and reducing glare in both daylighting and electric lighting may provide better living conditions for elderly citizens, and reduce the risk of accidents at home or in traffic. Elderly citizens are more prone to glare because of age-related changes in the lens (cataract), retina (age-related macular degeneration) and optic nerve (glaucoma)
- Proper glare metrics have the potential to empower Danish/Nordic architects, lighting designers and luminaire manufacturers and provide means for increasing world market shares for these industry groups.

2. Existing Danish Indoor Lighting Legislation and Standards

Lighting standards in general serve to provide minimum target levels for lighting quality (daylighting/electric lighting). Quality may be expressed through measurable criteria (illuminance/luminance, light distribution, uniformity, colour rendering etc.) and more visually evaluated criteria such as shadowing. In this context, glare is treated as a parameter that can be predicted with for instance the UGR-method, and therefore standardised, but cannot not easily be measured in practice. However, it is recognised that predicted glare values are not always in line with glare experienced on-site.

2.1. Indoor Electric Lighting Standards

Lots of standards exist word-wide to regulate the minimum quality and quantity of indoor lighting. In the European Union, the most important standard for indoor lighting is:

- EN 12464-1:2011 Light and lighting - Lighting of work places - Part 1: Indoor work places

Their importance is related to the fact that these standards are intended for working areas where occupational health and wellbeing is imperative. This is why En 12464-1 is referred to directly in the Danish building codes (BR15/BR18) thus becoming mandatory.

All standards have common denominators, such as specifying minimum illumination levels, colour rendering index and uniformity, as well as specifying glare limits expressed as UGR-values (see section 0).

To a certain amount, standards do also express local lighting traditions in terms of those same parameters. For instance, in Denmark there is a tradition of emphasising low glare ratings and also for specifying relatively low illumination levels.

2.2. Daylight Requirements in Building Codes

In the book “Daylight, Energy and Indoor Climate Basic Book” by Velux the following overview is given:

“Daylighting is met with very limited (or no) requirements or recommendations in existing standards and building regulations that are enforceable by law in any country. Legislation related to daylighting tends to be of three types:

- The access that buildings have to sunlight. This type of legislation, usually referred to as “solar zoning legislation”, attempts to guarantee building occupants access to sunlight for a predetermined period of time. “Solar zoning” (e.g. in Japan and China) relates to public health, safety and welfare.
- Requirements for windows and their glazing area in relation to the room area or façade area. It is important to emphasize that legislation, which mandates a minimum ratio of glazing area, cannot be considered as daylight legislation, since it does not translate the actual daylight presence inside the room or building; it is not considering outside boundary conditions, building overhangs, permanent shading, glass configuration or transmittance etc.
- The quantity of indoor illumination inside a room. Levels for daylighting are generally described as referred or recommended; either by specific illuminance (lux) levels on a work plane or by the daylight factor (DF) method.”

The latter is how Danish building regulations (BR15 supplemented by energy class 2020) standardize daylight in the built environment. Notably, daylight is considered to be a cheap, readily available and healthy light source, but the visual comfort as a result window distribution and size is seldom regulated.

Hence, requirements for daylighting are still missing in terms of specific illuminance and glare levels, but there is enough evidence in literature to indicate that illuminances in the range of 100 to 2,500 lux are likely to result in significant reduction of electrical lighting usage (Mardaljevic, 2008).

For good visual conditions some degree of uniformity of daylight is desirable, but this is not regulated in standards.

CEN TC 169 / WG 11 has produced a new European Daylight Standard (prEN 17037), which is expected to have effect as of spring of 2018. The scope of the standard is to specify minimum recommendations for achieving, by means of natural light, an adequate subjective impression of lightness indoors, and for providing an adequate view out. In addition, recommendations for the duration of sunshine exposure within habitable and occupied rooms are given. This standard gives information on how to use daylighting to provide lighting within interiors, and how to limit glare. This standard defines metrics used for the evaluation of daylighting conditions and gives methods of calculation (and verification). This standard applies to all spaces that may be regularly occupied by people for extended periods except where daylighting is contrary to the nature and role of the actual work done.

3. Glare and Human Physiology

3.1. Glare Fundamentals

The Illuminating Engineering Society of North America (IESNA) defines glare in the following way: “The sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility.” Glare can be perceived when the average luminance in the visual field is very high (saturation) – about 25,000 cd/m^2 corresponding approximately to a white sandy beach on a sunny day – or when distinctive light sources in the visual field have a higher luminance than that to which the eye is adapted.

This overall sensation of glare is then subdivided into two types: Disability glare and discomfort glare.

- Disability glare is “the effect of stray light in the eye whereby visibility and visual performance are reduced” (CIE, 1995). Disability glare is caused by scattering of light within the optical media of the eye. This reduces overall contrast and can be characterized by an equivalent veiling luminance which adds to, and is superimposed upon, the scene. The magnitude of the equivalent veiling luminance is a function of several factors, including the intensity of the glare source, the angular distance between the glare source and the visual target of interest, and the age of the observer. Disability glare can be measured experimentally in a particular scenario by determining the contrast thresholds for a visual task, with and without the presence of glare (Kent B. Christianson, 2009). The general consensus among researchers is that disability glare is the more important factor in traffic safety, since task performance (i.e. driving) can be directly affected, while pure discomfort glare results only in annoyance to the driver. Of course, many glare sources, including headlights from an opposing vehicle, might result in both kinds of glare.
- The CIE definition of Discomfort Glare is "glare which causes discomfort without necessarily impairing the vision of objects" (CIE, 1995). Discomfort glare is a subjective response of the observer, and can occur independently of the reduction in task performance associated with disability glare. The mechanism of discomfort glare is still undetermined, but some researchers believe that a physiological correlate is facial muscle tension in the vicinity of the eyes. It is also claimed by some researchers that discomfort glare is related to the scotopic luminosity function of the visual system, and thus might be mediated by rods (Kent B. Christianson, 2009). In indoor lighting, discomfort glare is most important because indoor environments often contain working environments where disability glare should be avoided entirely, and where discomfort glare influences performance and wellbeing (Danish Lighting Center et. al., 2014).

3.2. Normal Eye Vision and Reactions to Glare

3.2.1. Normal Vision and Limitations

For its visual functions, the human eye’s retina contains two types of photoreceptors: the cones for photopic (light adapted) and colour vision, and the rods for scotopic (dark adapted) vision. The rods are highly sensitive to light (about 100 times as sensitive as the cones) and allow for vision in fairly dark environments, e.g. at night, but they are not able to discriminate colours. Under mesopic conditions (twilight), both rods and cones are active and limited colour vision is possible.

- Photopic vision (light adapted; only cones active): above 30 cd/m^2
- Mesopic vision (twilight adapted; both rods and cones active): between 0.01 cd/m^2 and 30 cd/m^2
- Scotopic vision (dark adapted; only rods active): below 0.01 cd/m^2

The light-adapted eye (V(λ) curve) has its peak spectral sensitivity at approximately 555 nm, the dark-adapted eye (V’(λ) curve) has its peak spectral sensitivity at approximately 507 nm. The spectral sensitivity under mesopic conditions changes with the adaptation luminance and lies between 507 and 555 nm.

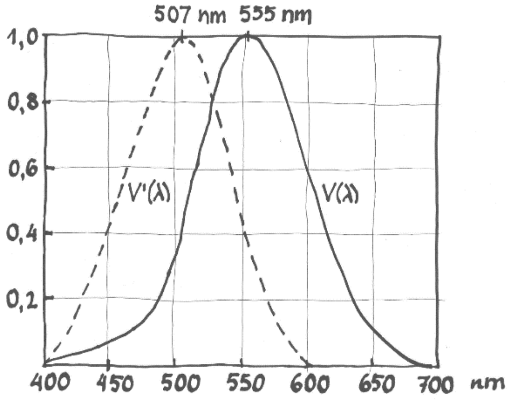

Figure 3-1 Spectral lightness sensitivity as a function of wavelengthof light-adapted (V(λ) curve) and dark-adapted (V’(λ) curve) eyes.

Light which arrives at a photoreceptor in the human retina can activate a photopigment in the photoreceptor and thereby initiate a photochemical reaction. Depending on the number of photons arriving at a photoreceptor and the resulting concentration of the photopigment, the electrical voltage of the photoreceptor drops by up to 40 mV which further triggers a response in the inner retinal layers (relay system). The function of the retina is thus to translate the energy from light (photons) into electrical stimuli which can be understood by the brain and the higher visual centres of the brain.

There are three different types of cones in the human retina, each responding to a different spectral range. These different spectral sensitivities are responsible for colour vision. The signals from the receptors are carried by a network of nerve cells to the retinal ganglion cells, which pass on the majority of the signals through a series of electrical impulses (action potentials) along the optic nerve to the visual cortex (located in the occipital lobe of the human brain) where they are evaluated as part of a process called visual perception. It is generally estimated that 2/3 of the brain is involved in visual processing. As there are fewer ganglion cells than photoreceptors, each ganglion cell receives bundled impulses from several photoreceptors. The area around a ganglion cell in which the ganglion cell can recognise light impulses is called the receptive field of the ganglion cell. In the central part of the retina (fovea, the part of the retina used for fine details such as reading) one photoreceptor connects to one ganglion cell. In the peripheral part of the retina, several photoreceptors connect to the same ganglion cell limiting the discrimination of small objects in the peripheral visual field. Some ganglion cells are activated by light impulses in the centre of their receptive field (on-centre), other by light impulses at the periphery of their receptive field (off-centre). This structure helps the human eye to better detect contrast detection, i.e. boundaries or edges between areas of different luminance, without creating an impulse overload for the brain. If both centre and surround field of a ganglion cell are equally excited, the resulting impulse is neutralised. Different distributions of light falling onto the centre of the receptive field of a ganglion cell cannot be detected. Only the sum of the receptor signals can be transmitted.

There are approximately 92 Million rods and 4.6 Million cones which are distributed unevenly across the retina. The cones are concentrated (have their highest density) in a field of ca. 2.5° around the centre of the retina (fovea), the rods reach their highest density at around 18-20° around the centre of the fovea. Cones are smaller than rods, thus the photoreceptors in the central part of the retina are densely packed allowing for resolution of small details. Under light-adapted conditions, a focussed visual image can only be obtained in the fovea. With dark-adapted eyes, the best focus (sharpest image of an object) is usually obtained a few degrees outside the centre of the fovea but fine details (e.g. reading letters) are not possible under scotopic conditions.

3.2.2. Adaptation, accommodation and other pupil reactions

The iris of the human eye forms a small pupil (ca. 2 mm) with high retinal illumination and a large pupil (ca. 8 mm) with low retinal illumination. This change in pupil size due to lighting conditions is known as the pupillary light reflex (PLR). The diameter of the pupil $D_p$can be determined by the following equation:

$$D_p = 7.75 - 5.75 * \left(\frac{x}{x+2}\right)$$

with

$$x = \left(\frac{L * \alpha^2}{846}\right)^{0.41}$$

Where

L is the luminance of the luminous surface in cd/m^2,

α is the visual angle of the luminous surface in degrees.

In addition to the pupillary light reflex and other neural influences, there is the pupil near response (PNR). When light or luminous objects approach the human eye, the pupil constricts. Lenses cannot refract light rays at their edges as well as they can closer to the centre. A smaller pupil size reduces the image error caused by spherical aberrations (somewhat blurrier image around the edges) and simultaneously increases the depth of field, i.e. the range of distances at which an image can be in focus or the effective focus range.

While the impulses of cones and rods are responsible for the immediate change in pupil size resulting from a change in lighting conditions, the pupil size under constant lighting conditions is retained by the impulses from ganglion cells. A small subset of retinal ganglion cells is intrinsically photosensitive (ipRGCs)(Münch et. al) and respond directly to light without inputs from the photoreceptors. The photopigment in ipRGCs is melanopsin which is sensitive to light around 480 nm. Apart from mediating pupil constriction, ipRCGs are directly linked to the suprachiasmatic nucleus of the brain which constitutes the body’s master clock (e.g. regulation of sleep, body temperature, blood pressure, stress hormones etc). Stimulation of ipRGCs is essential for circadian photoentrainment, i.e. constant readjustment of the body clock to the external light conditions (solar clock).

Adaptation is the adjustment of the eye to different illumination levels or light conditions. Adjustment to dark luminous environments is called dark adaptation, adjustment to light luminous environments is called light adaptation. Full dark adaption is usually obtained within 30 minutes, full light adaptation is shorter and is usually obtained within 10 minutes. Glare may influence visual function by re-setting the adaptational level to the brightest light source in the visual scene rather than the lighting on the visual task ahead (e.g. parts of machinery that needs adjustment as part of job related tasks). The pupillary light reflex is part of the adaptation process of the eye, as is the transition from photopic vision (via the cones) to scotopic vision (via the rods) through the mesopic range (in which both cones and rods are active), as well as the photochemical changes of the photopigment concentration in the receptors and the neuronal processes in the retina (neural adaptation). This adaptation process allows the eye to recognise objects across a luminance range from 10^{-6} to 10^5 cd/m^2. The change in pupil size covers a factor of 16, the transition from photopic to scotopic vision a factor of 100. However, changes in pupil size are greater for younger individuals and markedly reduced in older subjects. The largest impact in adaptation is attributed to the photochemical processes.

To reach the highest possible visual performance in a particular luminance range, the eye requires a certain adaptation time. Light adaptation is much faster (20 to 60 seconds) than dark adaptation (up to 30 minutes for complete dark adaptation). The adaptation process is very much determined by the starting and ending luminance average across the whole visual field. Normally, the retina adapts uniformly across its whole area. This is known as global retinal adaptation (GRA). When the fixation point of the observer remains constant for a specific luminous scene (i.e. the observer stares at a fixed point for a longer period), different regions of the retina can adapt independently to different luminances in different regions of the visual field. This is called local retinal adaptation (LRA). For longer observations with constant fixation point, this can lead to a loss of perceived contrast across the visual field.

Depending on the spectral distribution of the light, the three types of cones will be in different adaptation states. With changes in spectrum, each cone type adapts independently of the others. This is known as spectral adaptation.

3.3.Pupillary Response to Light

The function of the pupil is to adjust the amount of light reaching the retina. In this respect, the pupil functions an aperture. The size of the pupil is determined by the relative actions of the dilator muscle (makes the pupil greater) and the sphincter muscle (decreases pupil size). The action of the dilator muscle is regulated by sympathetic autonomous nervous system. The sympathetic nerve originates in the superior cervical ganglion of the sympathetic chain and travels along the cervical spine, through the upper thorax and via the internal carotoid artery into the skull and via the cavernous sinus it exits the skull and enters the orbit via the orbital fissure. The sympathetic nerve enters the eye via the arterial vessels.

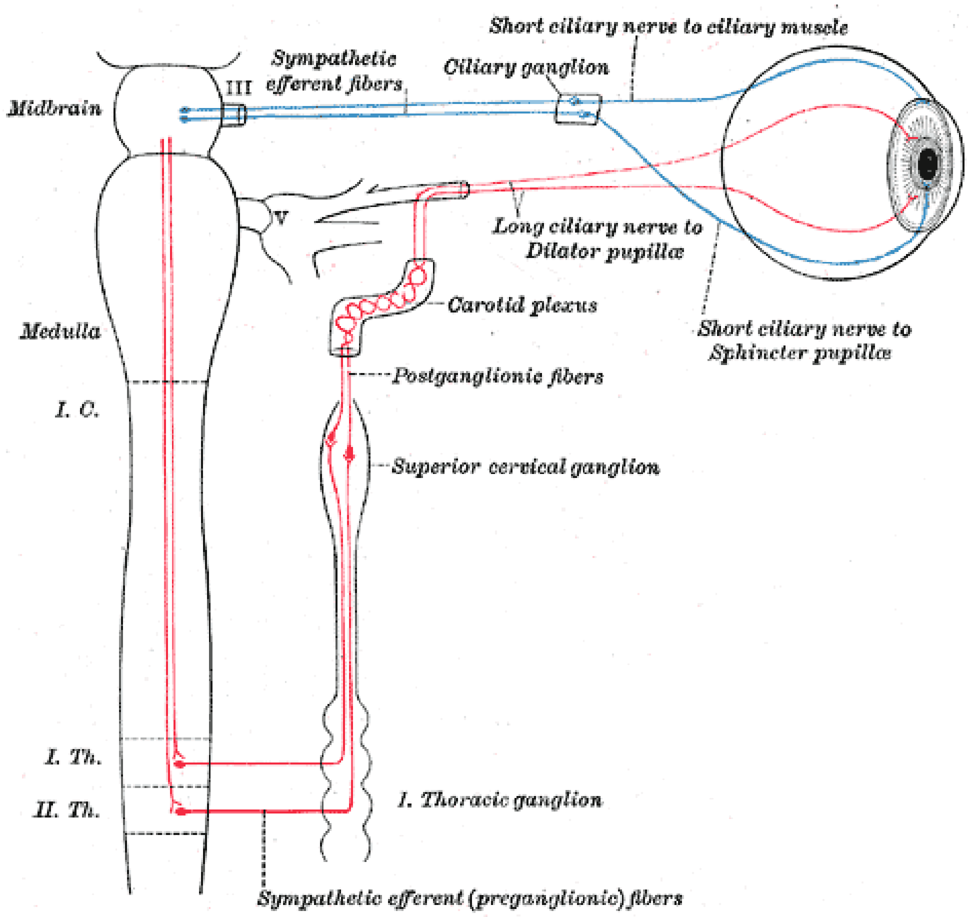

Figure 3-2 Central nervous pathways regulating the pupillary sphincter and dilator muscle (Gray, 1918)

The action of the sphincter muscle is regulated by the parasympathetic autonomous nervous system that travels to the iris via the oculomotor nerve. In addition to decreasing the size of the pupil, the oculomotor nerve also regulates the motility of the eye (especially up and downwards movements as well as movement of the eye towards the nose). The parasympathetic nerves enter the eye via the ciliary ganglion at the side of the eye. See Figure 3-2.

The above-mentioned pathways constitute the efferent pupillary light reflex. An efferent nerve tells the muscles what to do and regulates muscle tension.

The action of the parasympathetic and sympathetic nerves regulating the pupil size are in turn regulated via the Edinger-Westphal nucleus of the brain. This part of the pathway constitutes the afferent pupillary reflex. Afferent nerves convey sensory information to the central nervous system. The sensory information to the Edinger-Westphal nucleus is transmitted via the optic nerve. The light sensing (non-image forming) functions of the eye are located in a special subset of retinal ganglion cells (intrinsically photosensitive ganglion cells, ipRGCs). These cells are intrinsically photosensitive, which means that they respond directly to light without stimulation by from the photoreceptors but their action is also regulated by inputs from both rod and cone photoreceptors. See Figure 3-3 For the afferent pupillary light reflex.

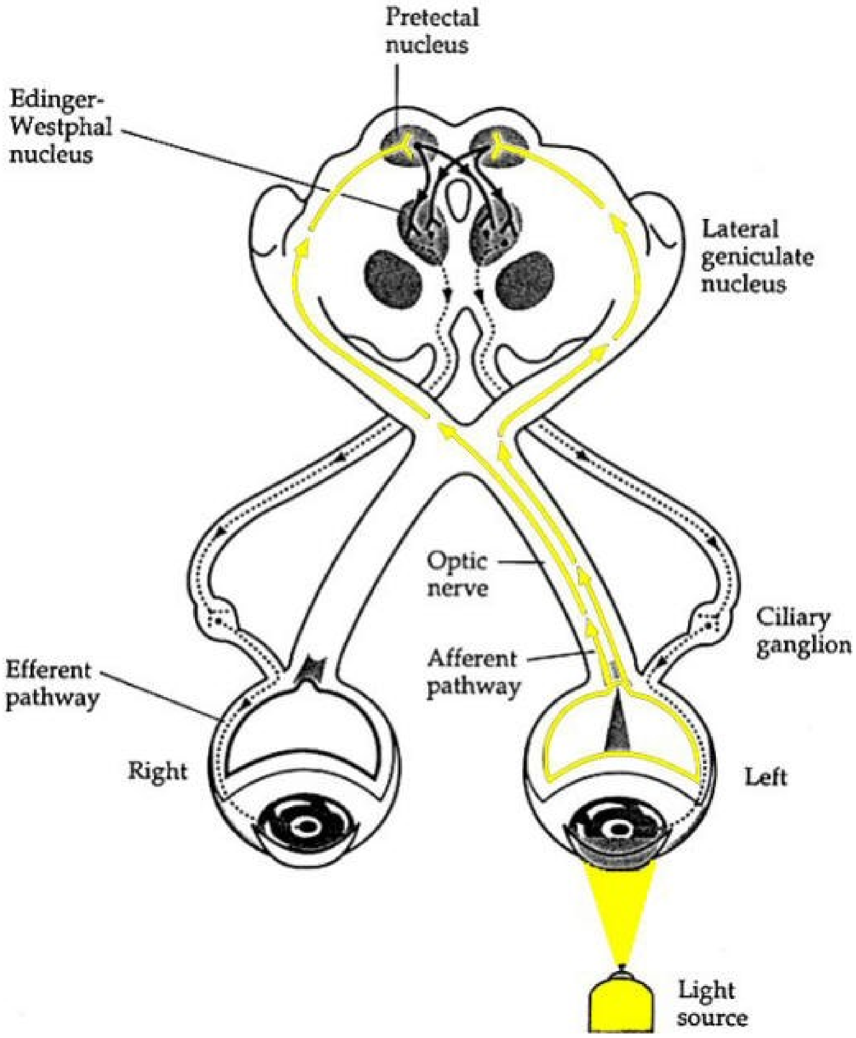

Figure 3-3 Pupillary light reflex (Wei Xiong)

The pupillary light reflex is paired between the eyes which mean that light entering one eye will regulate pupil size of both eyes. If there is a lesion of the optic nerve on side, this eye will contribute less to the regulation of the pupil size than the other eye, but the pupil size of the eye with the poor optic nerve will be the same as the pupil size on the eye with the better optic nerve, this is called relative afferent pupillary defect (RAPD). On the other hand, trauma to the iris (e.g. blunt trauma) may damage the iris sphincter and hence the pupil will remain big because of loss of action of the sphincter muscle. This will result in one eye having a large pupil and the other eye having a small pupil (anisocoria). Such damage is often permanent, e.g. Davie Bowies black left eye versus his normal blue right eye. Anisocoria can also be caused by infections (most often chicken pox in children), nerve damage (e.g. Horner syndrome when the sympathetic nerve is damaged by thoracic tumours of accompanying damage to the internal carotid artery) or be physiologic (e.g. 20% of “normals” will have varying degrees of anisocoria).

Apart from the above mentioned pupillary reflexes, a second mechanism adjusts pupil size: near-reflex. When objects are viewed at a close distance, the eyes converge, the ciliary body contracts and releases the tension on the lens of the eye allowing the lens to take a more spherical shape which moves the focal point of light rays reaching the retina (accommodation). The pupil constricts as the eyes converge and accommodates. Pupil constriction allows for larger depths of field and hence increases visual function. See Figure 3-4. Visual stimuli originating from less than 6 meters distance will induce an accommodative response and may hence, in theory, affect pupil size.

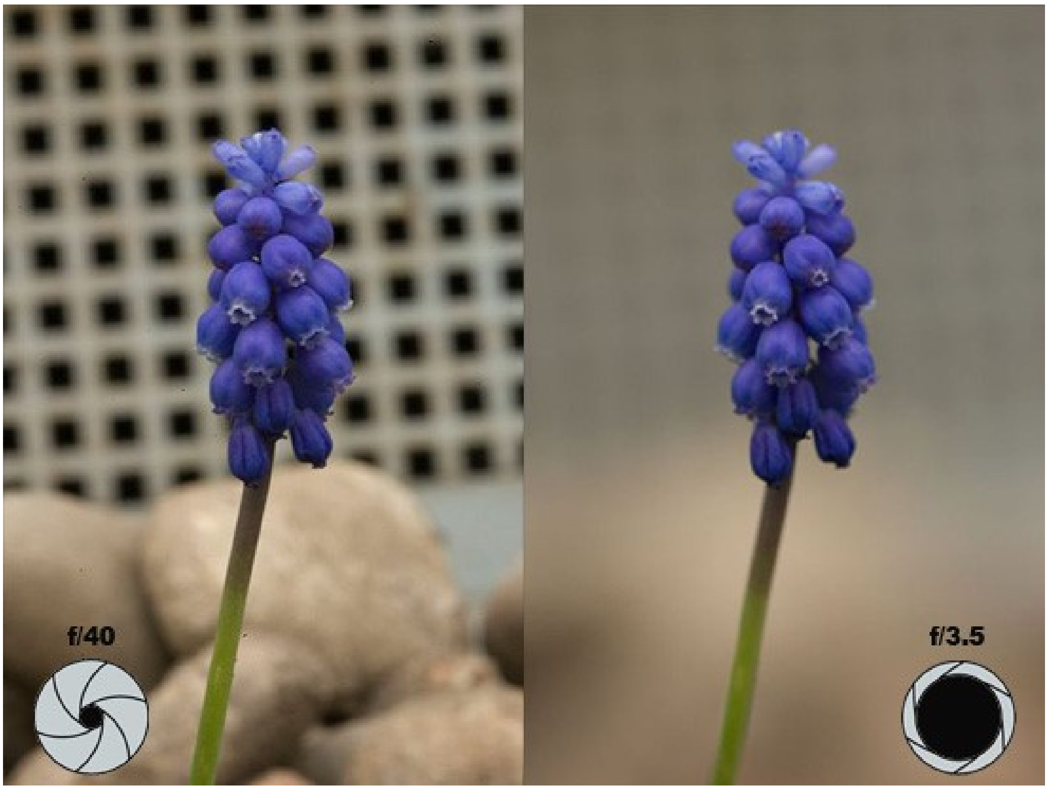

Figure 3-4 Effect of the aperture (in a camera "f-stop") on depth of field. A wider aperture will cause a shorter depth of field. (Moura)

Further, variations in pupil size are considered to be a reliable indicator of autonomic nervous system (ANS) activity. Importantly, pupil diameter is affected not only by changes in ambient light (the pupillary light reflex), but also by non-visual stimuli as well as cognitive load and affective processing. Indeed, pupillary dilation has been observed in response to emotionally relevant visual or even auditory stimuli (Gingras, 2015).

To summarize the above, the pupil diameter is governed by several involuntary reactions that include:

- Reacting to amounts of light shining into the eye (or the other eye) – up 4 mm changes (adaptation)

- Focussing on objects closer than approximately than 6 m from the eye (accommodation)
- Emotional responses, rarely greater than 0,5 mm or 20% increase
- Other stimuli might include colour, luminance patterns, and contrasts in the field of vision

Consequently, when designing a study that focusses on glare (i.e. large contrast/uncomfortable luminance patterns in the field of vision) and pupil reactions it is important to keep other factors as steady as possible.

3.3.1. Normal Subjective Response Variations due to Age, Sex, Eye Colour etc.

The visual system of people generally has the same structure, but there are individual differences that can be observed when different people assess the same lighting situation or are asked to perform visual tasks under such conditions. Many of such differences are typically ignored when considering lighting design for use by the general population. However, there are some differences sufficiently large that their effects need to be considered in some lighting applications. This is especially important when designing lighting systems for the aged and partially sighted.

As the human visual system ages, changes in structure and capabilities become evident. The first and usually most obvious change at around 45 years of age is the ability to focus at near-working distances (around 40 cm), a loss of accommodative function. This is known as presbyopia and can be corrected with optical help, e.g. glasses or contact lenses. At age 60, the visual system will usually have lost most accommodative function and the majority of the population essentially has a fixed-focus optical system. The loss of accommodation is related to loss of elasticity of the lens of the eye. The loss of elasticity is caused by aggregation of proteins in the lens cells. The aggregated proteins scatter light. Thus, loss of accommodation is usually accompanied by increased light scatter.

With increasing age, the pupil of the human eye becomes progressively smaller. The pupil size of a 75-year-old person is approximately 70% of the size of a 20-year-old. This results in a lower retinal illuminance and thus a reduced capacity to see under dim lighting conditions. On the other hand, the smaller pupil compensates somewhat for the lack of focussing ability because it increases the depth of field of the eye and to some extent it reduces the effect of light scattering in the lens.

As the lens ages, it gradually becomes cloudy (cataract). The aged lens preferentially absorbs short wavelength (those wavelengths required for entrainment of circadian rhythms by the ipRGCs and suprachiasmatic nucleus and for scotopic vision). With ageing, the retina often deteriorated (age-related macular degeneration) leading to loss of visual acuity and likely also to increased scatter in the central part of the retina. There is a gradual loss of retinal ganglion cells with age. In patients with glaucoma, the loss of ganglion cells is rapid and this reduces the function of the optic nerve and hence transmission of visual stimuli from the eye to the brain. The combined outcome of these modifications with increasing age are reduced visual acuity, reduced contrast sensitivity, reduced colour discrimination, increased time needed to adapt to large and sudden changes in luminance, and increased sensitivity to glare.

Problems with partial sight such as cataracts, macular degeneration and glaucoma can result in other changes to the ability to see effectively.

3.3.2. Pupil Size Changes and Glare

While alternative sources of light-produced visual discomfort have been suggested, one of the more dominant concepts discussed in the literature is that changes in pupil size are a key causative factor for the discomfort (King, 1976).

Research on the relationship between pupil size and visual comfort perception has been conducted on various occasions. Fry and King (1975) argue that "in order to build a comprehensive theory of discomfort glare it is necessary to deal with the case of steady stimuli applied to the eye as well as [with] momentary and intermittent stimuli.” They analysed the pupil fluctuations in four steps to obtain a baseline with which the actually resulting pupil size changes can be determined.

Fugate and Fry (1956), following up on earlier work by Luckiesh and Guth (1949) on brightness in the visual field at the borderline between comfort and discomfort (BCD), suggest that the BCD level under conditions of momentary exposure to bright light sources of varying angular size in the visual field is three or more log units above the threshold of the pupillary response and the pupil undergoes at the BCD a constriction of the order of 1.5 mm. The pupil constriction varies with stimulus size and stimulus location in the visual field, but the authors indicate that it was possible to determine a level of brightness which they called the threshold of involuntary blinking (TIB). They also found that variations in initial pupil size of individuals made it necessary to analyse data in terms of changes in pupil size instead of absolute values.

Hopkinson (1956) at the Building Research Station in the UK investigated glare discomfort and pupil diameter and concluded that the pupil diameter by itself cannot be used as an objective indicator of the degree of glare discomfort. Experiments showed that discomfort glare could vary between imperceptible and intolerable without any change in pupil diameter. When the eye is subjected to intolerable glare, the pupil not only contracts, but varies in diameter, opening and closing irregularly once every few seconds. Similar variations also occur when the subject focusses on a specific fixation point even in the absence of glare.

Fry and King (1975) attempted to develop a method for analysing the components of pupil fluctuations in order to sort out the environmental factors that generate discomfort, and factors that minimise or prevent discomfort.

Since the early days of pupil size research, technical developments have now made new methods available for researchers.

Lin et al. (2015) used new analysis approaches employing electro-oculogram (EOG) and Tobii glasses to document eye movements and pupil size in order to investigate the relationship of these measures to the experience of discomfort glare. The deBoer rating scale for discomfort glare was used to assess the subjective responses to glare of ten young (mean age 24.5 years) and ten senior participants (mean age 61 years). There was a high correlation with eye movement ($R^2>0.94$, $p<0.001$) and pupil constriction ($R^2=0.38$, $p<0.001$). Severe glare resulted in faster eye movements and larger pupil constriction. Seniors exhibited larger variations in eye movements. Pupil constriction and eye movements appear to be highly correlated with discomfort glare assessment and could be an objective approach to characterise and assess discomfort glare. Such measures could eliminate common problems found with subjective evaluation. Increased eye movements and pupil constriction also suggest why exposure to discomfort glare over longer periods can lead to visual fatique and eye strain.

While vertical illuminance at the eye from both ambient lighting and glare source and horizontal displacement angle between fixation point and glare source were found to be important factors in the assessment, correlated colour temperature (CCT) was not found to be significant for influencing visual discomfort. However, the authors suggest that CCT as a single number for describing complex spectral power distributions (SPD) might not be sufficient to capture the impact of spectral effects.

Eye Movement and Pupil Size Constriction Under Discomfort Glare (PDF Download Available). Available from: https://www.researchgate.net/publication/271519864_Eye_Movement_and_Pupil_Size_Constriction_Under_Discomfort_Glare [accessed Aug 22, 2017].

3.4. Visual Field Considerations (Position Indices)

3.4.1. Field of View

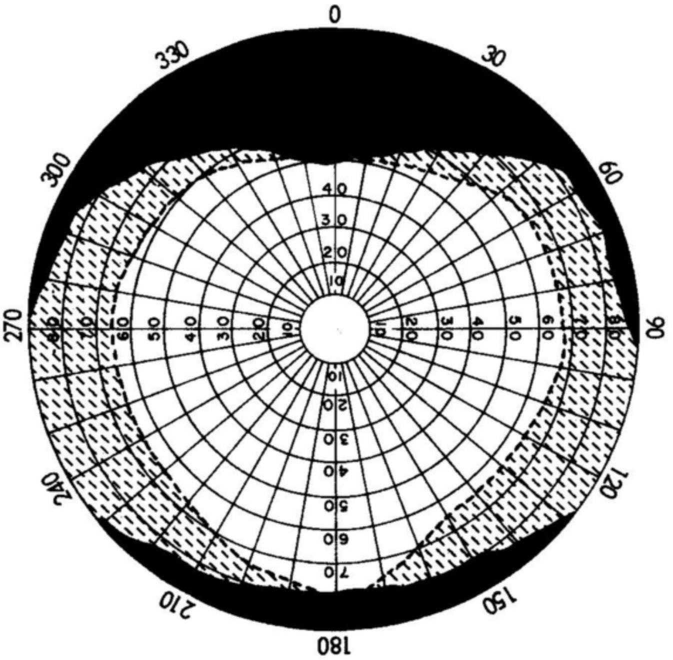

Figure 3-5 This diagram shows the normal field of view for both human eyes. The central white area represents the region seen by both eyes. The grey areas, right and left, represent the regions seen by the right and left eyes, respectively. The black area represents cut-offs by brows, cheeks, and nose. (Ruch and Fulton 1960)

The field of view of humans is a stereoscopic vision due to the placement of the eyes in the orbits. This allows humans to be able to judge a distance relatively accurately and to see in 3 dimensional views. The placement of the eyebrows, noise and cheeks restrict us from seeing an entire hemisphere but they also protect the eye from excessive sun light. The highest visual acuity is at an angle f +/- 2.5 degrees away from the fovea centralis and the field of stereoscopic vision is outlined in the figure below (Jacobs, 2004).

With fixed stereographic vision, humans are considered to see a field of 120° horizontally, as well as vertically. This can be approached with a 20 mm lens on a 35-mm film.

But these angles must be extended to take into account:

- Movement of the eye with a fixed head (extension of these angles)
- Movement of the head (mostly horizontal) Use of panorama type pictures

4. Modelling Discomfort Glare in Buildings

Although occupants experience discomfort glare, it may not necessarily mean that they notice any effect on their performance. They may also not attribute the subsequent experience of after-effects such as irritation or headaches to their previous experience of glare.

It might nevertheless affect their perception of the visual environment, well-being, performance, and maybe in the long term also their health. This is why it is important to detect and reduce the risk of discomfort glare.

Although research into the effects and underlying processes of glare has been on the agenda for lighting and vision in the 20th century, the understanding of it is still very much incomplete. Over the years, several glare models have been proposed for the prediction of the discomfort glare. These models combine the following variables into mathematical formulas to match the results of empirical research to the measured photometric data for the luminous conditions.

Most glare research has been focusing on glare from different electric light sources, but specific problems are related to glare from daylight because of its variation in luminance and patterns. This is due to changes in sky conditions such as cloud cover, solar altitude and time of day and year.

In daylight situations, the window causes glare, because the luminance is often not uniform and quite high, especially if direct sunlight occurs, and frequently covers a large part of the visual field. Glare from daylight in buildings can for example be a problem in computerised office environments, as computer screen and windows are both in vertical planes and frequently in close proximity. The luminance in the part of the window area dominated by the sky is frequently very high, which causes a large luminance contrast between the window and the computer screen. But the occupants appreciate other amenities provided by the window, such as the diffuse skylight and the view. This explains why glare from daylight is often more accepted than glare of the same magnitude from electric light sources.

This is also a reason for separate glare indices for daylight and electric light sources.

Different existing indices:

- British Glare index (BGI)
- Discomfort Glare Index (DGI)
- CIE Glare Index (CGI)
- Unified Glare Rating (UGR)
- Discomfort Glare Probability (DGP)
- Predicted Glare Sensation Vote (PGSV)

4.1. Review of Basic Methods to Evaluate Discomfort Glare

4.1.1. History of Glare Indices for Electric Lighting

Much research has been conducted on discomfort glare, especially in the earlier part of the 20th century. From that research, the main variables that affect the experience of discomfort glare have been established:

- the luminance of the glare source,
- the luminance of the overall field of view or background to which an observer's eyes are adapted (this may also include the glare source),

- the visual or projected angular size of the glare source, and
- the relative position of the glare source in relation to an observer's focal point.

To assess different lighting systems and their effect on the visual comfort of observers, methods are needed to objectively compare one lighting installation with another. Over the years, several models have been proposed to aid in the prediction of discomfort glare. These models combine the above variables into mathematical formulae to match the results of empirical research relating subjective responses of observers to measured photometric data of the luminous conditions presented. The various models differ slightly in the coefficients and exponents associated with the above variables and in the way, that they combine the effects of more than one glare source on the overall sensation of discomfort glare. The earliest experiments were conducted with small incandescent point sources against a uniform background. With the arrival of fluorescent lamps, linear glare sources and even large area glare sources were analysed. In order to develop an appropriate Glare Index for daylight, the history of glare indices, their parameters and limitations are reviewed. A useful review paper on various aspects of glare perception is presented by Clear (2013).

Luminance (L_s) of Glare Source

In the case of discomfort glare from electric lighting, all luminaires in a space for which the light source is visible to the eye can be considered potential glare sources. The luminance of a glare source can be measured from the observer's eye position.

In the case of discomfort glare from daylight, the glare source will most likely not have a uniform distribution across the daylight opening and the sky, so the source luminance should be the average luminance of the sky as seen through the window, or the average luminance of the whole window area.

For glare sources which result from reflections of light on highly reflective surfaces, it is also advisable to take an average luminance of the bright patch on the surface.

Background Luminance (L_b)

The background luminance is the normally defined as the average luminance across the visual field, but excluding the potential glare source(s). Because the glare sources typically occupy only a rather small area of the visual field in electric lighting applications, this average luminance usually represents the occupant's adaptation luminance against which the glare source luminance is seen.

In the case of discomfort glare from daylight, the background luminance (average luminance across the visual field excluding the potential glare source(s) such as windows or skylights) would normally be lower than the adaptation luminance, because the daylight openings tend to be large compared to those of electric luminaires and thus clearly affect the adaptation level.

Solid Angle Subtended by the Glare Source (ω) – Apparent Size

In the case of glare assessment from electric lighting, the solid angle of all visible electric light sources should be calculated.

For daylight glare assessment, the apparent size of the visible area of sky at the observer's eyes needs to be determined.

Guth Position Index (P)

The position index (Guth, 1963) expresses the change in discomfort glare experienced relative to the angular displacement (azimuth and elevation) of the source from the observer's line of sight. The position index is the ratio of luminance at an arbitrary position to the luminance on the line of sight that causes the same glare sensation. The analytical description for the position index located above the line of vision is:

$$lnP(\gamma,\sigma) = \left(35.2 - 0.31889\gamma - \ 1.22e^{\frac{-2\gamma}{9}}\right) \cdot 10^{-3}\sigma + (21 + 0.26667\gamma - 0.002963\gamma^2) \cdot 10^{-5}\gamma^2$$

Where:

γ is the $\tan^{-1}(x/y)$ [deg]

x and are the horizontal and vertical distances [m] between the point of view and the source respectively

σ is the angle between the line of sight and line from the observer to the source [deg]

To calculate the position index for the visual field below the line of sight, an equation was proposed by Einhorn on the basis of Iwata and Tokura (1998). However, the equation produces a discrepancy at the horizon line.

$$P = \ 1 + 0.8 \times \frac{R}{D} \ (R < 0.6D)$$

$$P = \ 1 + 1.2 \times \frac{R}{D} \ \ (R \geq 0.6D)$$

$$\mathrm{R} = \sqrt{H^2 + Y^2}$$

Where:

D is the distance between eye and plane of source in view direction

H is the vertical distance between eye and plane of source

Y is the horizontal distance between eye and source and view direction

British Glare Index (BGI)

In parallel with the work of Guth in the United States of America, Hopkinson embarked on extensive discomfort glare studies at the Building Research Station (later Building Research Establishment) in Great Britain between the late 1940s and early 1970s. He used a set of four semantic discomfort glare descriptors for his studies and proposed a glare assessment formula based on the four major variables mentioned above, known as the British Glare Index.

The British Glare Index first calculates a glare sensation rating for an individual glare source based on the main variables discussed above. Then the effect of several glare sources is established by simple addition (summation).

$$\mathrm{BGI} \ = \ 10 \log 0.478 \sum_{i=1}^{n} \frac{{L_s}^{1.6}{\omega_s}^{0.8}}{L_b P^{1.6}}$$

Where:

L_s: luminance of the glare source [cd/m^2]

ω_s: solid angle subtended by the source [sr]

L_b: luminance of the background [cd/m^2]

P: position index (Guth, 1963), the angular displacement of the source from the observer's line of sight [-]

n: number of glare sources.

Critics (e.g. Einhorn, 1979) point out that Hopkinson's formula places more weight on the adaptation or background luminance than other findings (Soellner 1965, Collins and Plant, 1971), a factor that might be related to how Hopkinson conducted his research.

Hopkinson essentially used a shoe-box model set-up viewed by an observer through an opening at one end and an opaque photograph representing a room interior at the opposite end. The photograph had small holes cut into it that were backlit from outside the box by a diffused projector lamp connected to a variable transformer. These backlit holes represented potential glare sources in the shape and appearance of diffusing globe luminaires.

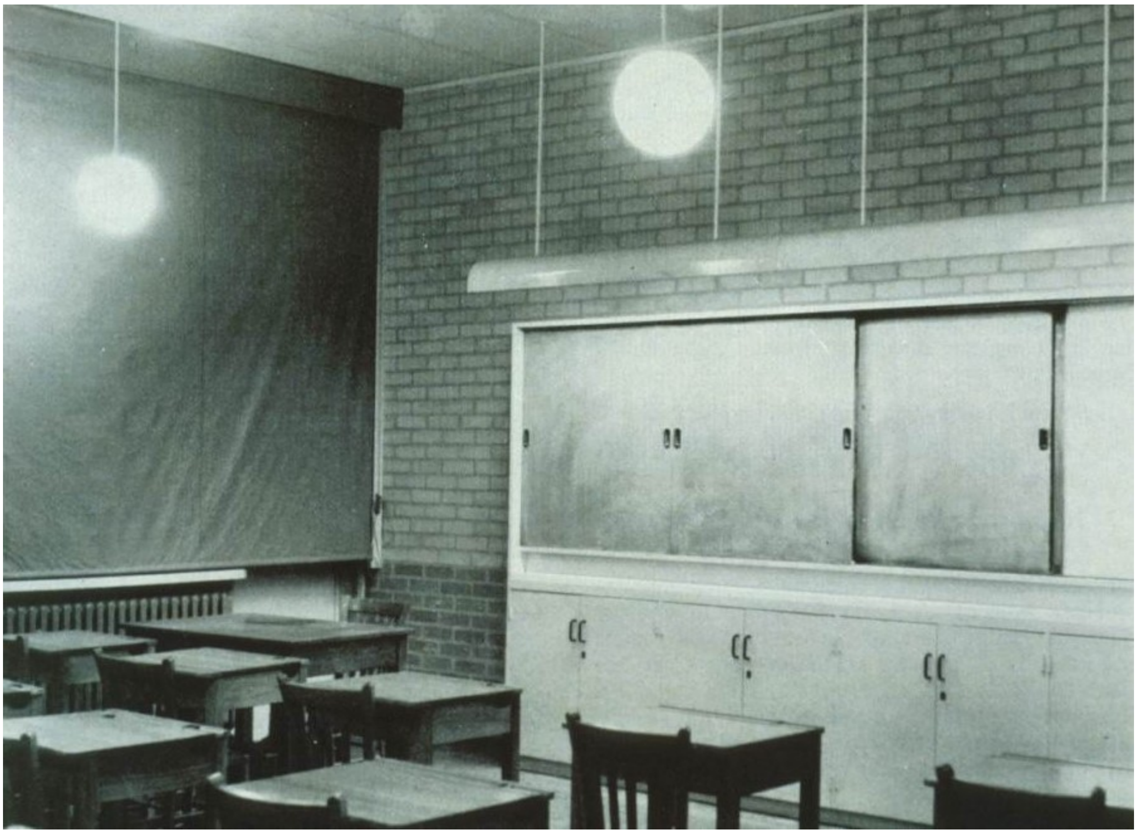

Figure 4-1 Hopkinson's experimental set-up. (Hopkinson. Architectural Physics: Lighting, 1963)

The interior of the box was illuminated by separately controlled lamps shielded from the view of the observer. These lamps determined the brightness of the room interior or background luminance (adaptation luminance) against which the glare sources were seen.

Under "real" lighting conditions, the source luminance of globe luminaires suspended in the room would directly affect the luminance of the room surfaces, thereby linking source and background luminance. In Hopkinson's experiment, background and source luminance were essentially de-coupled. He could increase the glare source luminance without affecting the background luminance, perhaps making the background luminance more influential in the glare appraisal process.

In addition, Hopkinson's selection of observers on the basis of consistency over a period of many days may appear out of line with human nature. Hopkinson eliminated observers who were unable to make consistent observations, resulting in only six observers making the final cut for participating in the experiments that form the basis of his findings which lead to the establishment of the British Glare Index (Hopkinson 1963, Architectural Physics: Lighting, p 204). The British Glare Index is limited to small sources with solid angles less than 0.027 sr.

The British Glare Index is no longer a recommended glare appraisal method. The 2002 CIBSE Code for Lighting (CIBSE, 2002) recommended the Unified Glare Rating (UGR).

Visual Comfort Probability (VCP)

The Visual Comfort Probability (VCP) method was officially adopted by the Illuminating Engineering Society of North America (IESNA) with the publication of the 1984 IES Lighting Handbook: Reference Volume (IESNA, 1984). VCP is based on discomfort glare research originally conducted by Luckiesh, Holladay, Guth and their collaborators between 1925 and 1964. That research established links between the psychological appraisal of lighting installations and their photometric descriptors and in particular the boundary conditions for glare at the borderline between comfort and discomfort (BCD).

$$\mathrm{VCP} = \frac{100}{\sqrt{2\pi}} \int_{-\infty}^{6.374-1.3227 \ln DGR} e^{-t^2/2}\, dt$$

$$\mathrm{DGR} = \left(\sum_{i=1}^{n} M_i \right)^{n^{-0.0914}}$$

$$M = \frac{0.50 L_s Q}{P F_v^{\,0.44}}$$

$$Q = 20.4\omega_s + 1.52\omega_s^{\,0.2} - 0.075$$

$$F_v = \frac{L_w \omega_w + L_f\, \omega_f + L_c \omega_c + \sum L_s\, \omega_s}{5}$$

Where

L_s: average luminance of the source [cd/m^2]

ω_s: solid angle subtended at the observer by the source [sr]

L_w: average luminance of the walls [cd/m^2]

ω_w: solid angle subtended at the observer by the walls [sr]

L_f: luminance of the floor [cd/m^2]

ω_f: solid angle subtended by the floor [sr]

L_c: luminance of the ceiling [cd/m^2]

ω_c: solid angle subtended by the ceiling [sr]

P: position index, the angular displacement of the source from the observer’s line of sight [-]

n: number of glare sources

Visual Comfort Probability describes the likelihood that an observer experiences comfort when viewing a lighting system. The VCP system first calculates a glare sensation rating for an individual glare source based on the main variables discussed above. Then the effect of several glare sources is established by summation before the combined discomfort glare rating is converted into a percentage of observers who would assess the respective lighting installation as acceptable. The VCP ranges from 0 to 100. The higher the VCP value, the greater is the probability that observers will assess the lighting system as comfortable.

There is, however, a significant drawback. The VCP system has only been tested and validated using ceiling-mounted, lensed, direct fluorescent luminaires of typical sizes and uniform luminance. It should not be applied to very small light sources such as incandescent and high-intensity discharge lamps or LEDs, or to very large sources such as luminous ceilings and indirect systems, or to non-uniform sources such as parabolic reflectors (IESNA, 2000). By extension of the argument the exclusions would also apply to the assessment of glare from daylight sources as they tend to be large and non-uniform. These restrictions essentially state that VCP is not an appropriate discomfort glare appraisal tool for many common lighting solutions experienced in today’s lighting design practice. Discussions in the IESNA are ongoing to consider an alternative metric for discomfort glare assessment, currently favouring the Unified Glare Rating (UGR) system.

CIE Glare Index (CGI)

The CIE Glare Index, published by the International Commission on Illumination in 1983 (CIE, 1983), was developed by a technical committee under the leadership of Einhorn and attempted to combine the best points of the major discomfort glare evaluation systems in use around the world. All previously available and peer-reviewed glare prediction methods were compared and correlated. No new perception studies with human observers were conducted during the development of the CGI metric.

The CGI formula is essentially split into two components, one describing the luminous environment of the room and one describing the combined effect of luminance, size and location of the glare sources.

$$\mathrm{CGI} = C_1 \times \log C_2 \frac{\left(1 + {}^{E_d}\!/_{500}\right)}{(E_d + E_i)} \sum_{i=1}^{n} \frac{{L_s}^2 \omega_s}{P^2}$$

Where

E_d: direct vertical illuminance at the eye due to all sources [lx]

E_i: indirect vertical illuminance at the eye ($E_i = \pi * L_b$) [lx]

L_s; luminance of the glare source [cd/m^2]

ω_s: solid angle subtended by the source [sr]

P: position index (Guth 1963), the angular displacement of the source from the observer’s line of sight [-]

n: number of glare sources

C_1,C_2: optional scaling coefficients

For optional scaling coefficients of $C_1 = 8$ and $C_2 = 2$, CGI values above 28 would be considered intolerable, while those below 13 would be considered imperceptible (see UGR below).

In contrast to previous methods, this glare index includes the glare source contribution to the adaptation luminance of the observer in the description of the luminous environment of the room, expressed through the direct vertical illuminance at the eye. This should be an advantage when assessing large area glare sources surrounding or adjacent to an observer’s visual task. Under such conditions, one would expect a large glare source to significantly contribute to the adaptation of the observer as it would essentially be part of the larger background against which the observer would view the task as well as the glare source(s).

It is important to note that the formula includes an exponent of 1 for the solid angles of the glare sources. Varying subdivisions of glare sources will thus yield the same results in the overall assessment of glare.

Unified Glare Rating (UGR)

Sørensen simplified the CIE Glare Index and developed the Unified Glare Rating which was adapted by the International Commission on Illumination in 1995 (CIE, 1995). While indeed providing a simpler calculation procedure, the potential glare source contribution to an observer’s adaptation, the direct illuminance at the eye, has been omitted. The Unified Glare Rating retains the component of the CIE Glare Index describing the combined effect of luminance, size and location of the glare sources in its formula. The description of the luminous environment of the room, however, is again reduced to the background luminance without inclusion of the glare sources. The CIE document states that “for practical purposes this has little effect when the formula is applied to rooms having illuminances within the usual range recommended for working interiors”.

$$\mathrm{UGR} = 8 \times \log \frac{0.25}{L_b} \sum_{i=1}^{n} \frac{{L_s}^2 \omega_s}{P^2}$$

Where
L_s: luminance of the glare source [cd/m^2]
ω_s: solid angle subtended by the source [sr]
L_b: luminance of the background [cd/m^2]
P_s: position index, the angular displacement of the source from the observer's line of sight [-]
n: number of glare sources

Sørensen simplified the CIE Glare Index and developed the Unified Glare Rating which was adapted by the International Commission on Illumination in 1995. While indeed providing a simpler calculation procedure, the potential glare source contribution to an observer's adaptation, the direct illuminance at the eye, has been omitted. The Unified Glare Rating retains the component of the CIE Glare Index describing the combined effect of luminance, size and location of the glare sources in its formula. The description of the luminous environment of the room, however, is again reduced to the background luminance without inclusion of the glare sources. The CIE document states that "for practical purposes this has little effect when the formula is applied to rooms having illuminances within the usual range recommended for working interiors".

UGR uses a similar numerical scale as the Daylight Glare Index (DGI) – see below. However, UGR predicts intolerable discomfort at a lower threshold. Any value above 28 is considered to be intolerable, while values below 13 are considered to be imperceptible.

The UGR equation combines aspects of the CIE Glare Index and the British Glare Index and incorporates the Guth position index to assess the impact of glare source placement. However, its application is limited to sources with solid angles between $3 * 10^{-4}$ and $1 * 10^{-1}$ sr, equivalent to projected areas between 0.005m^2 and 1.5 m^2. Smaller sources would be penalised by the formula with too high glare ratings, larger sources would be treated too leniently. It has also been noted that the formula would not be accurate for assessing glare sources of high complexity. Supplemental recommendations have been published in 2002 to address those concerns (CIE, 2002).

For very small sources recommendations are based on research (Benz 1966, Paul 1997) which suggests that source intensity and projected area determine the glare sensation from sources smaller than 0.005 m^2, rather than luminance and solid angle. A slightly modified version of the original UGR equation is provided.

For sources larger than 1.5 m^2, but specifically excluding luminous ceilings and large uniform indirect lighting, the CIE recommends a fairly substantial modification to the original UGR equation. The document does not explain how this equation was derived. No supporting research is referenced.

For luminous ceilings and uniform indirect lighting systems, research (Hopkinson and Collins, 1963) suggests that a single formula would not accurately express the glare sensation from luminous ceilings and "an extension of the UGR formula would be too tolerant and permit unacceptable glare" (CIE, 2002). Instead, a simple table of average maintained illuminances with corresponding glare ratings is provided. It is not specified where the illuminance is measured, but presumably at work plane height. No information is provided on how the corresponding glare ratings were established.

For non-uniform indirect lighting, a term that is not defined in the document, an equation to establish an average room illuminance limit – presumably at work plane height – is recommended. It is assumed that this illuminance limit would yield a glare rating of 19. For other desired glare ratings multiplication factors are provided for the average room illuminance. It is interesting to note that when the average luminance of bright spots on the ceiling increases, the corresponding average room illuminance decreases. No research is referenced explaining the rationale for this recommendation. This would appear to be counter-intuitive. One would think that to achieve a lower illuminance at work plane height, the number of indirect luminaires or the effective luminance they provide at the ceiling plane would need to be reduced.

For complex sources, the CIE document differentiates between diffusing and specular luminaires. Diffusing luminaires are defined as having a luminance across the projected area of the luminaire that appears constant when viewed from a given angle, but will change with the viewing angle. Specular luminaires, on the other hand, are defined as having a luminance across the projected area of the luminaire that will appear constant regardless of the viewing angle. Two modified equations are therefore identified for calculating glare ratings from these two types of complex sources. For semi-specular luminaires, it is recommended to calculate the glare ratings from both equations and average them. Again, no supporting research is referenced and concerns are raised about the validity of these equations (Eble-Hankins and Waters, 2003).

Luminance-based indicators: ratio of mean over median luminance of the visual field

Osterhaus (2008) explored discomfort glare prediction via high dynamic range (HDR) Radiance images which were created on the basis of prior discomfort glare experiments for which observers had made subjective evaluations (Osterhaus, 1998). He explored relatively simple indices using mean, maximum and median pixel luminance (luminance-based indicators) for the whole visual field (2 π). He especially investigated the relationship between average (mean) and median values of the pixel luminances, as maximum pixel luminance is subject to outliers, and assessed via rank orders whether or not a direct correlation existed between these values and the subjective perception of discomfort glare expressed by observers in the earlier experiment now simulated with Radiance. The analysis revealed that images of those experimental conditions with the highest rating for glare discomfort indicated also the highest ratio of average (mean) and median pixel luminance values across the visual field. In comparing original and position index weighted images, it was found that the weighted images correlated better with the subjective glare assessment of the observers. Existing glare assessment methods (Daylight Glare Index, Unified Glare Rating und CIE Glare Index) for the same conditions resulted in parts in significantly less predictive correlations.

Since maximum pixel luminance is susceptible to outliers, it is recommended to use median values. It is desirable to further investigate and test the proposed method with other data and in other situations.

4.1.2. Knowledge Gained from Glare Index Review

Additivity (Summation)

In order to evaluate discomfort glare from several glare sources, simple addition is usually used. However, various researchers (e.g. CIE 2002) noted the incompatibility of some discomfort glare formula with the theorem of additivity (summation) of the glare source areas. If, for the sake of easier calculation, a large glare source is subdivided into different smaller areas with the same overall solid angle, different subdivisions result in different results for the glare index values. This is inconsistent with the observer’s experience. The total effect of the glare sources should be consistent, independent of the subdivision of glare sources. A glare index formula should be linear with the total solid angle of the sources. This means that the exponent of the solid angle must be 1. The summation of the individual areas of the source leads to an overestimated glare index when the exponent of the solid angle is less than 1, as shown in Figure 2.2., indicating the results of $\sum_{i=1}^{n}({\omega_i}^{a})$ when the total solid angle of all glare sources is 1 sr ($\sum_{i=1}^{n}({\omega_i}^{1})$ = 1 sr).

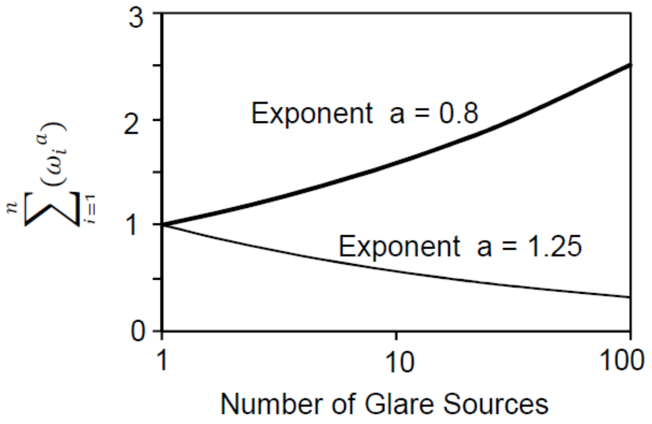

Figure 4-2 Additivity (summation) of glare sources does not work for exponents other than 1.

Applicable Range of Source Size

In order to apply the glare evaluation methods illustrated in 2.1 to discomfort glare from windows, the difference in source size between luminaires and windows must be taken into account. For the different glare evaluation methods discussed, the applicable ranges for the source size are shown Table 2.1.

Glare Index Metric	Range of solid angle of the source
British Glare Index (BGI)	up to 0.027 steradian
Visual Comfort Probability (VCP)	between $3 * 10^{-4}$ and $1 * 10^{-1}$ steradian
CIE Glare Index (CGI)	unknown
Unified Glare Rating (UGR)	between $3 * 10^{-4}$ and $1 * 10^{-1}$ steradian

Table 4-1 Glare indices and their applicable range of source size

Borderline between Comfort and Discomfort (BCD) vs. Glare Criteria

Lighting guidelines typically recommend limits for discomfort glare for different visual tasks or applications. These have been derived in experimental studies, especially in those assessing the borderline between comfort and discomfort.

For writing, typing, reading and data processing in an office, an upper Glare Index limit of 19 is suggested, while that for technical drawing is set at 16 to account for the added difficulty of the visual task, and that for a reception desk is set at 22, presumably because the visual task there is less demanding.

In his experimental work, Hopkinson applied criteria of ‘just imperceptible’, ‘just acceptable’, ‘just uncomfortable’, and ‘just intolerable’ to describe the various levels of glare a human subject might experience. ‘Just acceptable’ suggests that it lies at the boundary to being ‘unacceptable’. The term ‘acceptable’ suggests that the glare experienced by the occupant can be tolerated and that the glare is not in danger of being ‘unacceptable’. But it also says that there clearly is discomfort glare present.

There are serious difficulties coming to terms with the concept of ‘acceptable glare’ and the location of the borderline between comfort and discomfort (BCD) somewhere between ‘acceptable’ and ‘uncomfortable’ glare. If we are talking about discomfort glare as a phenomenon to be avoided in lighting installations, any discomfort glare that is ‘perceptible’ already constitutes ‘discomfort’ and should thus be placed on the discomfort side of BCD. While an observer might find slight discomfort ‘acceptable’, it could certainly not be classified as ‘comfortable’ as suggested by researchers like Hopkinson. The observer clearly experiences ‘discomfort’ by acknowledging that there is discomfort glare. There can be no ’comfortable’ discomfort glare.

The borderline between “acceptable” and “unacceptable” glare might depend on the type of space or the visual activity performed in it. Whether occupants accept certain levels of discomfort glare might also depend on whether there is daylight, whether there is a view out or whether an occupant perceives leaving the blinds open and accepting some glare might be more sustainable than closing the blinds and turning on electric lighting. But the differentiation between comfort and discomfort should not be confused with “acceptability”. Some occupants might accept very high levels of discomfort if that discomfort is somehow compensated by other factors of higher perceived value. Glare from the setting sun through a west-facing window might be more acceptable if it is combined with a view across the ocean rather than a view of an adjacent metal scrap yard - unless one is a scrap yard freak, of course.

But there is another problem with Hopkinson’s borderlines. The terms ‘just acceptable’ and ‘just imperceptible’ define borderlines which can only be approached from a condition of experienced discomfort glare which is gradually reduced until one no longer finds the experienced glare unacceptable or one is no longer able to perceive any glare at all. The other two borderlines of ‘just uncomfortable’ and ‘just intolerable’ assume that the discomfort glare experienced is increasing. It is therefore impossible to determine the borderline of ‘just imperceptible’ when one starts from conditions in which glare is not perceived to be present. It is equally impossible to determine the borderline of ‘just uncomfortable’ or ‘just intolerable’ if one starts from a condition with very high experienced discomfort. The word ‘just’ being added to all glare levels and the opposing directions of the various glare levels are creating difficulties which cannot be overcome. The blending of comfort and acceptability terms creates an equally insurmountable barrier. It compares apples with oranges. Hopkinson’s terms should therefore be abandoned.

One can, however, define borderlines between ‘imperceptible glare’ (glare is not perceived by the occupant) and ‘noticeable glare’ (glare is noticeable for the occupant), between ‘noticeable glare’ and ‘disturbing glare’ (glare is disturbing the occupant) and between ‘disturbing glare’ and ‘intolerable glare’ (glare cannot be tolerated by the occupant). The magnitude of the luminance contrast and thus the Glare Index number required to cross each borderline might vary from person to person and from time to time, but each person will be able to clearly determine such borderlines.

Recommended Glare Index limits will thus have to be average values determined in laboratory experiments or field studies with large numbers of subjects in order to be useful in practical applications. In addition, they should be combined with appropriate indications of variance to allow lighting designers to understand how many occupants might still perceive glare to be a problem even if one complies with the recommended Glare Index limits.

4.1.3. History of Daylight Glare Metrics

Glare indices developed for electric lighting conditions are not applicable to daylight situations. The main reason is the size of daylight openings which typically exceed solid angles of 0.01 steradians. In such a case it can be expected that the potential glare source covers a significant part of the visual field of the observer, thereby increasing the adaptation level of the eye and reducing the potential glare sensation and contrast effect. In contrast, when perceiving discomfort glare from small electric light sources, the observer’s adaptation level is virtually independent of the luminance of the small glare sources. The equations for such assessments are therefore only valid over the range of conditions where the adaptation level is determined primarily by the background luminances (Hopkinson and Bradley, 1960).

Glare indices for windows and daylight have therefore been developed.

“Cornell” Glare Index and “Chauvel” Glare Index: Daylight Glare Index (DGI)

The Daylight Glare Index was developed by Hopkinson on the basis of human subject research on large area uniform glare sources initially conducted at the Building Research Station in Britain and later also at Cornell University (Hopkinson 1963, Chauvel et al., 1982). The combined research resulted in a general equation for large sources known as the “Cornell Formula”. It is derived in its basic approach from the BGI shown in Chapter 2. Initially, a glare rating is calculated for each individual glare source. The glare ratings for all sources are then summed to determine the overall glare index.

$$\text{"Cornell" GI} = 10 \times \log 0.48 \sum_{i=1}^{n} \frac{{L_{si}}^{1.6} {\Omega_{si}}^{0.8}}{L_b + (0.07 {\omega_{si}}^{0.5} L_{si})}$$

Where:

L_{s}: luminance of the glare source [cd/m²]

L_{b}: average luminance of the background without the luminance of the glare source [cd/m²]

ω: solid angle subtended by the source [sr]

Ω: solid angle subtended by the source, modified for its position in the field of view by means of the position index *P* [sr] (Guth 1963)

For daylight glare assessments, the average sky luminance (typically assumed to be uniform), and the solid angle of the sky patch and its position index in the field of view are determined. The background luminance is slightly adjusted by the second term in the denominator, thus accounting to some extent for the influence of the luminance of the large (daylight) glare source and its position in the visual field on the adaptation level of the observer.

The use of the Cornell GI in the prediction of glare due to daylight is reasonably well supported by field research in hospital wards and school classrooms published by Hopkinson in the early 1970s (Hopkinson 1970, 1971 and 1972). However, there appears to be greater tolerance of observers to mild degrees of glare from the sky seen through windows than to glare from electric lighting sources of comparable size (Hopkinson and Collins 1970, Chauvel et al. 1982), although this tolerance does not extend to severe degrees of glare. To account for this, an analytical relationship between the glare indices for corresponding degrees of discomfort glare from daylight and from electric lighting was defined.

$$DGI = \frac{2}{3}(GI + 14)$$

This Cornell formula is often referred to as the Daylight Glare Index (DGI), particularly in the most recent publications on discomfort glare from daylight. It is also used for the calculations contained in this report.

However, some publications (e.g. Bellia et al. 2008, Nazzal 2001) mention another equation when referring to the Daylight Glare Index.

Chauvel (Chauvel et al., 1982) proposed a modification of the Cornell formula.

$$\text{Chauvel GI} = 10 \times \log 0.48 \sum_{i=1}^{n} \frac{{L_{si}}^{1.6} {\Omega_{si}}^{0.8}}{L_b + (0.07 {\omega_{si}}^{0.5} L_{wi})}$$

Where:

L_{s}: luminance of each part of the glare source [cd/m²]

L_{b}: average luminance of the surfaces in the visual field (presumably including the glare source) [cd/m²]

L_{w}: weighted average luminance of the window, in function of the relative areas of sky, obstruction

and ground [cd/m²]
ω: solid angle subtended by the window [sr]
Ω: solid angle subtended by the source, modified for its position in the field of view by means of the position index *P* [sr] (Guth, 1963)

Hopkinson also recognized that reflections off other surfaces could also be experienced as glare sources. These effects, however, are not included in either of the two formulae.

As Einhorn (1979) pointed out, the weakness of the BGI lies in the mathematical inconsistency (additivity). DGI has the same weakness.

Inoue and Itoh (1982) suggested that DGI resulted in the contradiction shown in Figure xx. When the source extends to the whole visual field, DGI should be independent of the background luminance, meaning that all curves should meet at solid angle 2π (or around 5) sr. DGI shows discrepancy. Similarly, when the luminance of the background equals that of the source, DGI should be independent of the solid angle of the source; meaning that the curve for $L_b = L_s$ should be parallel to x-axis. Again, DGI shows discrepancy

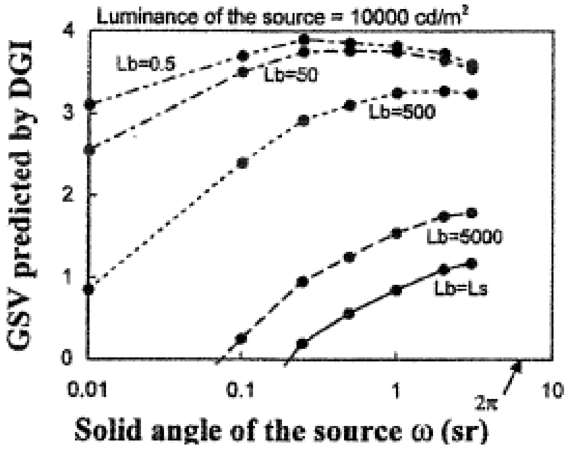

Figure 4-3 Inconsistencies in DGI

Predicted Glare Sensation Vote (PGSV)

The Predicted Glare Sensation Vote (PGSV) is a formula based on experiments with simulated windows (Iwata et al. 1992a, Tokura et al. 1993, Tokura et al. 1996). Over 200 subjects participated in these experiments under 120 different test conditions. The perceived degree of discomfort glare was reflected in the Glare Sensation Vote (GSV), marked by subjects on a multiple criterion scale:

0 = just perceptible,
1 = just acceptable,
2 = just uncomfortable,
3 = just intolerable.

The corresponding DGI values are given in Table 4-2.

Degree of perceived glare	**GSV**	**DGI**
Just (im)perceptible	0	16
		18
Just acceptable	1	20
Borderline between Comfort and Discomfort	1.5	22
Just uncomfortable	2	24
		26
Just intolerable	3	28

Table 4-2 Comparison of GSV and DGI for the evaluation of glare

The indices can be converted into the other using the following equation:

$$GSV = (DGI - 16) / 4 \text{ (Tokura et al., 1996)}$$

Glare Sensation Votes obtained in the experiments with the simulated windows and calculated Daylight Glare Indices showed good correlation in the central vision. Iwata and her colleagues assumed that the DGI predicts the subjective evaluations under real sky conditions well. This means that the GSVs acquired in the experiments with the simulated window also reflect the subjective evaluations under real sky conditions. Therefore, they were used to draw up a new prediction method, the Predicted Glare Sensation Vote (PGSV):

$$\mathrm{PGSV} = 3.2 \log L_s - 0.64 \log \omega + (0.79 \log \omega - 0.61) \log L_b - 8.2$$

$$L_b = \left(\frac{E_v/_\pi - L_{wp}\varphi_w}{1 - \varphi_w} \right)$$

Where:
E_v: vertical illuminance at the eye [lux]
L_{wp}: luminances visible within the window plane [cd/m²]
ω: solid angular subtense of the source [sr]
φ_w: a configuration factor of the window

Whereas the PGSV was based on glare assessments under artificial lighting conditions, it needed to be validated in respect to its applicability under real sky conditions. For this purpose, a comparison was made between GSVs obtained in an experiment under real sky conditions and the PGSVs – the calculated degrees of discomfort glare (Iwata et al., 1992b).

46 subjects participated in this experiment. The study showed that the PGSV gives more plausible degrees of glare than the DGI does, but generally these values are still too high.

To use the PGSV the following needs to be taken into consideration:

- The PGSV does not include a position index and therefore only aims at the evaluation of glare from windows located in the line of vision. In contrast with the Daylight Glare Index, this formula takes into consideration the transition of the adaptation luminance level of the eyes and the total amount of light coming into the eyes.

- The Predicted Glare Sensation Vote is also based on experiments with uniform light sources (Tokura et al., 1996) and might therefore not be applicable in situations with daylighting systems that realise a non-uniform luminance distribution within the window plane.
- The PGSV has a comparable application problem as the DGI. The PGSV is not independent of source size when the background luminance equals the source luminance, although it should be independent. In contrast to the DGI, Iwata and Tokura expect that it can be applied to sources larger than 1 sr (Iwata and Tokura, 1998).

The input parameters for the PGSV can be obtained through simulations or measurements, comparable to those for the DGI.

The formula predicts the glare sensation note (GSV). 0 is just perceptible, 1 is just acceptable, 2 is just uncomfortable, 3 is just intolerable. The Position Index P, an inverse measure of the relative sensitivity to through the field of vision, is not included in PGSV because PGSV at the evaluation of glare from windows commonly located in the line of vision.

A particular feature of the PGSV formula is that the coefficient of log L_b is expressed as a function of ω meaning the effects of the background luminance on glare sensation depend on the source size. On the other hand, UGR shows that the exponent of L_b or the coefficient of log L_b is a constant negative value, and that consequently, an increase in background luminance should cause a decrease in e sensation. In equation 2 the value of the solid angle of the source is always less than 2π corresponding approximately to the solid angle of the whole visual field, so that the coefficient of log L_b is mostly less than zero. Thus, PGSV agrees with UGR in rear to the general tendency of the effects of the background luminance on glare sensation.

Modification of DGI and UGR

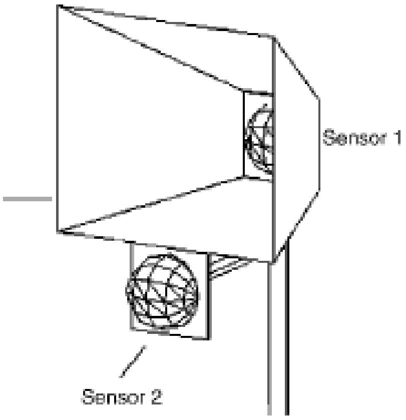

Table 4-3 Measurement of the vertical illuminance Eun (unshielded illuminance – sensor 2) and that of the window Es (shielded illuminance – sensor 1)

Fisekis et al. (2003) modified the “Cornell” Daylight Glare Index (DGI). The background luminance, Lb, is the average luminance of the interior surfaces of the room, which contribute to the visual field of the observer. It is defined as that luminance of the whole surroundings which produces the same illuminance on a vertical plane at the observer’s eye as the visual field under consideration excluding the glare sources. L_b is derived as follows:

$$L_b = \frac{E_{un} - E_s}{\pi\,(1 - \varphi)}$$

Where
E_{un}: average unshielded vertical illuminance from surroundings (lux)
E_s: average vertical shielded illuminance from glare source
φ: configuration factor of source with respect to the measurement point

The problem with L_b when calculated according to the above equation is, that when the source is increased in size, the vertical illuminances measured by the two sensors tend to become equal ($E_{un} = E_s$). This means that the field factor is governed only by the contribution of the source which leads to an overestimated DGI.

In physiological terms, a large glaring source such as a window covers a very large area on the retina, and so it cannot be clearly distinguished from the background. For this reason, another representation of the background luminance has also been used previously to avoid this limitation. It is the average luminance (L_a) over the hemisphere of view given by:

$$L_a = \frac{E_{un}}{\pi}$$

$$\mathrm{DGI}_{mod} = 10\log 0.478\frac{{L_s}^{1.6}\ \cap^{0.8}}{{L_a}^{0.85} + 0.07\omega^{0.5}L_s}$$

Where
L_s: glare source luminance (cd/m^2)
L_b: background luminance (cd/m^2)
L_a: average luminance (cd/m^2)
ω: solid angular subtense of the glare source at the eye of the observer (sr)
Ω: solid angular subtense of the glare source, modified for the effect of the position of the source in relation to the observer (sr)

Fisekis also suggests an approach based on modifications to a rearranged UGR formula used by Sørensen to examine the causes of the sensation of discomfort glare is shown. It is considered to be a ‘grand total effect’ and a ‘contrast effect’.

An initial suggestion is that the grand total effect can be represented by the average luminance (L_a) (expressed as a logarithmic function to bring it to the Glare Index scale).

$$\text{Grand Total Effect} = 8 \log L_a$$

The performance of the ‘grand total effect’ as a stand-alone measure of discomfort glare is consistent over the whole range of criteria with high accuracy over the Just Perceptible (16-18) criterion and reflects the role of average luminance in the sensation of glare. Better agreement is achieved if the contrast effect is included. It is represented as the ratio between the source and the background luminance (L_s/L_b). The model then has the following form:

$$\mathrm{UGR}_{\mathrm{exp}} = 8\log L_a + 8\log\sum\frac{L_s}{L_b}\frac{\omega}{p^2}$$

Where:
L_s: glare source luminance (cd/m^2)
L_b: background luminance (cd/m^2)
L_a: average luminance of the visual field (cd/m^2)
ω solid angular subtense of the glare source at the eye of the observer (sr)

Daylight Glare Probability (DGP)

The Daylight Glare Probability (DGP) metric is based on human subject studies conducted at the Danish Building Research Institute and the Fraunhofer Institute for Solar Energy Systems in Germany in simulated office spaces with side windows and was formulated by Wienold and Christoffersen (2006). It differs significantly from other glare index formulae in its approach and compares areas of high luminance in the visual field to the vertical illuminance at the eye with a viewing hemisphere of 2π steradians.

The basic idea for the new DGP formula was a combination of using the vertical illuminance at the eye as the glare measure, using the central sum of the glare source term of the CIE glare index and using an empirical fit of some parameters. Furthermore, the use of Lb as a measure for the adaptation level is seen as not suitable, since the large glare sources themselves have impact on the adaptation level. Therefore, the authors suggest use of the vertical illuminance at the eye Ev as a measure for the adaptation level. There is some indication (Osterhaus, 1998) that ocular illuminance (vertical illuminance measured at the eye of an occupant facing a task and associated glare source) and overall brightness in the visual field correlate well with the subjective assessment of discomfort glare from non -uniform large area sources when the source surrounds the task. On the other hand, it is likely that this is not applicable when glare sources are further off the line of sight. The use of E_v appears to also be supported by the work of Wienold and Christoffersen, achieving somewhat higher correlations for E_v than using L_b for the adaptation term in the equation. The structure of the equation is then

$$DGP = C_1 E_v + C_2 \log(1 + \sum \frac{{L_{si}}^2 \omega_{si}}{{E_v}^{c_4} {P_i}^2}) + C_3$$

$C_1 = 5.87 \times 10^{-5}$ $C_2 = 9.18 \times 10^{-2}$ $C_3 = 0.16$ $C_4 = 1.87$

Where
L_s: glare source luminance (cd/m^2)
E_v: vertical illuminance at the eye (lux)
ω: apparent solid angular size of the glare source (sr)
P: the position index

In exceedingly bright scenes, discomfort can be predicted even without significant visual contrast on the basis of the first half of the equation. The latter half of the equation uses the familiar comparison of the source luminance and size against the scene luminance and the position index of the glare source, an evaluation of visual contrast. In this sense, DGP is the evaluation of glare which considers the most factors that contribute to discomfort. It also resolves some of Hopkinson's original concerns about the DGI metrics' validity by allowing for direct glare sources other than the sky, something which no other subsequent metric has done. Similar to VCP, DGP's value scale is intuitive. A glare probability >0.45 corresponds to intolerable glare – an estimated 45 percent of people would feel discomfort in such a lighting situation, while a value <0.3 is considered imperceptible. DGP's equation is fit to substantial subjective user sampling in both Denmark and Germany under careful testing conditions. A program, EvalGlare, was developed at the Fraunhofer-Institut für Solare Energiesysteme in Freiburg for the evaluation of DGP and other glare metrics from the Radiance RGBE image format and also allows for the visualization of contrast-based sources of glare.

5. Laboratory Studies

5.1.Concept

5.1.1. Hypothesis

As mentioned in section 1.2, the hypothesis of this project is, that a visual comfort (i.e.- the absence of glare or “low glare” luminous conditions) affects the perception of the quantity of light (illuminances and luminances) in the space by occupants. If this hypothesis is confirmed, opportunities for reduction of lighting electricity use could be expected in proposing lighting schemes with reduced glare conditions: Lower light quantities would be required to achieve equivalent appropriate lighting conditions.

At least three different physiological mechanisms restrict the amount of light reaching the retina:

- squinting,
- pupil size, and
- photo-pigmentation

In this his project, we limit ourselves to the study of correlation between glare and its effect on pupil sizes, because it is a purely physiological reaction, and is considered as operating rather independently from observer’s moods or facial aspects.

The increase of the quantity of light reaching the eye (increased illuminances on the vertical plane of the eye) leads to a reduction of the pupil size (or diameter). This reduction affects overall sensitivity to brightness in the environment, and consequently to glare perception.

Hence our hypothesis:

“through reducing glare conditions, it is expected that pupil size will increase, and therefore leading to an increase in the overall perceived brightness of the surrounding spaces”.

If such a hypothesis is confirmed, it would demonstrate that equivalent perceived brightness could be achieved with less energy, when using low glare lighting scheme.

But there is also another aspect of vision which may impact pupil size: Gaze directions. Depending of the activity, observers tend to modify direction of vision (gaze) around the visual task, and this may be also affected by visual comfort conditions. If so, glare be detected in the viewing patterns in distracted observers.

Therefore, we have planned to study these effects through launching series of experiments. Relevant parameters are:

- Vertical illuminance in the plane of the eye of observers (to characterize quantity of light reaching the eye
- Glare conditions (relative contribution of glare sources to vertical illuminances, UGR value – which is the most accepted and used parameter to rate glare conditions. UGR is not ideal (as detailed in section 4.1.2), but as it is commonly used worldwide and embedded in many lighting standards, UGR is currently the most acceptable metric for the present study.
- Pupil size (to evaluate physiological response to glare)
- Gaze (to explore dynamic effect related to the presence of a glare sources in the field of vision of the observer)

5.1.2. Success Criteria

The first concern of our experiment is to identify if a significant response could be found using the parameters above. A second concern is to identify if variations of the response is coherent with the changes of the glare conditions.

There are also other kinds of expected results: homogeneity of results, individual discrepancies, possible differences in behaviour by observers.

Finally, we found it critical to explore if glare conditions significantly affects human behaviour: Directions of vision (gaze) in relation to the position of the glare source in the field of view.

5.2. Pilot Studies

Pilot studies were conducted in SBI's meeting room (a window-less space) to test measuring equipment, conduct sensitivity studies and define the future campaign if tests related to the hypothesis.

Pilot studies were conducted to explore if pupil size could be correlated to glare conditions. The objective was to get familiar with a allowing the measurement of the pupil size, and to conduct preliminary campaign of measurements under various glare conditions.

To do this we have looked at current generation of hardware with pupil size recording capabilities.

We have looked at the Eye Tribe Tracker Pro (~199 $) (see Figure 5-1) and Tobii Pro glasses 2 (~5,000 $, not including software) (see Figure 5-2). Even though there is a considerable price difference between the two, both can be used if the testing is properly designed. Tobii glasses allow also to record gaze.

Figure 5-1 "Eye Tribe" detection unit

Figure 5-2 Tobii Pro Glasses 2 detection unit

5.2.1. Pilot Study 1: Test of the Eye Tribe Tracker Pro (available June 2016)

The Eye Tribe uses infrared sensors to capture the pupils to track eyes movement on screens up to 50 cm x 30 cm at 65 cm distance. The pupil size is given in mm (however in the hardware used to test it was in arbitrary units).

To test the hardware, we conducted a very small experiment where a user would have a direct glare source in the field of vision turned on and off whilst recording the pupil dilation and contractions.

The results from the test can be seen in Figure 5-3.

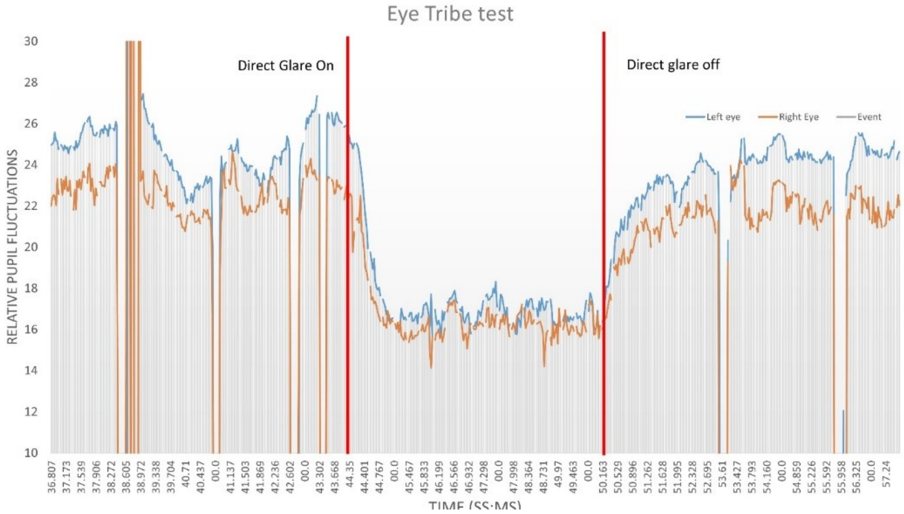

Figure 5-3 Data from Eye tribe experiment with a glare source switched on and off. Blue and orange are the left and right eye pupil diameter respectively

Results

The Eye tribe allows to relate pupil size variation to variations of glare, but this was only for very large variations in glare conditions. The eye tribe appears to have a limited capacity to measure large pupil size variations

Further, the Eye Tribe system requires for the participants that their head and eye position stays more or less fixed, which seemed like quite a disturbing prerequisite for this study.

5.2.2. Pilot Study 2: Computer Monitor Used as Glare Source (Tobii Glasses)

Using the Tobii glasses we wanted to investigate the range of pupil dilation whilst being exposed to different lighting conditions. We set up a small experiment using a luminance uniform screen as a source of glare. See Figure 5-4.

Figure 5-4 Test setup using a monitor as glare source, with target in the centre

Observers were instructed to focus on a dark letter shown on the screen while the luminance was altered. The luminance varied from 0.25 cd/m^2 to 193 cd/m^2 while the background luminance remained constant at approximately 25 cd/m^2. See Figure 5-5.

The test participants sat approximately 60 cm from the target.

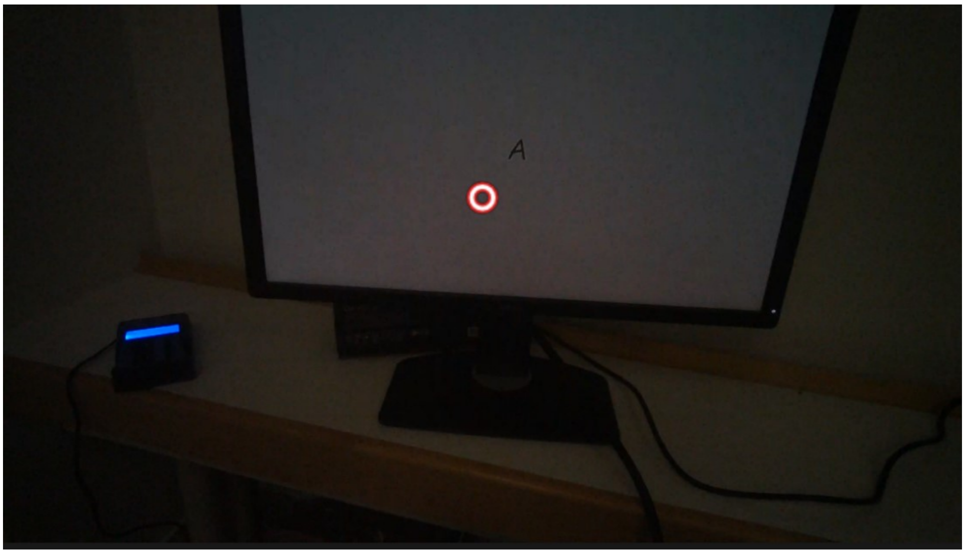

Figure 5-5 Screen capture from the Tobii glasses, the circle denotes gaze area

The results from the test can be seen in the following figures with <30 years old test persons.

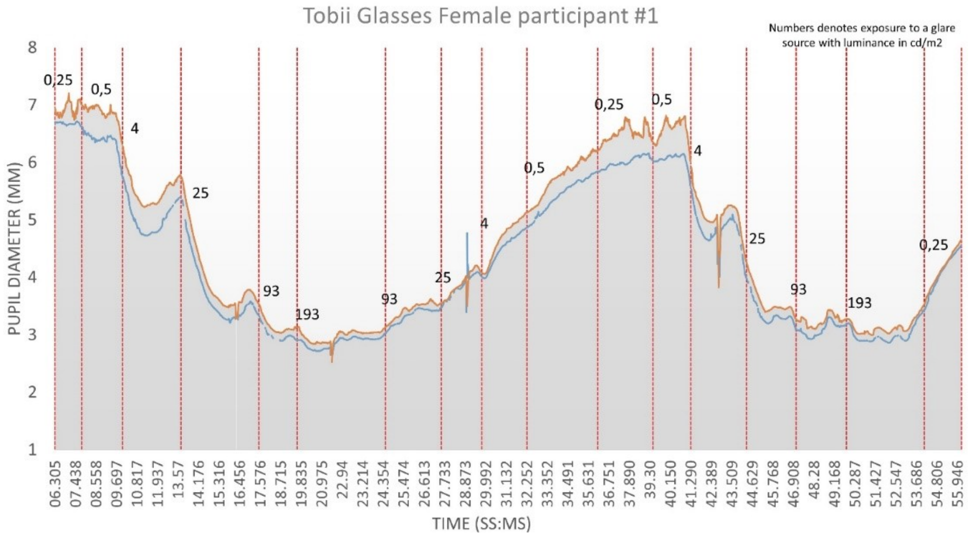

Figure 5-6 Monitor as glare source, with female observer. Orange and blue lines correspond to pupil diameter of the left and right eye respectively. Vertical lines indicate a change of luminance of the glare source.

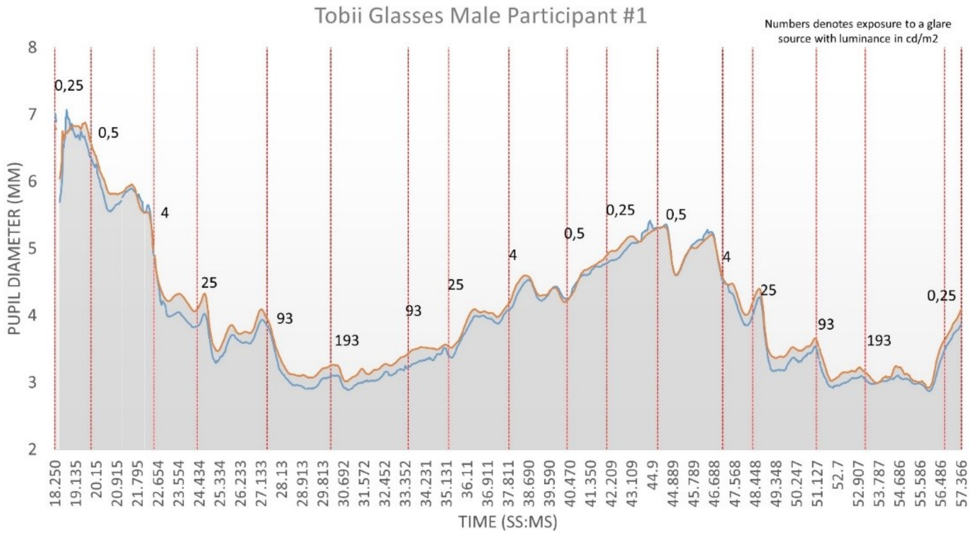

Figure 5-7 Monitor as glare source, with male observer. Orange and blue lines correspond to pupil diameter of the left and right eye respectively. Vertical lines indicate a change of luminance of the glare source

Results

It appears that left and right eyes behave almost simultaneously: no discrepancy between eyes of the same observers can be detected. We can also note that there are no rapid variations of pupil size when luminance is changed. We also find that there is no safe correspondence between luminance and pupil size, which suggest influence of context or history of exposure.

Tobi glasses also can read significant variations in pupil sizes, better that the Eye Tribe Tracker Pro.

5.2.3. Pilot Study 3: Exposure to Direct Glare Source During Task with Two General Illuminance Settings (Tobii Glasses)

To effectively relate the pupil diameter together with task lighting we set up an experiment with two task lighting conditions: 100 lux and 300 lux to see of the general illuminance conditions could affect glare perception (and pupil size), which is the general hypothesis of this program.

The task was to focus on a small symbol hanging on an A3 piece of paper on a wall 3.2 m from the observer. A glare source (Ø = 12 cm) was placed close to the centre of vision of the observer. A setup of the test can be seen in Figure 5-8.

Figure 5-8 Test setup with glare source close to gaze point

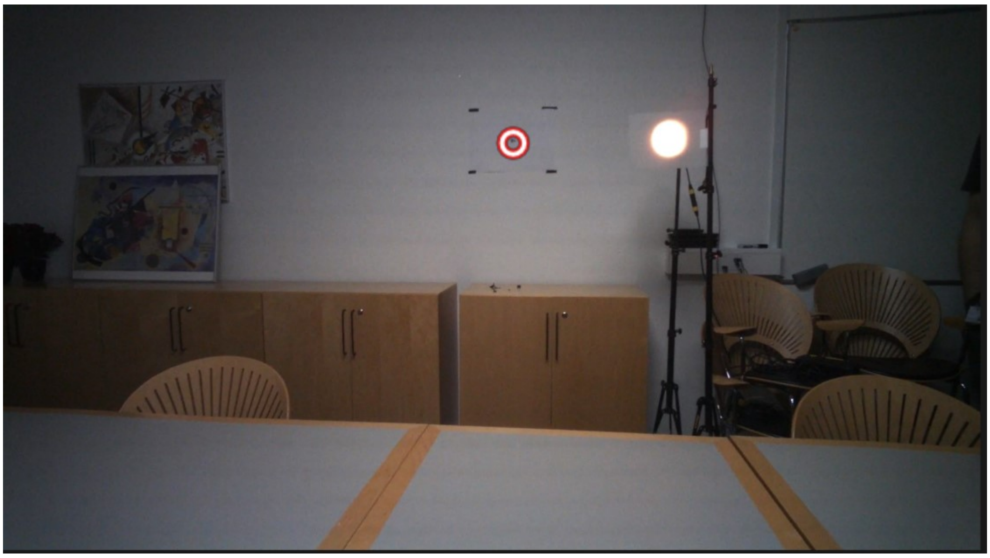

Figure 5-9 Screen capture (from Tobii Glasses) from the observer’s point of view

The outputs of the test can be seen in Figure 5-10 and Figure 5-11.

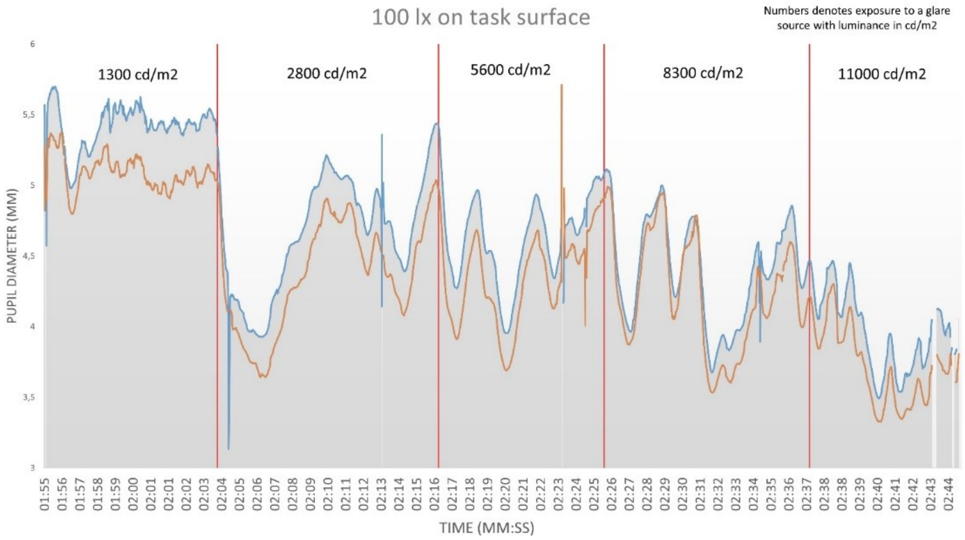

Figure 5-10 Pupil diameter fluctuations during the experiment in 100 lux work area scenario

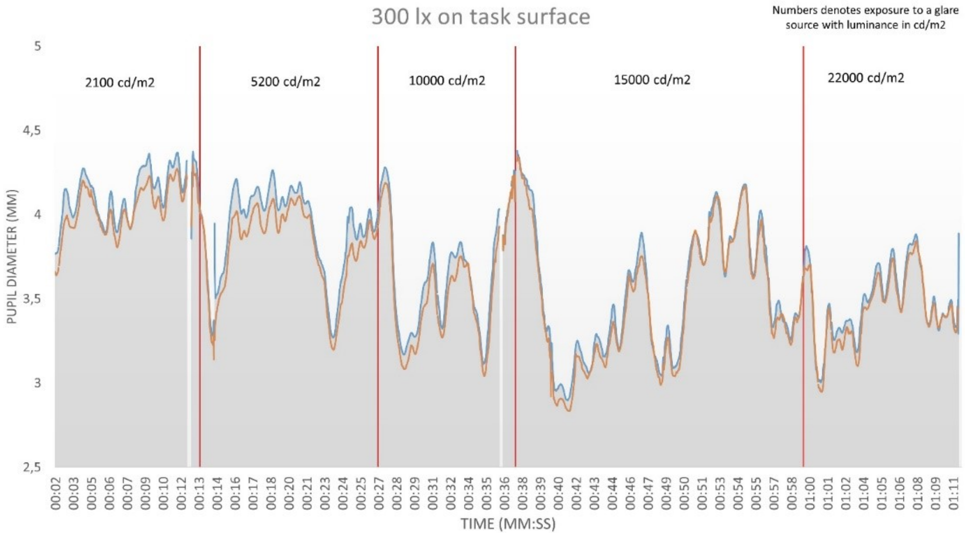

Figure 5-11 Pupil diameter fluctuations during the experiment in 300 lux work area scenario

The task area had a luminance of 23 cd/m^2 in the 300 lux scenario and 8.4 cd/m^2 in the 100 lux scenario.

To relate this to UGR values, we made luminance maps (as Figure 5-12) from the observer’s point of view and thereby calculate the UGR index. The luminance of the glare source was, however, very sensitive due to the high luminance. Because of this very sensitive method it was impossible to get the same luminance values as experienced during the experiment. In some cases, the camera’s shutter synced incorrectly up with the ceiling LED’s refresh rate, resulting in no luminance data in that particular image. This is an inherent problem with LED’s and occurs with very fast shutter speeds of any camera. The calculations can be seen below.

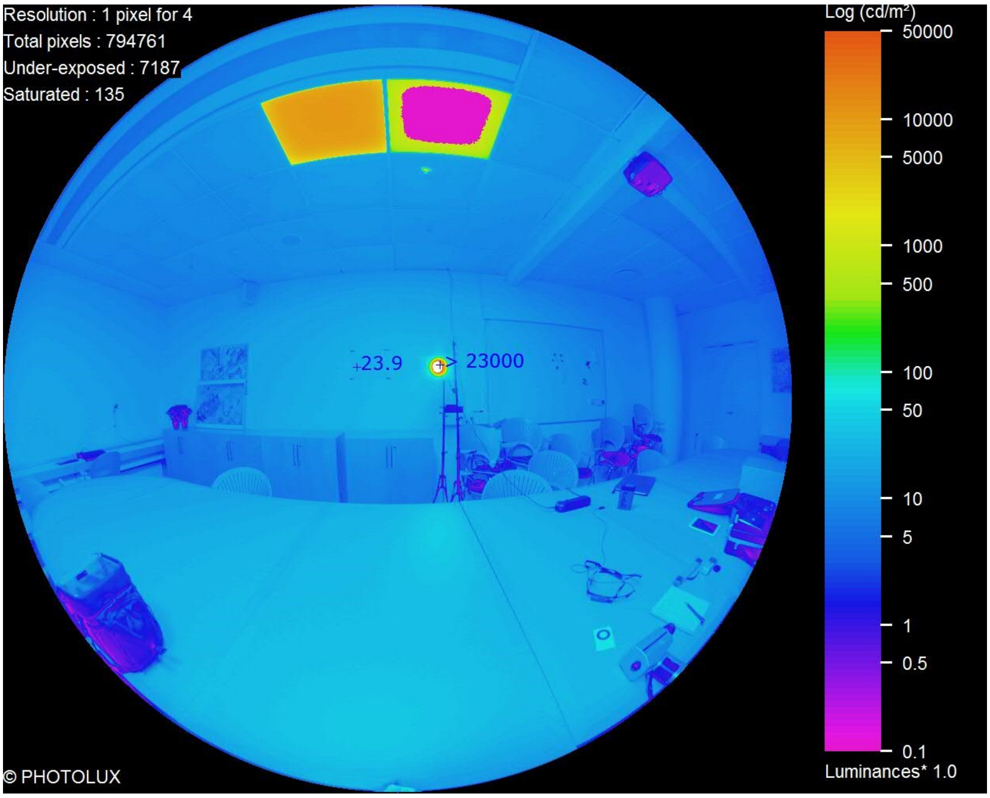

Figure 5-12 Luminance map from the 300 lux scenario with a glare source of 28,000 cd/m2. Note the ceiling LED's different colours, which is a result of the asynchronization of the camera's shutter and the LEDs refresh rate.

	300 lux	100 lux
1	28,000 cd/m^2 (UGR 32)	30,000 cd/m^2 (UGR 34.4)
2	16,000 cd/m^2 (UGR 30.7)	12,000 cd/m^2 (UGR 31.1)
3	4,300 cd/m^2 (UGR 21.4)	4,400 cd/m^2 (UGR 25)
4	1,700 cd/m^2 (UGR 22.1*)	1,700 cd/m^2 (UGR 19.4)

Table 5-1 Luminances captured with luminance camera

Results

We observe from the readings rapid variations of pupil size, with an amplitude which is of the same order than the variations related to changes in glare conditions. It was found as probably linked to myosis: the instability of pupil size when observers tend to accommodate to a given target. This is a phenomenon not related to lighting conditions, but to the efforts of the observers to read details, see section 0.

We note that pupil size is significantly affected by the general illuminance of the room: Pupil size is generally smaller when illuminance is 300 lux that when it is equal to 100 lux.

Instability of flickering of light appeared to lead to some lack of accuracy in the assessment of UGR values calculated from luminance reading from the HDR camera

5.2.4. Pilot Study 4: Reduction of Myosis (Dynamic and Fixed Stimuli)

This pilot proposes to define a visual target which will not lead to rapid pupil constrictions (myosis) which most likely was the cause of vary little variance in the first pilot test. We used the same conditions as the former test s but with a number of alterations:

- Have a target without fixation need. Compared to pilot test#1, where the users were told to fixate on a movie clip, having a non-fixation task such as looking at a static face (picture) or painting, should relax the eye and avoid myosis.
- Distance to fixation target must be increased. Ideally the distance should be 5m or more. (source: Glostrup Hospital)

Other measures to increase the likelihood of success:

- Some subjects should be “glare sensitive” – self-reported, e.g. inclined to wear sunglasses etc.
- General space lighting and glare comparable working conditions, such as general lighting level 200 horizontal lux, and glare within glare rating of UGR 26-30.
- Harsher glare conditions can be added to provoke extreme results in pilot test if needed.
- Measure other glare reactions, such as eye movements (to avoid glare), lack of concentration (?)

The design of the experiment relies heavily on the measurements obtained by Tobii glasses which was proven useful in the first pilot project (could measure from a range of 8 mm dilated pupils to 2 mm pupils). We decided to use the Tobii glasses again for this pilot test.

The test consisted of periodic exposure to a glare source with a low position index over a time frame of 10 minutes. The test persons experienced two types of stimuli, static and dynamic. The static stimuli consisted of an image which the test person gazed upon but not focus on. The dynamic stimulus was a short movie clip. The reason to use both dynamic and static stimuli is to see if the dynamic task induces myosis. During the task of looking at the stimuli a glare source was turned on for half the duration of stimuli exposure. Broken down a typical test proceeded as follow:

1. Introduction to test, calibration of eye tracking, light adaptation to room (200 lux) **- 4 min**
2. Exposure to stimuli 1 (dynamic|static) – **2.5 min**
3. Exposure to stimuli 1 (dynamic|static) plus glare source – **2.5 min**
4. **1 min break**
5. Exposure to stimuli 2 (dynamic|static) – **2.5 min**
6. Exposure to stimuli 2 (dynamic|static) plus glare source – **2.5 min**

Total time estimate at ~ 15 min, per test participants.

The room was calibrated to provide around 200 lux on working surface (table) and the average luminance of the room was set not to exceed 40 cd/m2. The stimuli were shown on a TV screen which is more than 5 m away from the test participant. The luminance output of the screen did not exceed 200 cd/m^2. See Figure 5-13.

Figure 5-13 Configuration used in pilot study 4, with observers looking at a fixed image or a movie on a screen located 5 meters in front of her/him. The study was conducted for a horizontal illuminance of 200 lux and with or without glare source (UGR around 27)

Expected Outcome: The outcome was expected to validate that the pupil size is a good indicator when assessing glare situations. The expected outcome of pilot study was to find a significant difference between the two stimuli. The hypothesis is that a static image will not induce myosis over the course of 2.5 min and thus the glare source will have a bigger impact on pupil diameter.

Results:

Pilot study 4 seemed to confirm that showing a video film to participants at some distance (> 5 m) would ascertain that results were not biased by pupil constriction due to myosis.

The measured data are presented in Appendix V. Particapant are Eik (27) and Anne (50). Pupil sizes are different in the two general setups (wall washers on(of) and glare source seem to affect at least the younger test person. Pilot study 4 also rendered a good way of presenting the collected data.

There seemed to be no differences with regards to static or dynamic inputs on the TV-screen – and since static stimuli in general are more difficult to concentrate on, dynamic stimuli seem to be the best option to keep participants from getting bored, and being inclined to look away from the target.

A short test was performed with the stimulus being an actual conversation with a person sitting at a 5 m distance (interview on the subject “how did you spend your holidays”). However, a natural conversation also triggered for instance gazing into the ceiling while contemplating the answer, thus looking away from the target (the face of the interviewer). Further, the topic of almost any conversation might evoke emotions. Consequently, a normal conversation did not seem suitable as a stimulus for further tests.

5.3. Experiment Design

5.3.1. Test Room

The laboratory test room was situated in the ground floor of Aalborg University’s Copenhagen facility on A.C. Meyers Vænge.

It is a window-less space, 11m by 6 m, with a high ceiling height (3.5 meters) offering large plane white walls and sufficient depth for observation

- Wall washers Fagerhult Gondol t5, dimmable by percentage.
- ERCO LED Spot lamps
- Panasonic TV screen (1,000 x 600 mm)

5.3.2. Experimental Set-up

The luminance environment which was offered was:

- A white wall with two possible luminances, obtained with installations of 58 W fluorescent and dimmable wall washers. Able to vary wall luminances from 10 to 80 cd/m^2.
- A visual target consisting of a TV monitor, 1,000 mm x 600 mm, with an average luminance of 50 cd/m^2 with the ability to provide luminance of pixels up to 200 cd/m^2.
- Glare sources: 3 led spots fixed to a rail, equipped with diffusers to allow a constant luminance distribution across the diameter of the spots. Luminance of spots were, from left to right 27 kcd/m^2, 53 kcd/m^2 and 72 kcd/m^2, with a diameter of 140 mm. For the experiment only two were used.
- A seat for the observers, allowing a viewing distance of 6 meters from the TV monitor: to avoid efforts of accommodation (reduce myosis) and provide a less stressful experience.
- A table next to the observer, receiving an illuminance of 350 lux from the overall lighting (as the entire work plane.

The stimulus was a video and content was an issue. The idea was to propose a content which would not stimulate efforts of vision (to avoid myosis), but also stimulate interest of the viewer. We selected a human face, with no significant movements within the frame of the TV set. For this reason, we selected a speech by her Majesty Queen Elisabeth II from England, given on the occasion of Christmas.

See video at https://www.youtube.com/watch?v=zscqxgDc9f8)

Correlated Colour Temperature of fluorescent tubes and LED light spots was set up at 3,000 K.

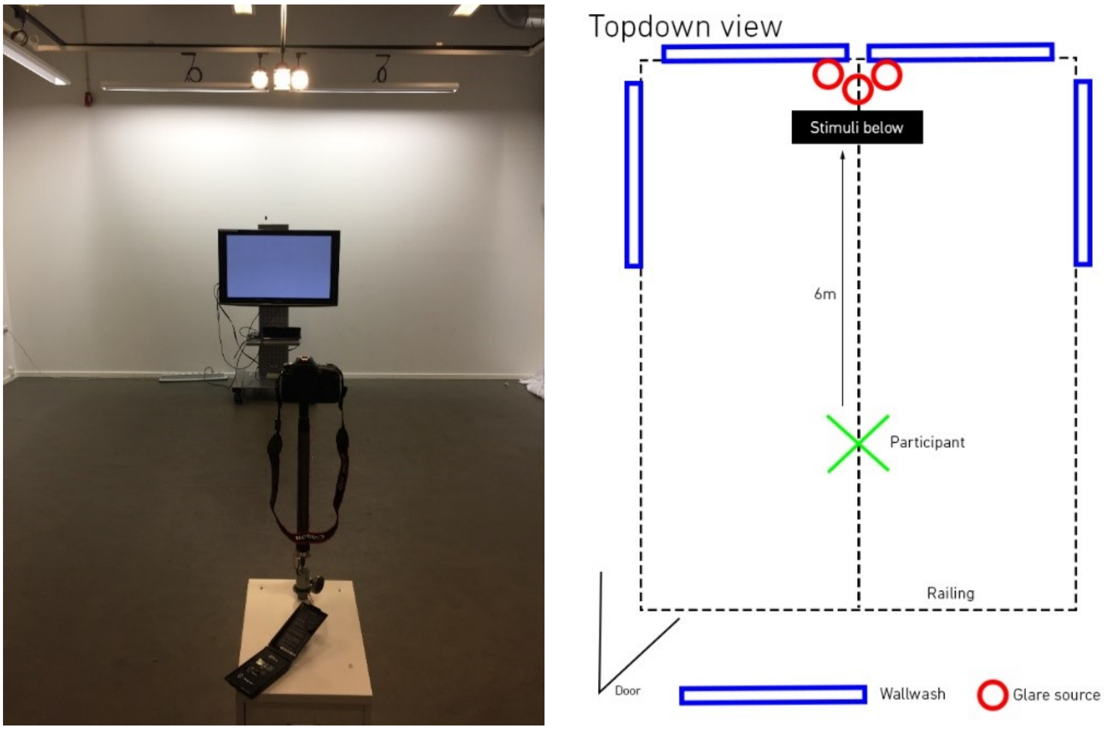

Figure 5-14 Configuration used for the test, showing the walls lit with wall washers, the TV monitor used as the target for vision, the 3 spots as glare sources, the table next to the position of the observer (wearing Tobii glasses)

5.3.3. Choice of Test Participants

Possible participants were contacted by mail and telephone in June 2017. Most of them were coming from the campus of Aalborg University in Copenhagen and were eiher students or staff.

We selected participants with “normal vision” and be able to see the stimuli in a 6-meter range without wearing spectacles that would otherwise interfere mechanically with the Tobii glasses.

5.3.4. Eye Tracking and Pupil Size Measuring Equipment

Following the preliminary pilot studies 1 and 2, it was decided to monitor pupil size and gaze of the observers with Tobii glasses during the entire experiment.

5.3.5. Photometric Equipment

During the experiment, illuminances were measured with a Hagner Luxmeter, and luminances with a Konica-Minolta LS110. When luminance mapping was necessary, we used a calibrated through the lens camera equipped with a Fish eye lens. HDR images were taken using the protocole defined by the software for luminance measurements (Photolux).

5.3.6. Other Equipment

We also tested the relation between UGR values and the luminance maps using immersive display equipment. Images were collected with spherical acquisition systems (Gear VR 360 cameras) and projected afterward inside the VR display systems (Samsung S7). This technique was used to validate the models, and check possible errors. Various simulataneous participants of SBI participated in the evaluation. We also tested the possible glare sension with tone mapping adjustment of luminance range to adapt to the range of luminance of the Samsung screens. The range was found to limited to generate the sensation of glare. It was found however to be sufficient for judging interesting general lighting patterns.

5.3.7. Test Procedure

It was decided to invite about 20 observers to participate to the tests, or more if this was possible during the month of July, which is a month with difficulties to get hold of staff and students.

The test was conducted in three phases:

1. Calibration of Tobii glasses for the participant
2. The 8-minute visual test, with the observer wearing Tobii glasses.
3. A questionnaire divided in two parts. First part to assess possible specific sensitivity of subjects to glare conditions. Second part on the test to record comments (see Appendix I)

Questionnaire dealt with recording:

- Age
- Time of day
- Possible known visual disabilities
- Self-reported glare sensitivity.
- Driving at night
- Accommodation
- State of alertness/wakefulness/focus

Visual test was introduced with the following explanations:

“You will in this test experience different glare level and your task is to remain seated, sit still, and watch a video on the television. During the test, you will be equipped with a pair of eye-tracking glasses which will track your gaze direction and pupil reactions.

While you are watching the video clips, some of the lamps will turn on and off. Try not to focus or look directly into the lamps! If you feel too uncomfortable you may stop the test at any time.

After the experiment, you will be asked to fill out a questionnaire based on the experience you just had.”

5.3.8. Content of the Test: Stimuli

Horizontal illuminance in room was fixed (355 lux, corresponding to typical illuminance in offices).

There was a total of 6 configurations (2 wall luminance and 3 levels of glare), see Table 5-2 The six possible lighting scenarios which were presented.

The lighting options were as follows:

- The general lighting in the room (a constant 355 lux at work plane from this source only)
- Diffuse wall wash lighting (variable): Off and on (adding appox. 90 lux on the work plane)
- Spot lamps: Spots off, one spot on, or two spots on (the latter adding approx. 44 lux on the work lane)
- The TV screen luminance did not influence illuminances in proximity of the participants

Wall washer conditions	**Glare sources** Spot Light OFF ● Spot Light On ○	**UGR value** Calculated from HDR images with the Photolux software.	**Vertical illuminance** On the eye of the participants	**Horisontal Illuminance** 1 m in front of participants, height 85 cm
No wall washers	● ● ●	9.4	168 lux	355 lux
	○ ● ●	30.0	181 lux	#N/A
	○ ● ○	31.4	206 lux	412 lux
Wall washers 100%	● ● ●	6.4	340 lux	463 lux
	○ ● ●	24.2	353 lux	#N/A
	○ ● ○	28.5	380 lux	484 lux

Table 5-2 The six possible lighting scenarios which were presented

The six configurations were presented in the following orders, with experiments starting either with wall washers on, or without wall washers. Between the glare situation, a phase with spots turned off was inserted, leading to a total of 8 sequences of 1 minute each, for a total duration of 8 minutes.

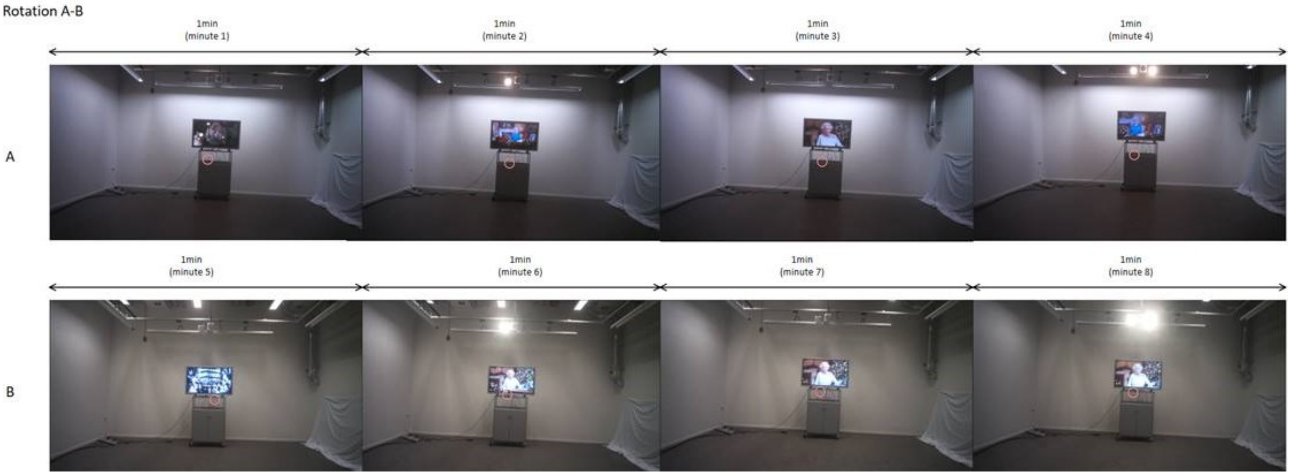

Figure 5-15 The six possible lighting schemes were presented along a total of 8 sequences (solutions without spot lamps presented twice)

Figure 5-16 Configuration with wall washers, and only one spot on

Figure 5-17 Configuration with wall washers, and two spots on

5.3.9. Data Acquisition

Prior to the test, the following photometric quantities were measured:

- Vertical illuminance at eye level of the observers, for each of the 6 configurations
- Horizontal illuminance on the work plane
- Luminance maps from the point of view to compute UGR values.

During the tests, the person in charge of the experimentation:

- Installed the Tobii glasses on the face of the observers and conducted calibration adjustments
- Launched data acquisition of the Tobii glasses (pupil dimensions and gaze)
- Changed the lighting schemes according to the planned process
- Stored the data
- Recorded comments of observers following the experiment.

5.3.10. Examples of Recording and Data Processing

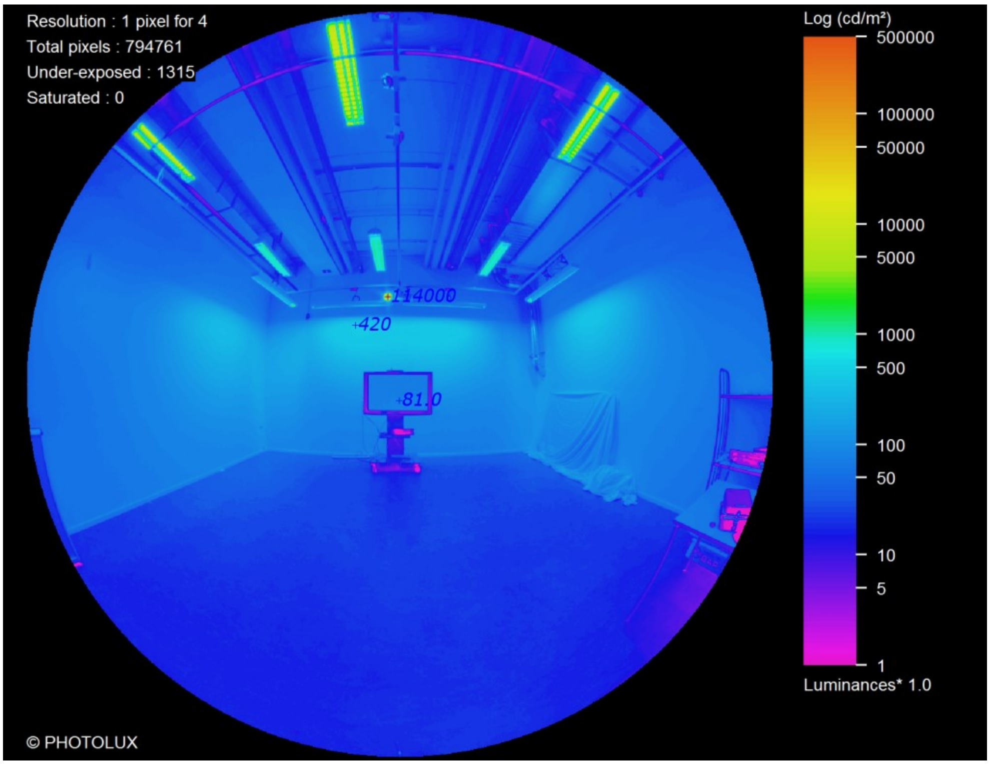

Figure 5-18 Luminance maps from the point corresponding to the eyes of the observers, generated using calibrated HDR photography (Photolux software)

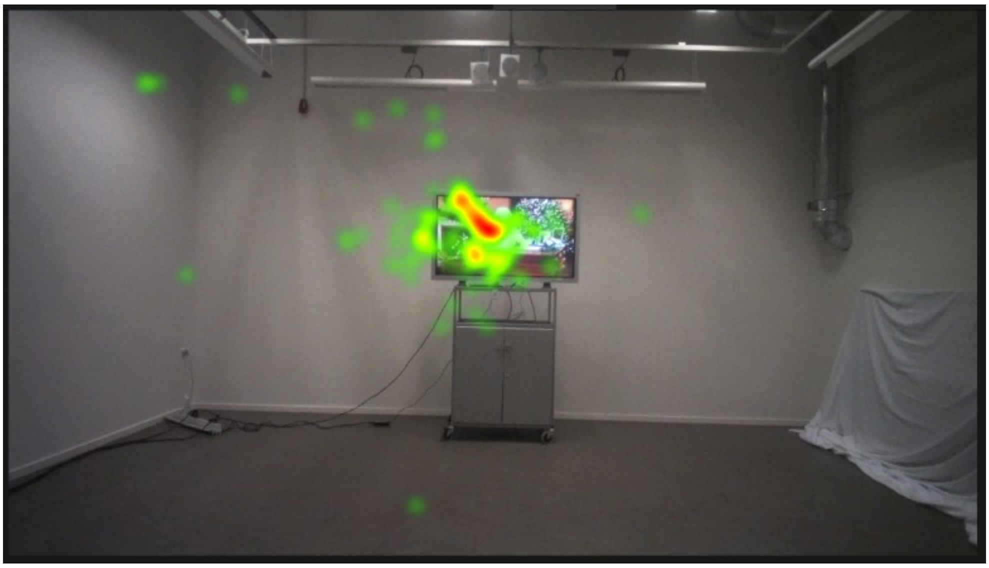

Figure 5-19 Spatial recording of gaze from one observer (also see section 5.4.1)

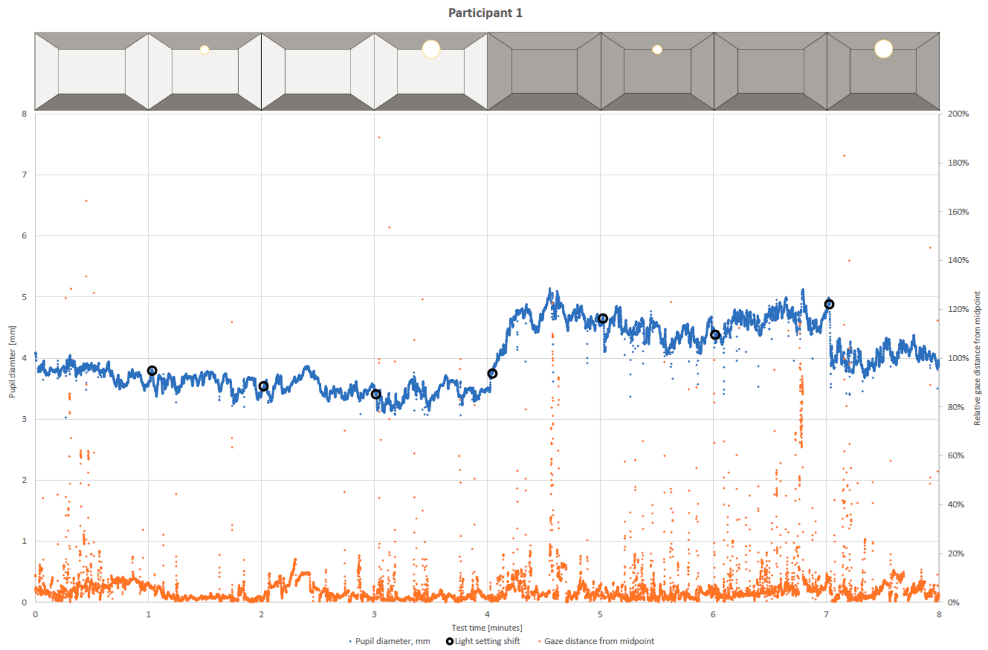

Figure 5-20 Variations of pupil sizes during the 8 lighting sequences (also see section 5.4.1)

5.4. Results and Analyses

5.4.1. Basic Results

All participants were presented with a questionnaire presented in Appendix I posterior to the test.

All in all, 16 individuals participated, 9 females and 7 males.

The age of one male was not recorded. The other 8 males ranged between 27 and 39 years of age with an average of 32.7. The 9 females ranged between 22 and 63 years of age, with an average of 38.4. Se Figure 5-21.

All participants stated that they had normal alternatively corrected-to-normal eyesight.

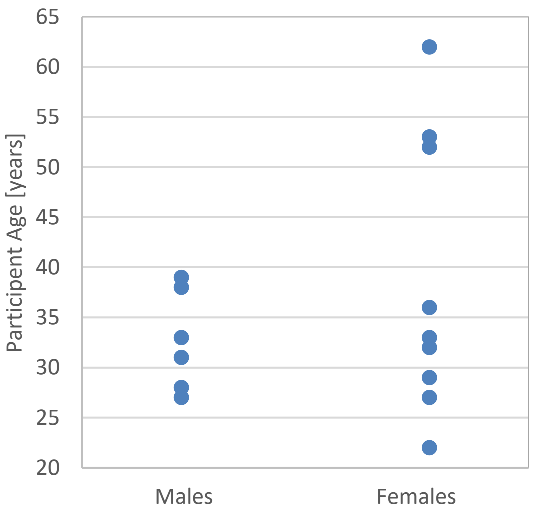

Figure 5-21 Plot demonstrating the 16 participants’ distribution on age and gender

5.4.2. Self-Reported Sensitivity to Glare

To assess the participant own impression of their sensitivity, they were all asked to answer 8 questions (Q1-Q8) as listed in Table 5-3 and in Appendix I.

In addition, the participant answered 5 questions (Q9-Q13) related to their impression of glare in the test, and whether they were bothered with the test glasses.

	Mean	Standard deviation
Q 01: Are you bothered by glare in general? (10=Yes, often)	4.5	2.5
Q 02: How serious are these glare problems? (10=They prevent me from doing my tasks)	4.0	2.2
Q 03: Are you bothered by glare from cars travelling in the opposite direction at night? (10=Yes, often)	6.0	2.7
Q 04: Do you find it hard to read road names or the like because of headlights on cars? (10= Yes, often)	4.4	2.2

Q 05: Is your eyesight poorer in sharp light (as a on sunny day with blue sky)? (10= Yes, often)	4.6	2.5
Q 06: Is your eyesight poorer in dim light? (10= Yes, often)	6.3	2.7
Q 07: Do you experience problems with focussing on object close to you? (10= Yes, often)	3.9	3.0
Q 08: How bothered are you by focussing problems? (10= They prevent me from doing my tasks)	3.4	2.4
Q 09: In which of the two configurations did you find the glare least bothering? (1,2 or 3)	1.4	0.6
Q 10: To which degree was the glare bothering when there was light on the walls (10=very bothering)	5.4	1.7
Q 11: To which degr. was the glare bothering when there wasn’t light on the walls (10=very bothering)	6.9	2.5
Q 12: How bothered were you by the test glasses (10=very bothered)	3.5	2.4
Q 13: To which degree were you able to follow the film on the TV screen (10=couldn’t follow at all)	1.8	1.0

Table 5-3 Results of subjective assessments, average responses

In general, participants responded with some glare sensitivity which also seems normal. See Table 5-4. One female (participant 13) reported of almost no sensitivity, and two females (participants 9,4) reported that they were quite bothered by glare in their everyday life (7.0 and 6.75 – maximum being 10) (participants 2 and 12). Males were less extreme, but both genders reported a similar average sensitivity around 4.6. Se Figure 5-22

Questionnaire responses	Rotation	Time	Gender	Vision	Age	Q 01	Q 02	Q 03	Q 04	Q 05	Q 06	Q 07	Q 08	Q 09	Q 10	Q 11	Q 12	Q 13	Average of Q1:8
Participant 01	A-B	09:33	m	1	27	5	7	8	4	7	7	3	4	1	7	9	4	3	5,6
Participant 02	B-A	10:00	f	1	36	10	8	10	6	4	8	3	7	1	3	10	1	1	7,0
Participant 03	B-A	10:45	f	1	52	6	6	10	1	1	10	1	1	1	6	10	1	1	4,5
Participant 04	A-B	11:45	f	1	53	2	2	3	3	6	9	9	7	1	7	9	6	3	5,1
Participant 05	A-B	12:50	m	1	39	2	3	5	5	7	7	5	2	1	5	7	2	3	4,5
Participant 06	B-A	13:20	m	1	28	4	7	3	2	2	4	1	1	2	6	4	3	2	3,0
Participant 07	A-B	14:10	m	1	33	7	4	3	4	3	1	1	1	1	3	9	1	1	3,0
Participant 08	B-A	14:40	f	1	27	4	2	7	6	2	2	3	3	1	7	9	6	3	3,6
Participant 09	A-B	10:00	f	1	33	3	3	8	4	1	7	1	1	3	7	7	4	1	3,5
Participant 10	B-A	12:45	m	1	38	6	4	9	7	3	7	7	8	1	6	9	2	1	6,4
Participant 11	A-B	13:00	f	1	32	2	3	4	4	7	2	8	3	2	3	5	8	1	4,1
Participant 12	B-A	10:45	f	1	29	7	7	8	8	8	9	3	4	1	4	7	4	4	6,8
Participant 13	A-B	11:20	f	1	22	1	1	2	1	2	4	1	1	2	3	2	4	2	1,6
Participant 14	B-A	12:00	m	1	31	8	2	7	7	8	8	1	2	2	8	6	8	1	5,4
Participant 15	A-B	14:15	m	1		2	2	2	2	5	6	9	7	2	7	5	1	1	4,4
Participant 16	B-A	14:30	f	1	62	3	3	7	7	7	9	7	3	1	5	3	1	1	5,8
Mean					36,1	4,5	4,0	6,0	4,4	4,6	6,3	3,9	3,4	1,4	5,4	6,9	3,5	1,8	
Variance					117,6	6,4	4,8	7,5	4,7	6,2	7,4	8,9	5,9	0,4	2,9	6,1	5,6	1,0	
Standard deviation					10,8	2,5	2,2	2,7	2,2	2,5	2,7	3,0	2,4	0,6	1,7	2,5	2,4	1,0	

Table 5-4 Individual scores on questionnaire

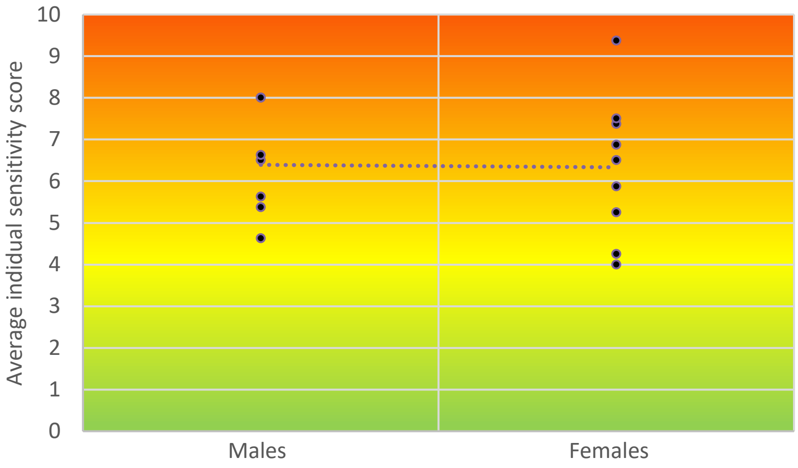

Figure 5-22 Self-assessed glare depending on gender. Sensitivity score rated from 0 = “no sensitivity” to 10 = “high sensitivity”

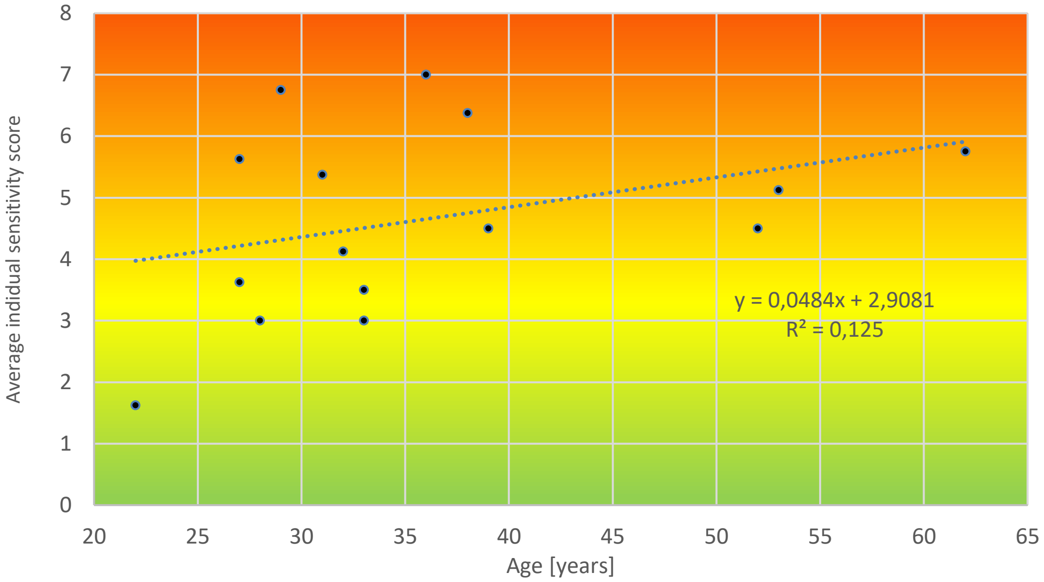

Figure 5-23 Self-assessed glare sensitivity depending on age

Plotting the self-reported sensitivity (in Figure 5-23, average answers, questions 1-8) shows that self-assessed glare sensitivity tends to increase with age (as expected, higher ratings equalling higher sensitivity). However, the correlation is not strong (R^2 is only 0.125).

The influence of background lighting (wallwashers) was sampled via question 9 – see Figure 5-24. Most participants (10) answered that background lighting reduced glare sensation (as expected), but 5 participants found the configuration without background lighting less glary. One participant did not sense a difference.

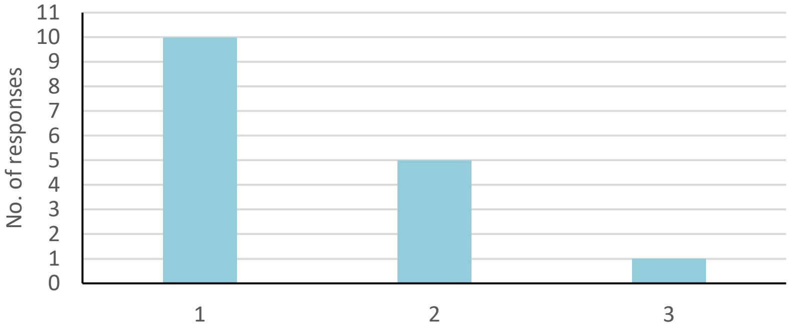

Figure 5-24 Participants' evaluation of effects of background lighting on glare. Question 9 - Which configuration is least glary: 1 = with background lighting, 2 = without background, 3= no difference

5.4.3. Individual Data Recordings

Individual data recordings are presented in Appendix I – see example in Figure 5-25 . Sets of pupil diameter and gaze direction are sampled approximately 50 times per second. Consequently, each individual data set consists of approximately 120,000 spreadsheet rows, so only the graphical representations are included. Graphs include:

- A row of graphical icons illustrating the test room lighting conditions minute by minute
- Plots of the average of left and right eye diameters [mm] vs time
- Plots of the calculated figure "gaze distance from midpoint" vs time [%]
- Plots of the pupil diameter vs time at shifts of lighting conditions (approximately one minute between changes)

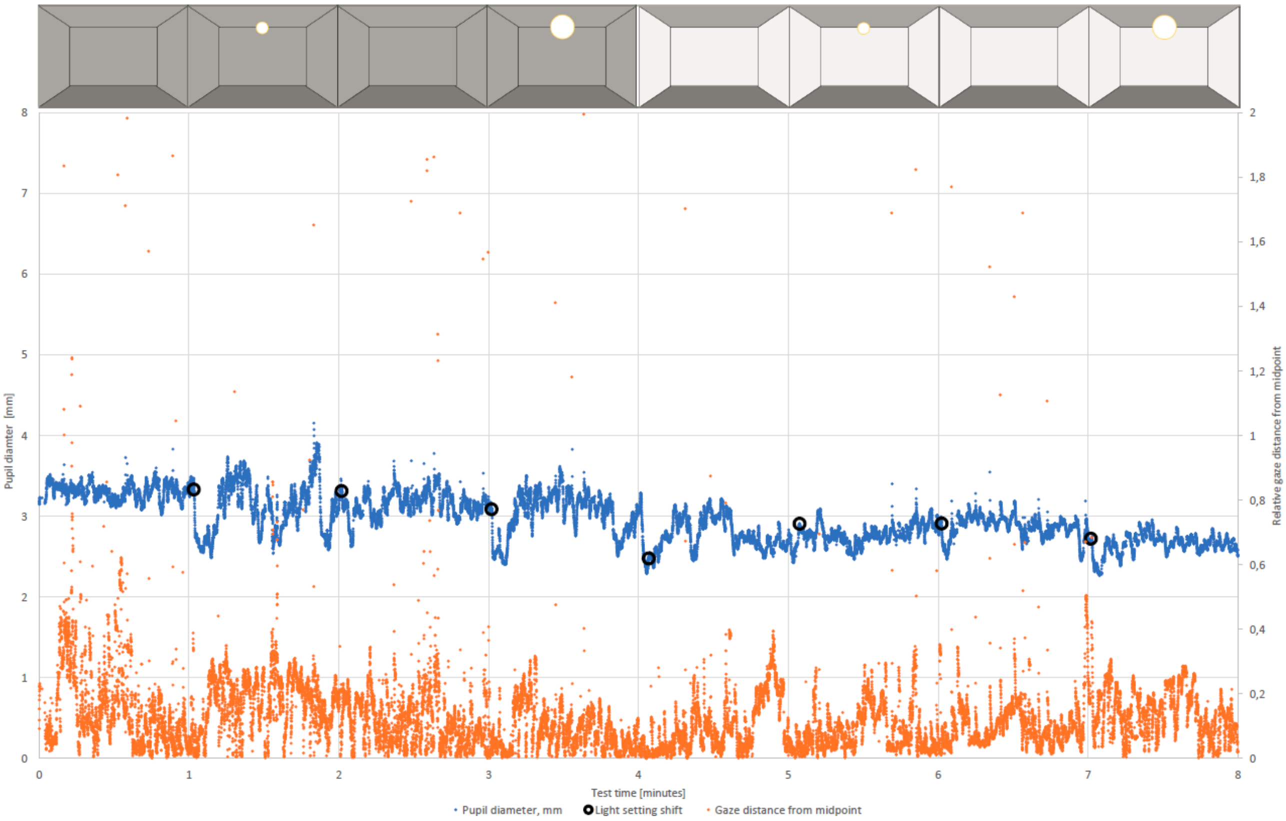

Figure 5-25 Example of output, participant 12

Pupil diameters from 2 to 6 mm were observed, but with great individual differences:

- Some participants have almost steady pupil diameters with small fluctuations and no big difference depending on wallwashers being on or off. In Figure 5-26, such individual fluctuation patterns are illustrated via the minute-by-minute standard deviations of the pupil size.
- Some participants react with immediate pupil constriction upon glare source onsets (start of minute 1,3,5,7), and some reactions are almost negligible

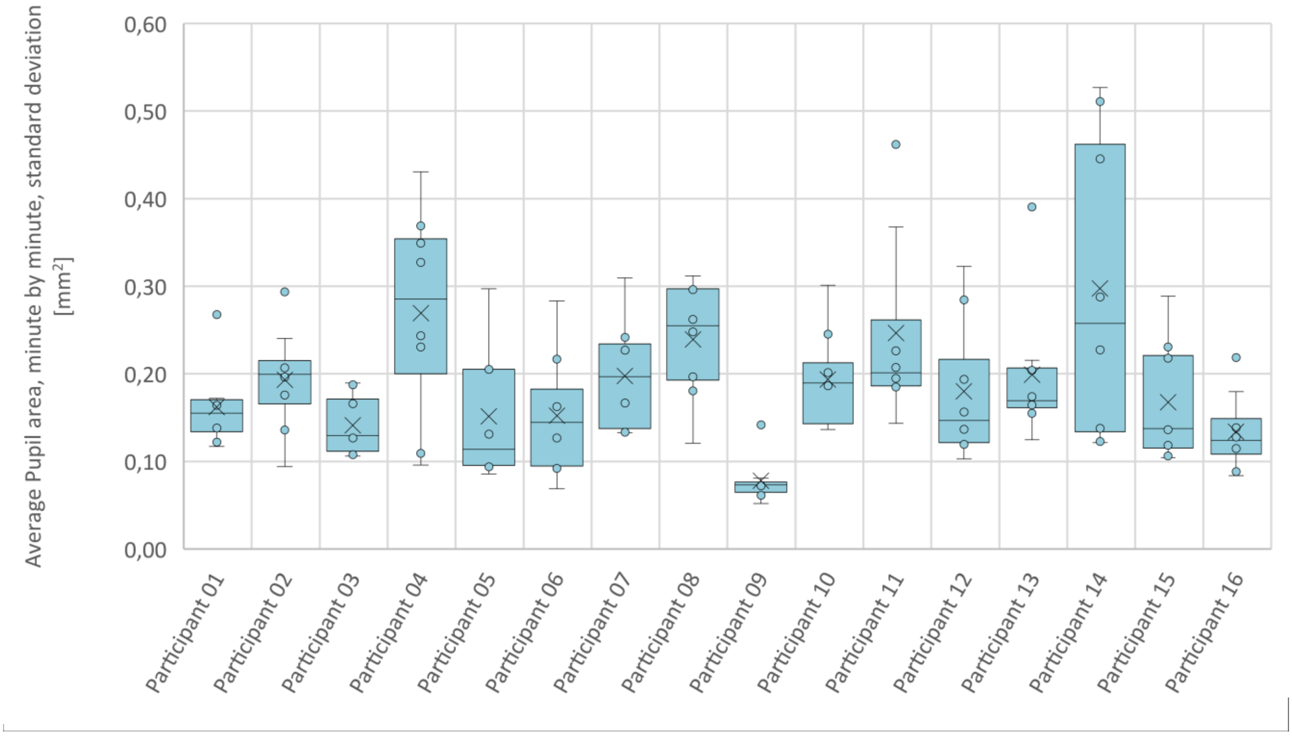

Figure 5-26 Individual pupil area stability illustrated through a box plot of standard deviations of the minute-by-minute pupil area (there are 8 rings per participants, but some rings cover each other. Each ring represents the individual minute-by-minute standard deviation of the pupil area. Each cross represents the individual 8-minute standard deviation of the pupil area

Observed pupil diameter averages do not seem to depend on gender – both genders average around 3,4 mm with similar standard deviations. See Figure 5-27.

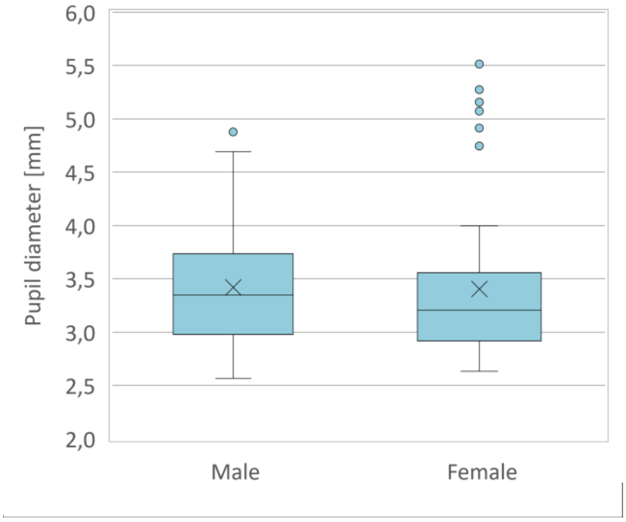

Figure 5-27 Observed average individual minute-by-minute pupil diameters as a function of gender. Only outlying data points shown with rings.

5.4.4. Variations in Gaze Directions

Great variations with regard to gaze steadiness were observed as well. Some gazes are extremely steady (e.g. participant 14) and some fluctuate a lot (e.g. participant 03) – see Figure 5-28. No directly apparent relation between pupil size fluctuations and gaze fluctuations is seen.

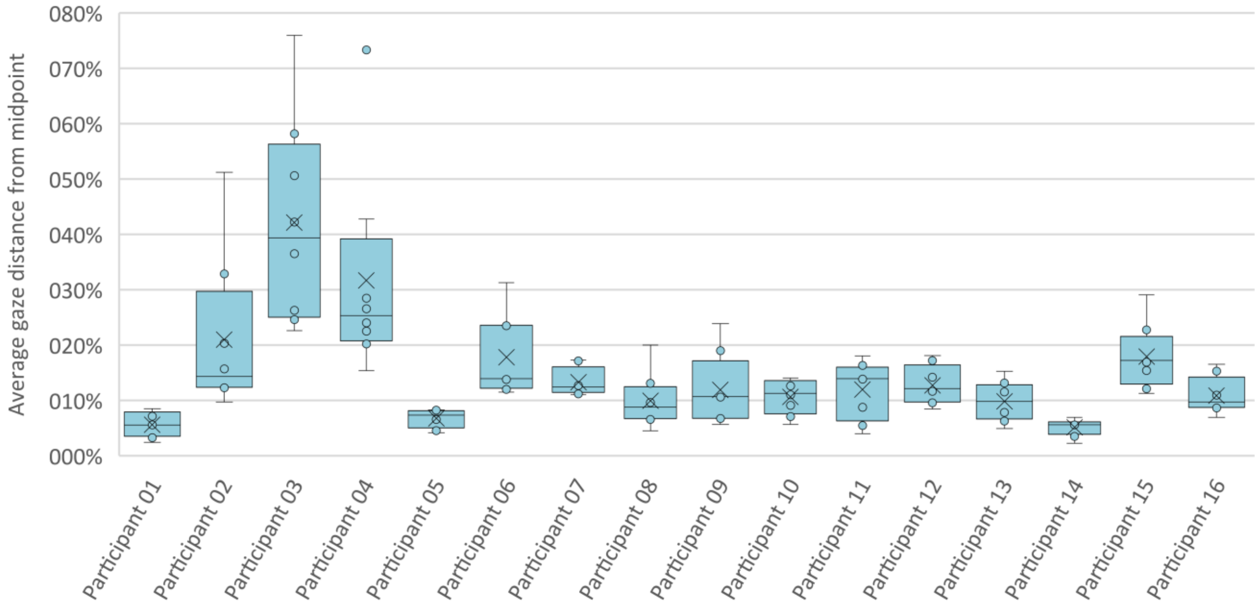

Figure 5-28 Individual gaze instability illustrated through a box plot of minute-by-minute average gaze distances from midpoint

Gaze instability does not seem to depend on neither wall washer presence or vertical illuminance, see Figure 5-29 and

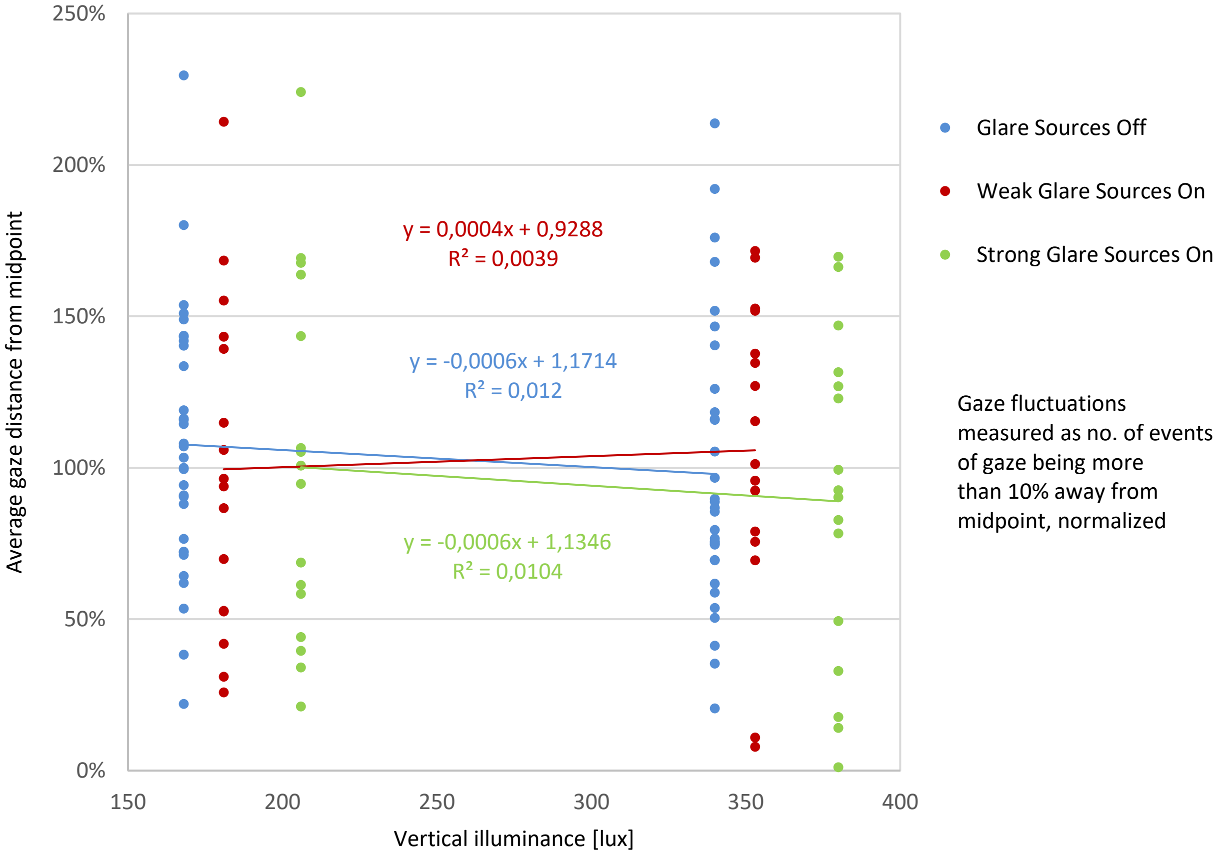

Figure 5-30.

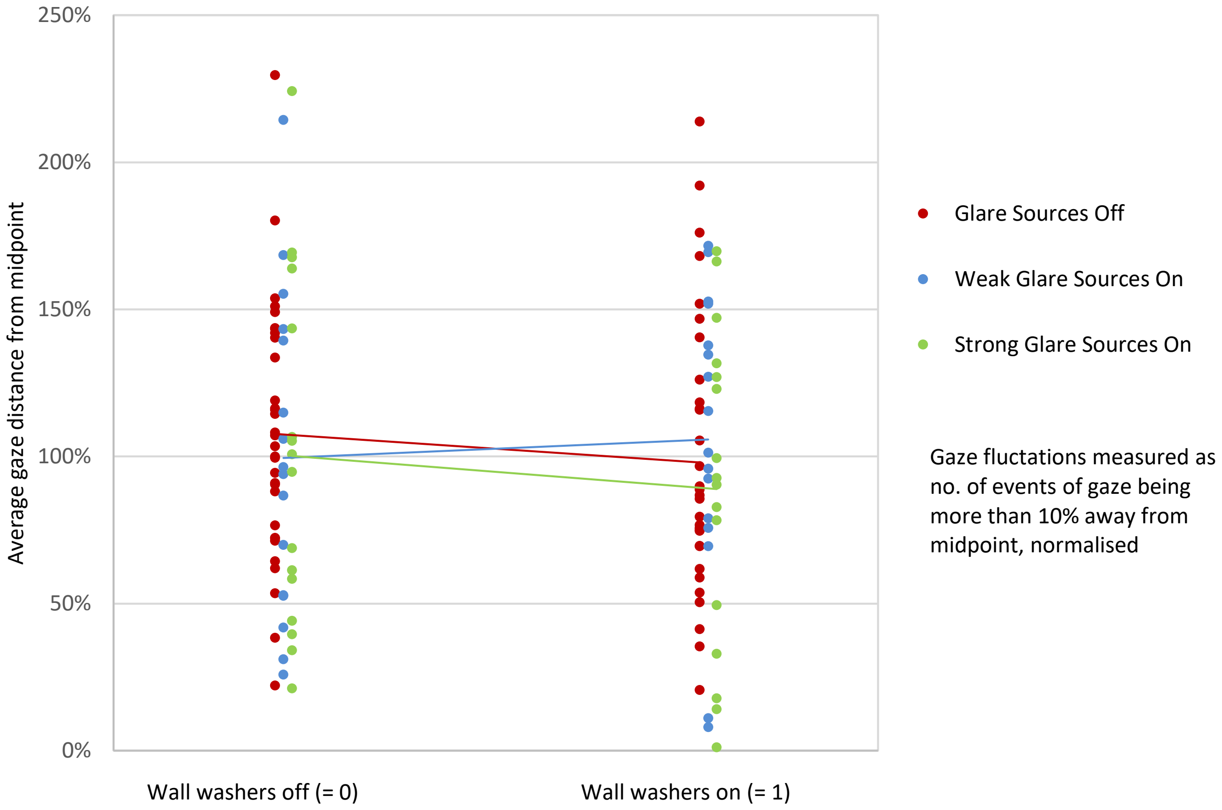

Figure 5-29 Average fluctations and dependency on wallwashers presence

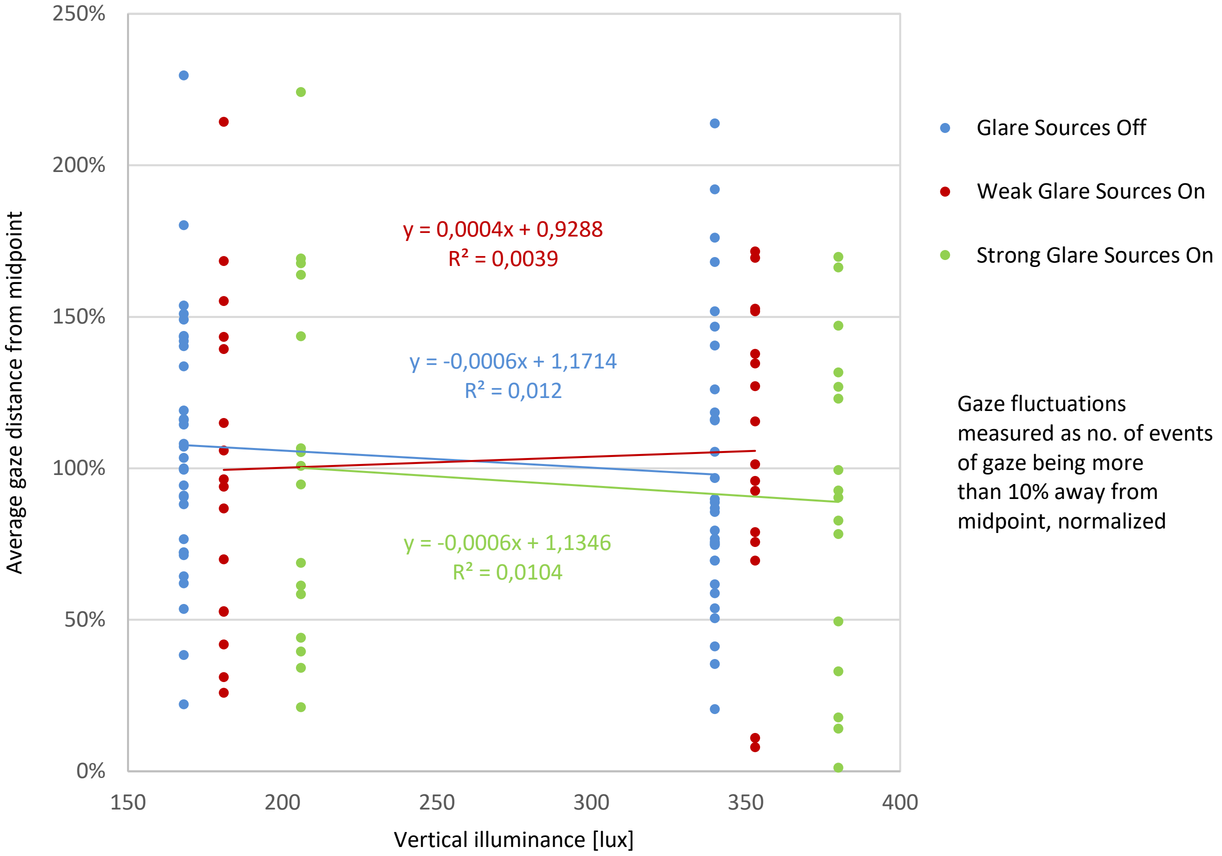

Figure 5-30 Average gaze fluctuations and dependency on vertical illuminance

Gaze/view directions can also be illustrated quite effectively via output directly from the Tobii software. Heatmaps and gaze plots that shown gaze directions and durations directly on snapshots from the built-in camera in the Tobii glasses is an effective way of showing predominant visual interests. An example of a gaze plot is shown in Figure 5-31. An example of a heat map is shown in Figure 5-32.

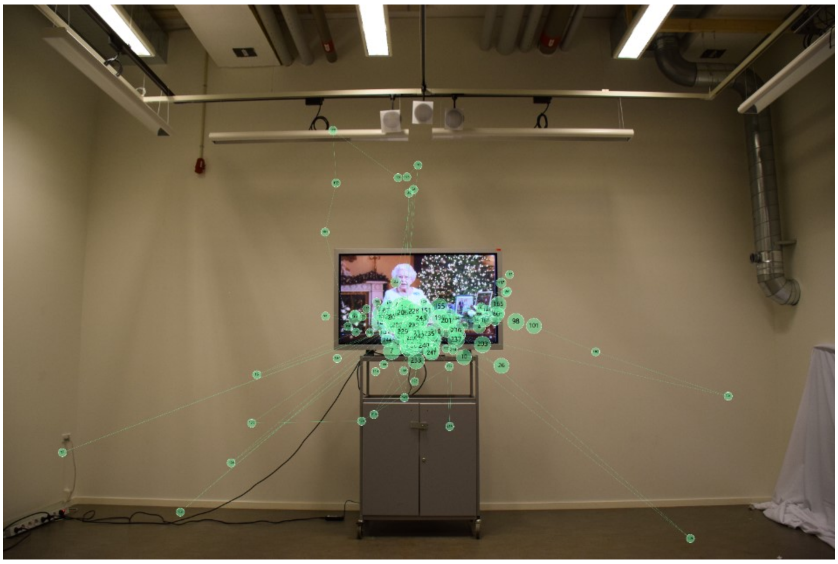

Figure 5-31 Example of gaze plot from Tobii software. Gaze from one participant through all 8 minutes

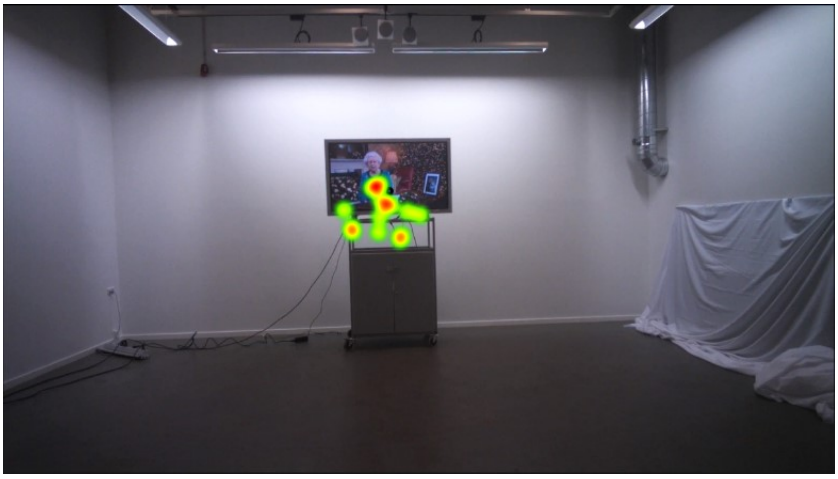

Figure 5-32 Example of a heat map from the Tobii software. Gaze from one participant during 1 minute of test

5.4.5. Sensitivity to Shifts in Light Settings

Just after changing a light setting, the pupil will react rapidly. Retinal photo-pigmentation reacts rather slowly, so decreasing the pupil size is probably the fastest adaption mechanism to protect the retinal cells from overload and to gain good vision as soon as possible. Hence, after making big changes (e.g. turning on wall washers, or turning on the most powerful glare scenario) in many cases we can observe a big shift in pupil diameter followed by some stabilisation, see Figure 5-33.

As it can be seen from analysing the individual output in Appendix II, this effect cannot be found generally – or may be hidden in general instability patterns.

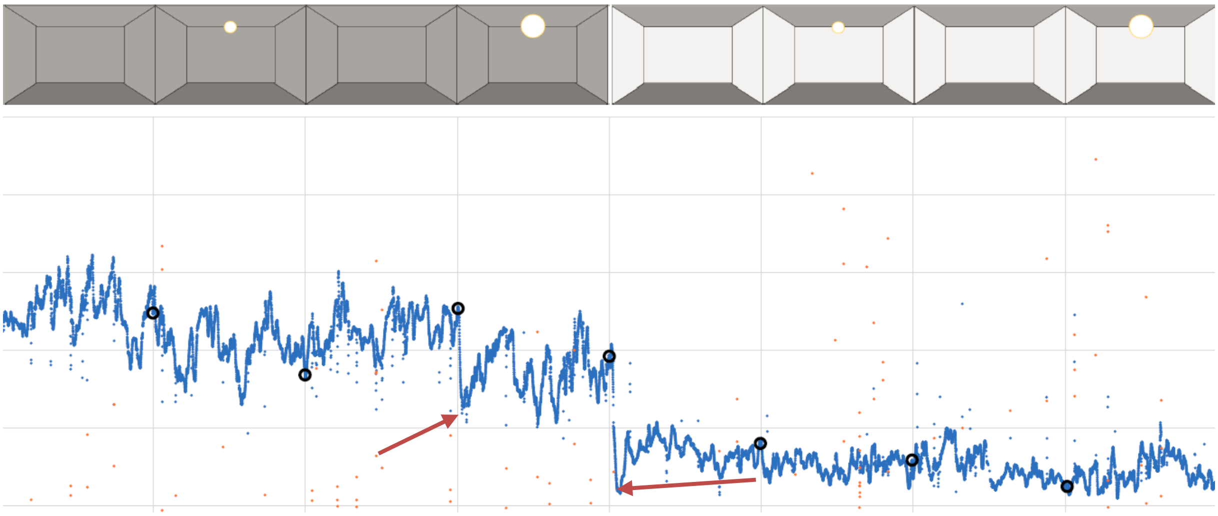

Figure 5-33 Example of pupil diameter shifts following big changes in light settings

Nevertheless, the amplitude of the pupil diameter shift appearing within the first 4 seconds after changing light setting can be deducted from data and analysed.

All participants seem to have a tendency for fast pupil constriction rather than fast pupil expansion. Males seem to have a wider reaction range and slightly larger amplitude on constrictions. See Figure 5-34.

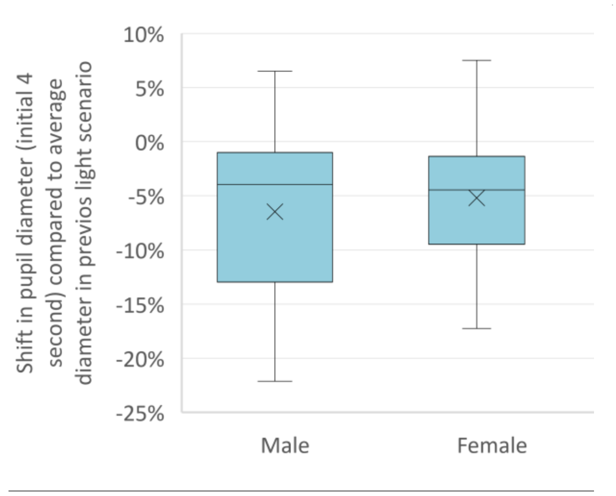

Figure 5-34 Observed sensitivity to light setting shifts as a function of gender

As this spontaneous reaction has the potential to immediately reduce vision, it is interesting to see whether this effect is correlated to the participants’ self-reported glare-sensitivity. Figure 5-35 illustrates the 16 times two events of harsh shift in glare: Wall washers are off, and a glare source is turned on. The shift amplitudes are plotted against the self-reported glare sensitivity, and no apparent correlation is found.

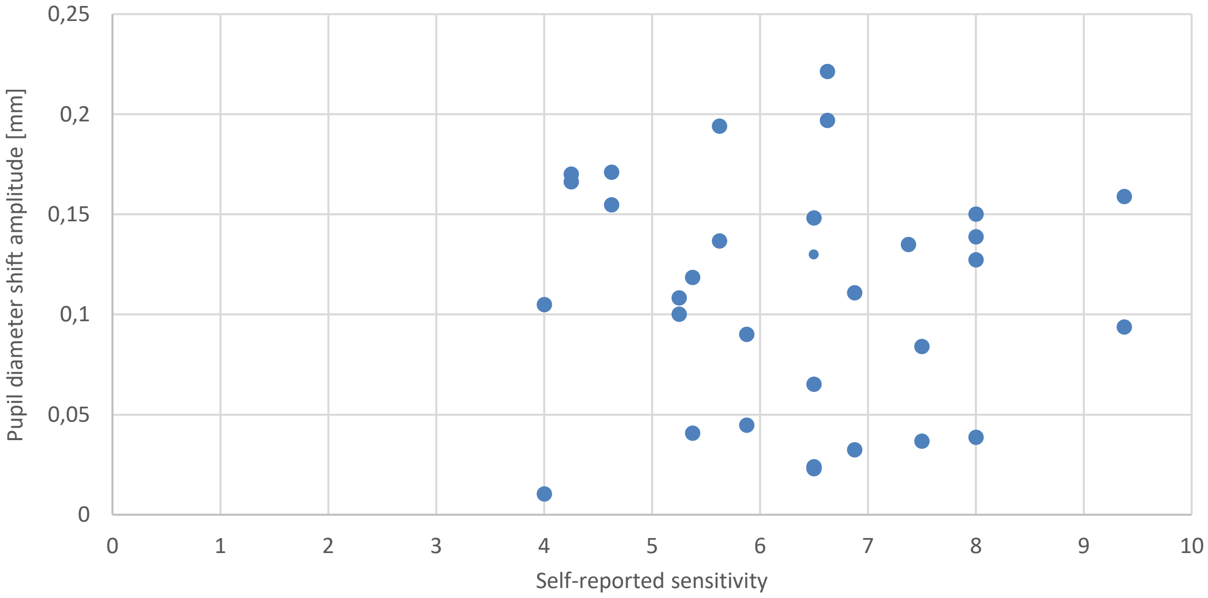

Figure 5-35 Pupil diameter shift amplitude [mm] (interval 4 seconds after shift to wall washer off, glare source on) as a function of self-reported glare sensitivity

5.4.6. Participant Fatigue and Effects of Experiment Rotation

It is important that the set-up of the test influences the results as little as possible. As participants were asked to focus their attention to the TV-set for a total of 8 minutes under varied lighting conditions, some fatigue could be present. However, plots of gaze and pupil size fluctuations (see Appendix III) as a function of time do not show any apparent patterns, as e.g. an increase in gaze fluctuations.

All participants found it relatively easy to stay focussed on the task (self-reported), which might be another indication of fatigue not being a problem.

Experiment rotation (initially wallwashers on for four minutes/initially wallwashers off for four minutes) does not seem to impact significantly on average results although a slightly larger spread in average pupil size seem to occur if wallwashers are off initially (see Appendix III).

All differences in fluctuations in gaze seem to be governed by individual factors not recorded (e.g. different levels of boredom with the stimuli).

5.4.7. Analyses of Effects of Glare and Wallwashers

All light settings influence both the horizontal illuminance in the space and the vertical illuminance on the eyes of the participants, see Figure 5-36. When the vertical illuminance is low (≈180 lux), the pupil diameters vary between 2.8 and 5.5 mm. When the vertical illuminance is high (≈360 lux), this variation is much smaller, only about 2.5 to 3.6 mm.

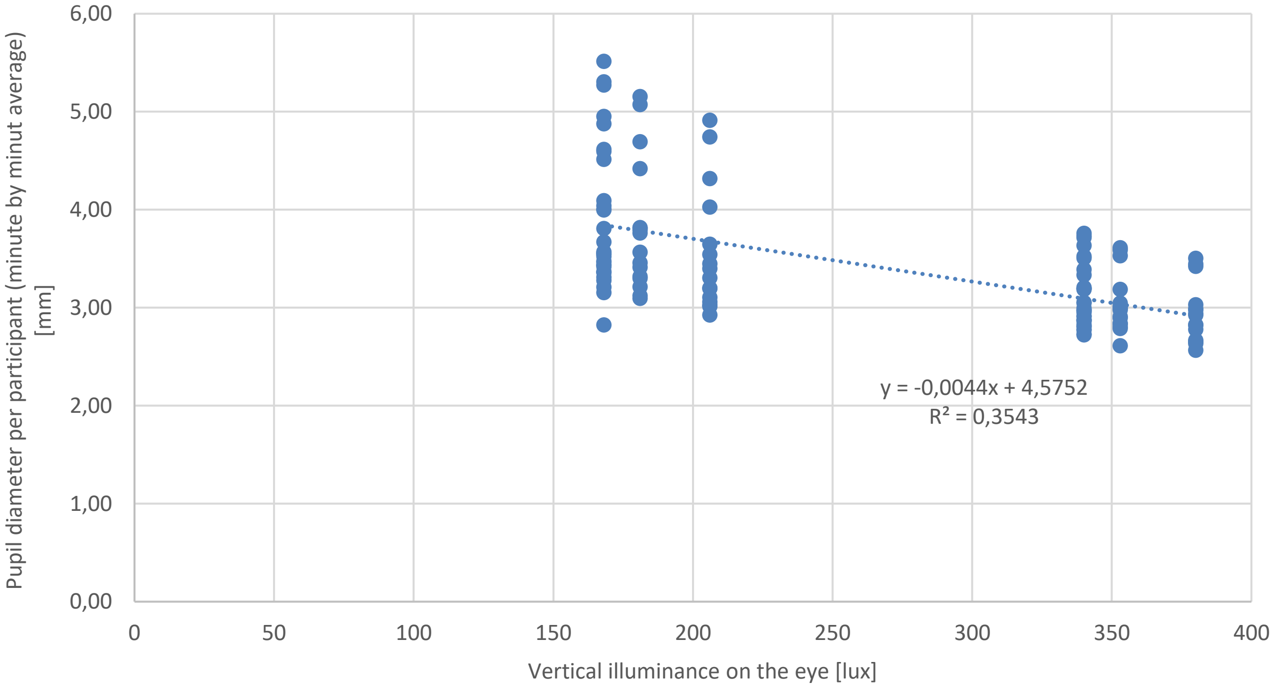

Figure 5-36 Average pupil diameter [mm] as a function of the vertical illuminance

In the following pupil areas are generally calculated as individually normalised values (% of overall individual average) instead of mm^2. This is done to overcome considerable individual differences and enable comparisons between individuals.

Normalised pupil areas are considerably smaller when wallwashers are on, see Figure 5-37.

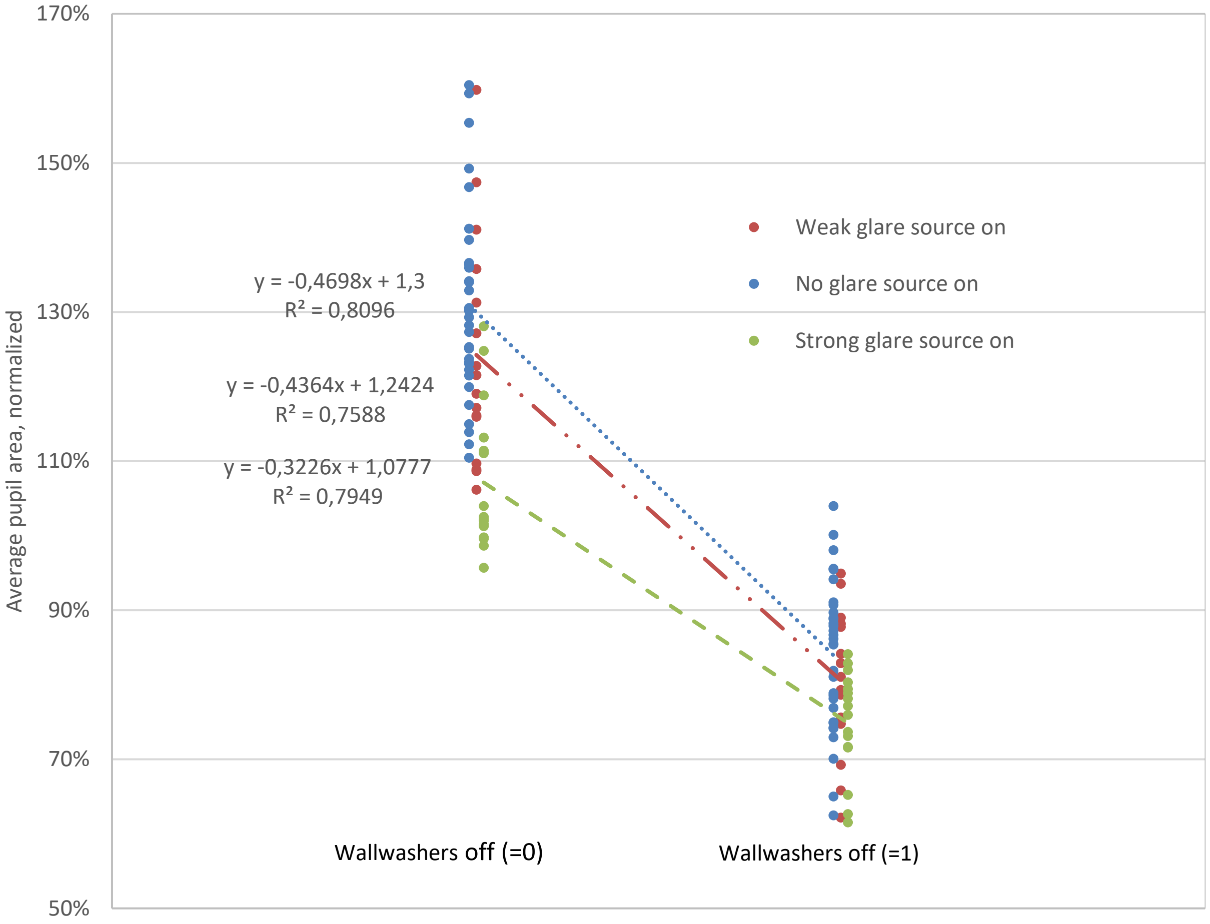

Figure 5-37 Average pupil areas (normalized) dependency of wall washer presence

More than anything else the normalised pupil areas seems to depend on the vertical illuminance on the eye, see **Fejl! Et bogmærke kan ikke henvise til sig selv.**. The weak glare source did not alter the vertical illuminance on the eye much (from 168 lux to 181 lux, and from 340 to 353 lux) – thus the tendency lines almost line up. The tendency line connecting the two situations with strong glares source on (with and without wall washers) is not quite as steep, suggesting that vertical illuminance is not the only factor influencing the relative pupil area.

The normalised pupil area (in relation to individual participant averages) is much stronger correlated to vertical illuminances (Figure 5-40, $R^2 \approx 0.80$) than just the average measured pupil diameter (Figure 5-39, $R^2=0.39$).

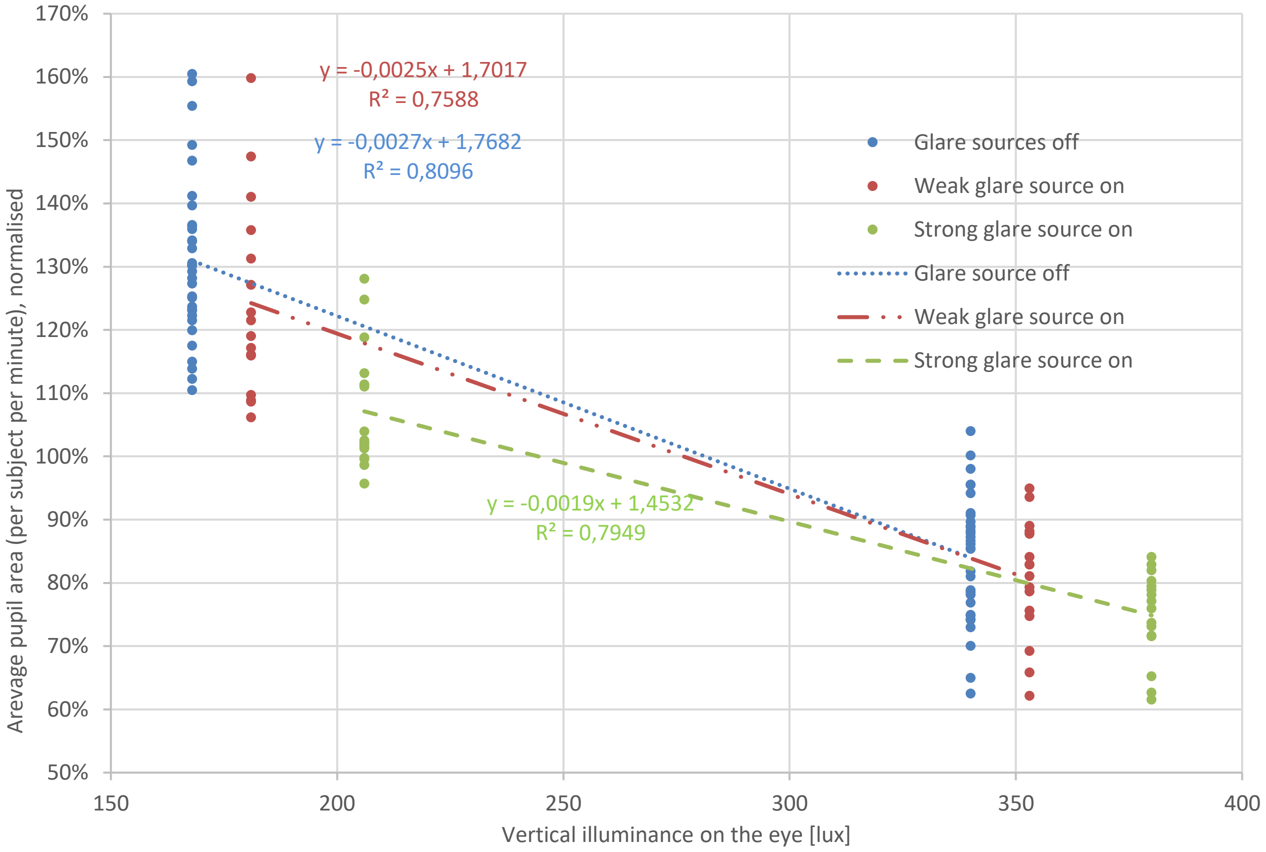

Figure 5-38 Average pupil area dependency of vertical illuminance

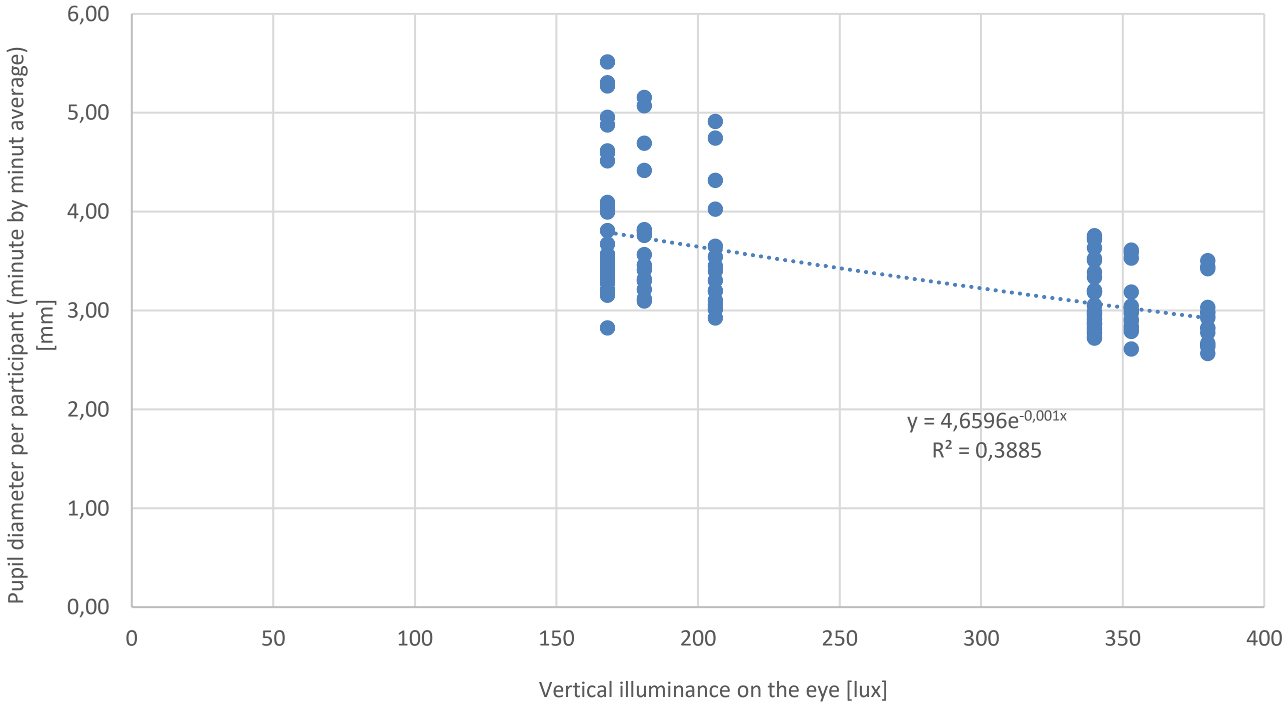

Figure 5-39 Average Pupil diameter [mm] as a function of the vertical illuminance

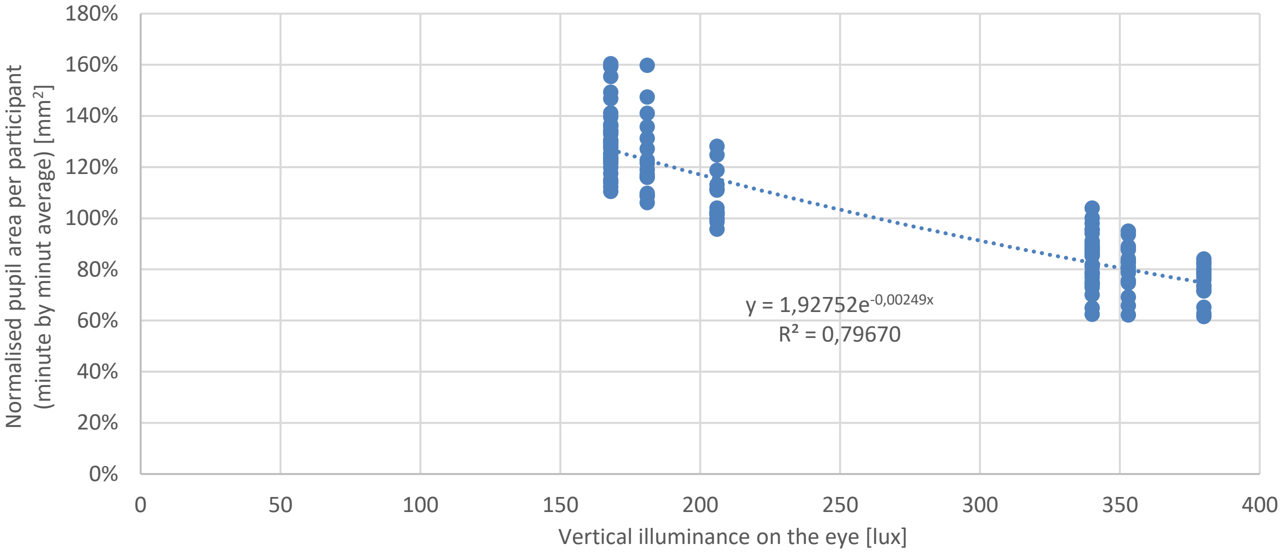

Figure 5-40 Normalised average Pupil area [mm²] as a function of the vertical illuminance

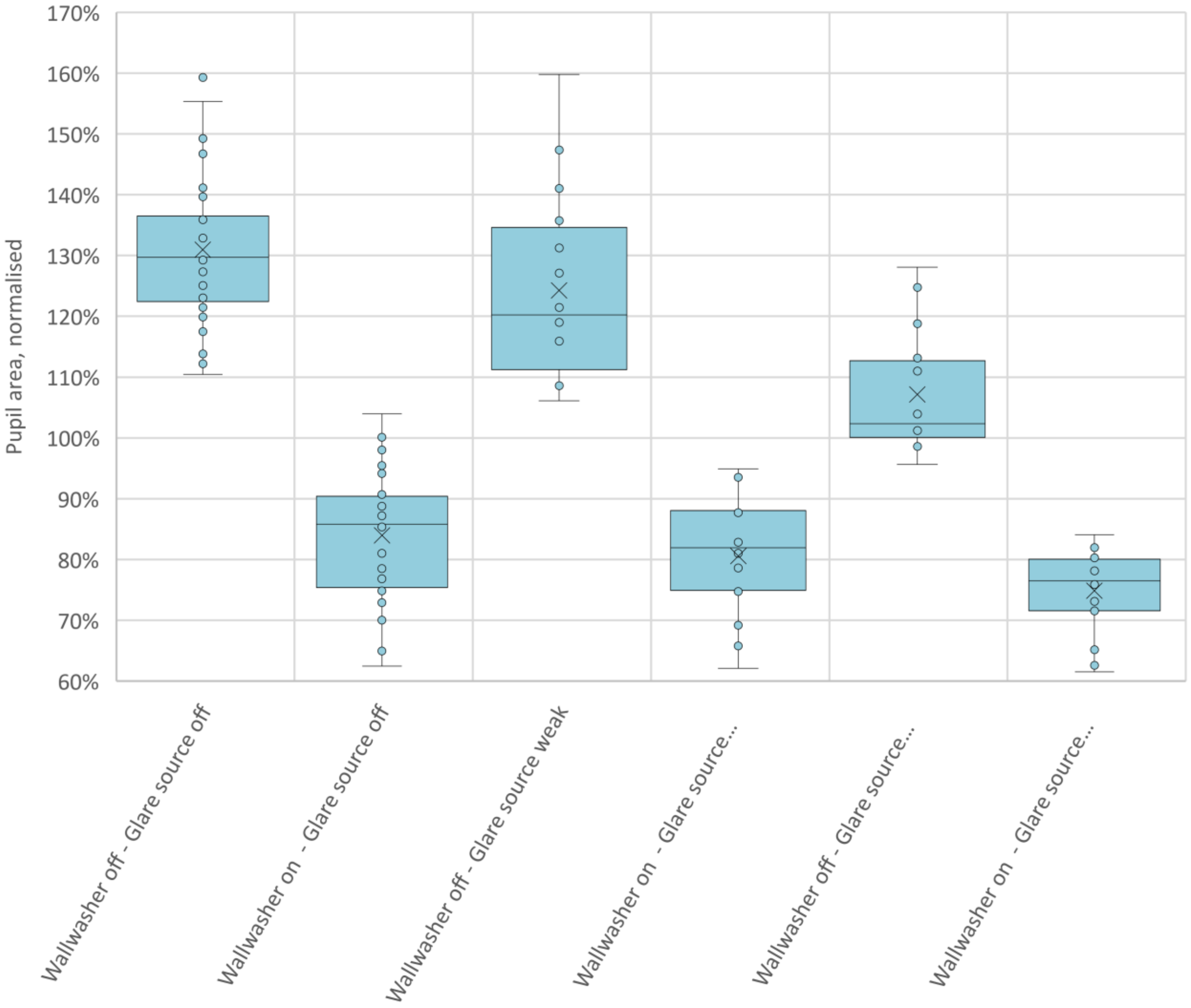

Figure 5-41 Pupil area as a function of light settings

Plotting the average pupil area (normalized, subjective, minute by minute) as a function of the UGR value it is clear that UGR is not the only factor influencing the pupil sizes, see Figure 5-42. The plotted values fall in two different clouds depending on wall washer presence. All though the wall washer presence is implicit in the UGR formulation represented as L_b, the background luminance, the UGR value does not itself explain effects on the relative pupil area. Tendency lines are presented as exponential relation, since this is the best fit, and further limit responses not to go below 0.

Further the correlations are not very strong (R^2 is 0.28253 and 0.10566). If UGR was the only important factor, the two clouds would have been one. All though the weak glare source causes the UGR to increase a lot (from 6.4 to 24.2 with the wallwashers on, and from 9.4 to 30.0 with the wallwashers off), only the strong glare source seems to make sizeable changes in the pupil area (as it is also seen from Figure 5-41). Thus, with the wallwashers off, the change in UGR from 9.4 to 30.0 will decrease the pupil area on average with around 16%. With the wallwashers on, the change in UGR from 6.4 to 24.2 will only decrease the pupil area on average with around 7%.

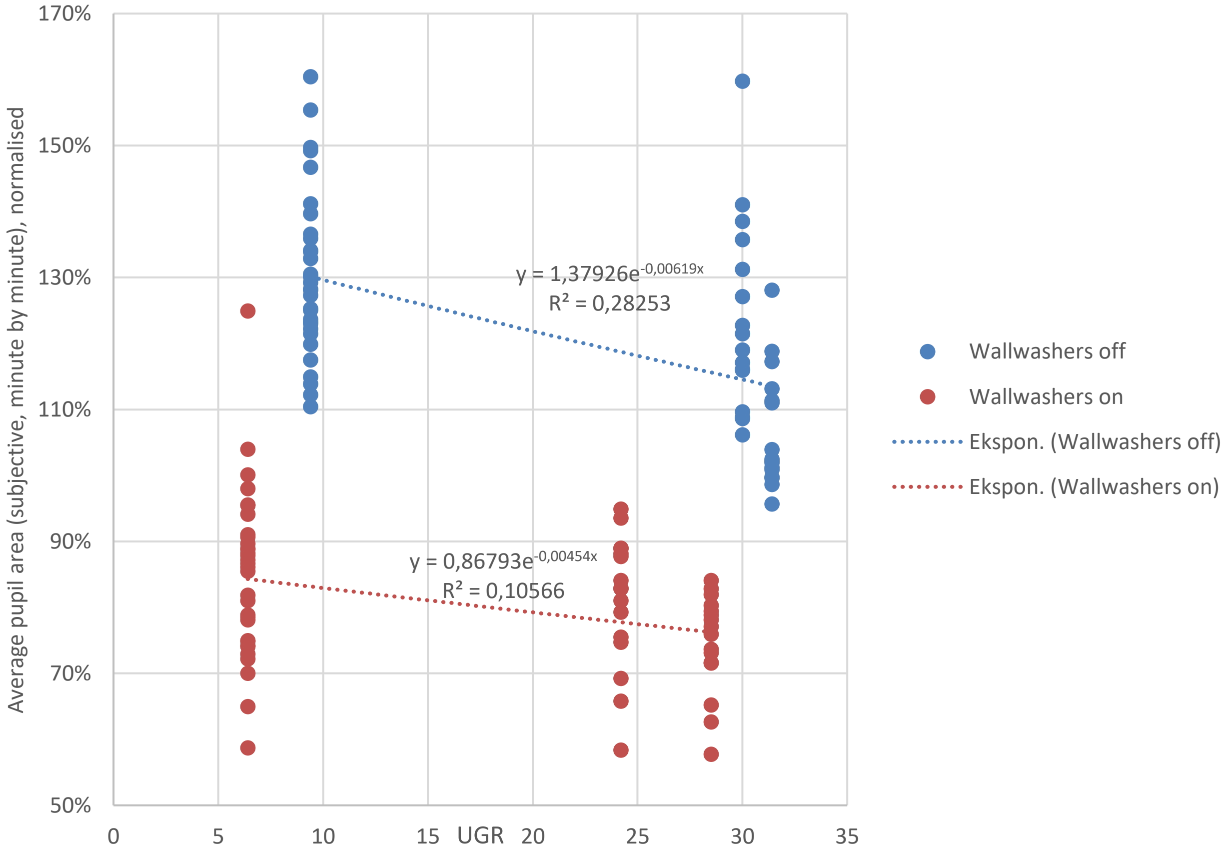

Figure 5-42 Pupil area (normalized) as a function of UGR value

5.5. Discussion

5.5.1. Statistical Analyses and Results – Illuminance Dependency

As seen in section Figure 5-40, the best predictor for the observed changes in the pupil sizes is the vertical illuminance on the eye of the observers.

The tendency line (exponential function) with the following equation describes the measured data best (R^2 = 0.80):

$$A_r = 1.93 * e^{-0.00249*I_v}$$

Where
A_r is the (individually normalised) measured pupil area [%]
I_v is the measured vertical illuminance [lux] on the eye of the observer

Nevertheless, this equation has a problem:

When increasing the illuminance to e.g. 10,000 lux (a very high, but possible illuminance indoor), the result of the equation above is about 0%. When decreasing the illuminance to zero (darkness), the equation renders 193% as the result. Thus, his equation renders result in the range

$$[lower\ limit; upper\ limit]_{simulation\ 1} = [0\%; 193\%]$$

Normal pupils will operate in the range 2-8 mm diameter, corresponding to areas 4 – 64 mm^2. The global average of all pupil diameters measured is 3.42 mm, corresponding to an area of 11.7 mm^2 (= 100% in the graph). Expectations should therefore be that the normalised pupil area should be found in the interval

$$[lower\ limit; upper\ limit]_{expected} = \left[\frac{4\ mm^2}{11.7\ mm^2}; \frac{64\ mm^2}{11.7\ mm^2}\right] = [34\%; 547\%]$$

Given these limitations, the simulation in Figure 5-43 may be a more relevant description of data (the two limiting data points added: [5 lux, 547%] and [10,000 lux; 34%).

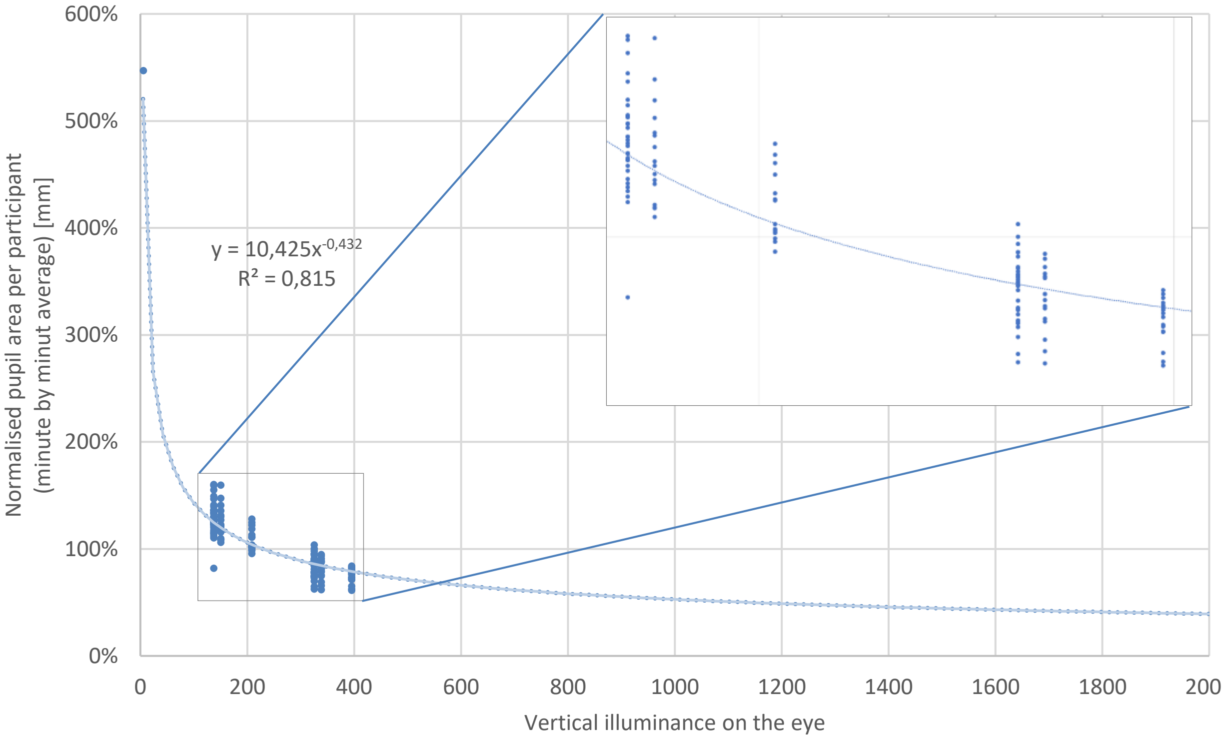

Figure 5-43 The normalised pupil areas of the participants as a function of the vertical illuminance on the eye. A tendency line has been added to the observed data and two extra limiting data points.

The new tendency line (power function) with the following equation describes the measured data + the two added points best ($R^2 = 0.815$):

$$A_r = 10.425 * {I_v}^{-0.432}$$

Where
A_r is the (individually normalised) measured pupil area [%]
I_v is the measured vertical illuminance [lux] on the eye of the observer

This equation still predicts the measured data reliably (R^2=75.3 without the two extra points), and is regarded a the closest approximation that can be made from the study.

As mentioned previously, the vertical illuminance on the eyes of the participants is not independent from UGR, as turning on the glare sources will inevitably also increase the vertical illuminance. Hence, the vertical illuminance also expresses the power of the glare source.

In Figure 5-44, the normalised pupil area is plotted against the vertical illuminance again – but divided into two different clouds: Wall washers turned off and on. Although the correlation is not very strong (R^2=0.37 and R^2= 0.15), it is seen that with the background illuminance (i.e. the wall washer setting) fixed, turning on the glare sources causes the pupil area to decrease. From the slope of the two linear tendency lines, we can deduce that the impact of turning on the glare sources is less when the wall washers are on (in red 0.00227*I_v versus in blue 0.00626*I_v). This corresponds to decreases in normalised pupil areas from -24% to -9%, see Table 5-5.

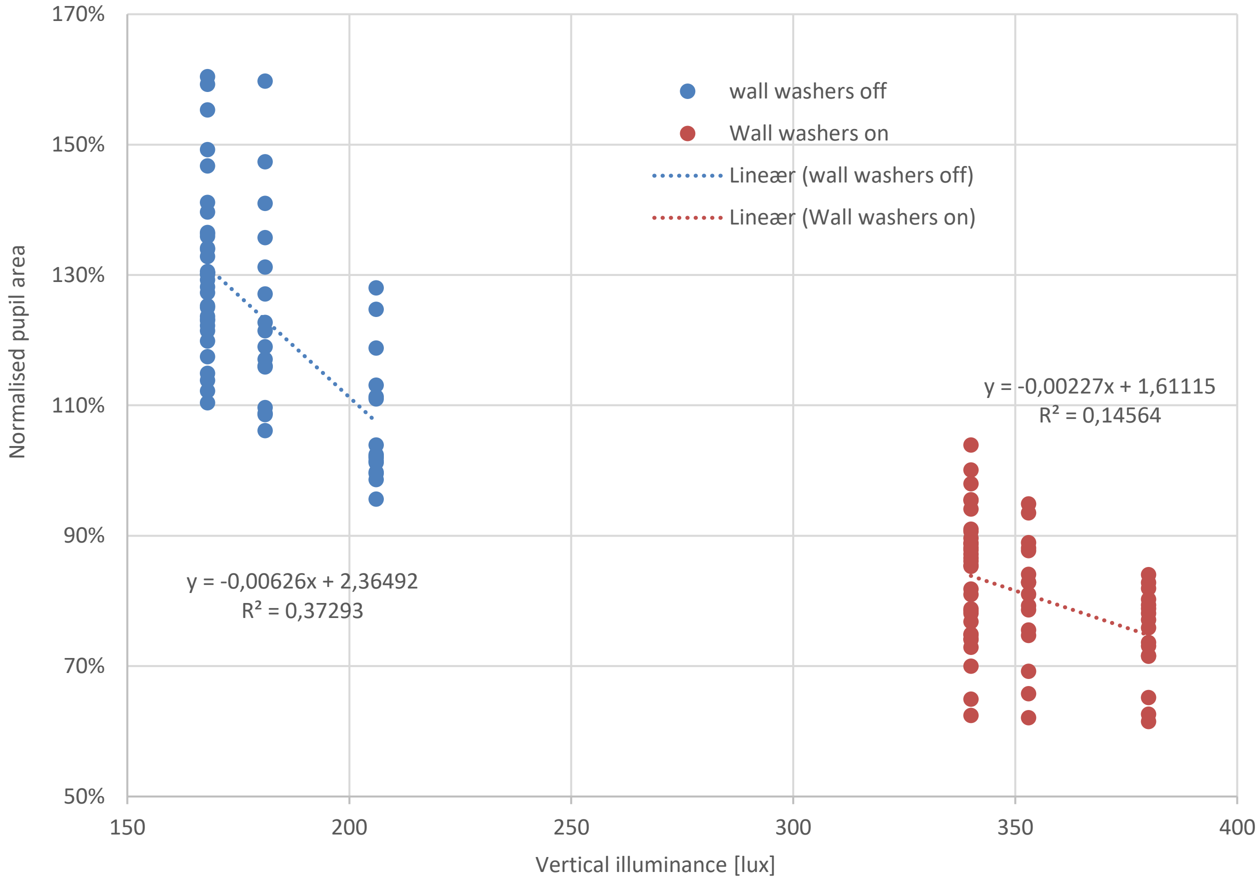

Figure 5-44 Normalised pupil area plotted against vertical illuminance - divided into two different clouds: Wall washers turned off and on

Light settings		Vertical illuminance	Simulated* normalised pupil area	Difference
Wall washers off	No glare source	168 lux	131%	-24%
	Strong glare source on	206 lux	108%	
Wall washers on	No glare source	340 lux	84%	-9%
	Strong glare source on	380 lux	75%	

*from regression lines in Figure 5-44

Table 5-5 Calculation of effects on light settings on normalised pupil areas

5.5.2. Statistical Analyses and Results – Glare and UGR Dependency

UGR and vertical illuminance on the eye of the observer are not independent figures. The vertical illuminance increases, when the glare sources are turned on.

As seen from Figure 5-42, it cannot be concluded that UGR is a proper predictor for pupil area. However, there is a tendency, that in a given visual environment (i.e. with a steady background luminance) a high UGR will lead to pupil constriction. The two tendency lines suggest that when going from imperceptible glare (≈UGR 13) to intolerable glare (≈UGR 13) one should only expect a decrease in pupil area of 6.1% to 12.6%.

As the UGR formula has many year of proven practical applicability, it is fair to propose that most of the discomfort emanating from glare does not come from pupil reactions, but may arise from processes in the retina or brain processes, that have not been studied in the current experiment.

In normal office environments, glare should be below UGR 19 for all work stations (EN 12464-1: 2011). In some installations glare may be higher – UGR 22 or maybe even UGR 25.

According to the tendency lines in Figure 5-42 we should expect the pupil area to decrease by 1-2% when increasing UGR by 3 (from 19 to 22), or to decrease by 2-4% when increasing UGR by 3 (from 19 to 25).

It is notable, that a larger relative decrease in pupil area should be expected when the scene is not very bright (equalling a low background luminance), as it is also seen from Table 5-5. Turning on the glare sources also increase the vertical illuminance, leading decreased pupil area.

In this study, none of the settings were actually very dark. Even without the wallwashers, the general lighting in combination with white ceilings and wall contributed to making the scene quite normal in terms of perceived brightness. Hence, in some environments e.g. with darker room surfaces or dark furniture a strong dependency between glare and UGR may be expected.

5.5.3. Statistical Analysis – Glare and Pupil Fluctuations

It is interesting to analyse whether the presence of a glare source has an impact on pupil fluctuations in the adapted stage (i.e. after initial pupil reactions, estimated to 4 seconds after shift I light settings), as this may be an indicator of general visual discomfort.

The severity of the fluctuations (=the general instability of the pupil area) can be illustrated by calculating the standard deviation of the pupil diameter for each participant and for each light setting excluding the initial 4 seconds after shifts in light settings. The output of the calculation can be seen in Appendix VI and Table 5-6.

From these figures (comparing cells marked with blue and yellow) there is no apparent relation to the severity of glare, which is remarkable.

Wallwasher	On	On	On	**On**	Off	Off	Off	**Off**	**Off:On**
Glare source	Off	Low	High		Off	Low	High		
UGR	6.4	24.2	28.5	**All**	9.4	30.0	31.4	**All**	
	0.139	0.120	0.147	**0.135**	0.220	0.235	0.221	**0.228**	**1.689**

Table 5-6 Excepts from Appendix VI - Pupil fluctuations after initial adaptation. Pupil diameter standard deviation [mm] - excl. 4 initial seconds after shift. Average for all participants per light setting

An interesting and important output is, that the pupil fluctuations seem to depend on the presence of wallwashers. On average, the pupil diameters seem be much more stable when the wallwashers are on (bright environment, less contrast), as the standard deviation of the pupil diameter is about 70% higher (cell marked with green) with the wallwashers turned off. Consequenty, it looks as if *low illumination levels* or *a rather dark field of vision* triggers pupil size instability.

This tendency is the same for all individuals (cell marked with light green) except participant 16, where pupil fluctuations seem unchanged throughout the test.

5.5.4. Light Settings and Visual Comfort Parameters

In this study, we have looked for several objective metrics of visual discomfort:

Possible metrics for visual comfort	Results of study	Advice for practitioners
Fluctuation of gaze (possibly measuring annoyance with glare)	No correlation with neither vertical illuminance at the eye, nor glare source luminance, age, gender or others	-
Size of normalised pupil area (possibly measuring overreaction related to glare)	Small dependency on glare source strength. (strong depency of vertical illuminance not considered as a visual comfort issue).	Avoid glare, and provide light as ambient light to the space. Keeping the pupil area small may lead to better accommodation / focussing on details, but glare will lead to unnecessary pupil constriction. Avoiding glare and providing ambient light may have the potential for decreasing need for horizontal illuminance.
Fluctuation of pupil area (possibly measuring annoyance with glare)	Correlated with vertical illuminance at the eye, but not with glare source luminance	Provide ambient light to the space.

Table 5-7 Listing results of study with advice for practitioners

5.5.5. Discussion of Method

This study has deviced a method to investigate objective relations between indoor lighting conditions, pupil reactions and gaze. The method has been successful due to:

- Robustness against exterior disturbances and ease of replication (enclosed space with ordinary white walls and ceiling, standard furniture, lighting equipment, TV-set, stimuli, measuring equipment etc.)

- Robustness in experiment design (no bias from rotation detected, no bias from fatigue detected, equipment and setup fits all subjects)
- Ease of process completion
- Robustness of metrics
- Method applicable to all participants (except participants needing spectacles to view stimuli in a 6-meter range)

Hence, the method developed has the potential to be reused in many other experiments.

5.6.Conclusions

This project hypothesises that glary light causes the pupils to constrict excessively, thereby preventing part of the light from reaching the retina. The lighting becomes ineffective physiologically.

Through several pilot tests and a large experiment comprising 16 participants, the project has identified and disseminated a novel description of the relationship between the eye's reactions (pupil areas and gaze directions) in various office-like glare conditions. It has been shown, that indeed some excessive pupil constriction appears, and that up to 4% light may be saved in ordinary office environments alone through careful design.

Further, the project has produced some other unexpected, but important findings:

1) Pupil constriction is not (as hypothesized) governed by glare conditions as expressed in the UGR formula, but is strongly correlated simply to the vertical illuminance level measured at the eye. This leads to the conclusion that pupil constriction is just a minor part of the impact that glaring light produces in the visual system and that the mechannisms responsible for the perception of discomfort glare are likely to be be found in retinal reactions or in the nervous system including brain processes.
2) The use of wallwashers that reduced contrast in the field of vision greatly affected the pupil constriction stability, which may be an important visual comfort metric.
3) There are great individual differences in both pupil reactions and gaze reactions to the simple and rather ordinary lighting scenes presented to the participants.

Some results of our study were not as conclusive as expected, as far as the possible benefits for the perception of brightness of indoor surfaces, associated with reduction of glare.

Beyond the very new knowledge of behaviour of pupil in relation to lighting conditions, we can conclude that glare conditions lead to reduction of pupil size, even if pupil size still fluctuates a lot in relation to the visual task. It should be noted that the ambitions of the experiments were quite high, with conditions of experiments being very close from real life.

This is a major contribution to the scientific context. Experiments on glare are often conducted is very simplified viewing conditions.

Here we innovated with a realistic target (a soft moving video image), an appropriate distance of vision (to avoid excessive pupil constrictions related to myosis) and interesting balance of luminances between background and light sources.

The results suggest (but does not prove) that the use of wallwashers or the use of light distribution patterns with emphasis on vertical surfaces more generally can reduce energy consumption if the illuminance on horizontal surfaces could be reduced, because the overall perceived brightness and visual comfort of the room is improved due to the lower contrast provided by the more balanced luminous surroundings with the wallwashers.

If a smaller pupil size results in better visual acuity, then it would make sense to increase the adaptation luminance of a person completing visual tasks. With focus on computer screens as work task area, it would make sense to argue for increased luminance of the vertical surfaces of a room, perhaps in exchange for reduced luminance of horizontal surfaces.

Current focus of standards is on horizontal illuminance and glare reduction. Recessed downlighting systems and luminaires with sharp cut-off angles often result in dark walls and light horizontal surfaces, sometimes leading to a feeling of gloom. Lighter walls balance the impact of potential glare sources and provide a perception of a brighter space overall. The increased luminance on walls should provide better visual conditions overall.

Hence, the study points to direction for future standardisation, that would benefit from a focus on luminance distributions in a room and not illuminance on horizontal surfaces.

This holds true for both electric lighting and daylighting. Daylight glare can also be mitigated by providing splayed window reveals to introduce intermediate luminance values between the bright window glazing surface and darker adjacent wall surfaces.

6. Dissemination of Results

The results have been communicated in the following ways:

- Article for the magazine LYS (to be published 1st December 2017)
- Electronic newsletters of Danish Lighting Center
- Electronic newsletter of Danish Lighting Innovation Network.
- This report will be accessible through the webpage of Danish Lighting Center.
- A theme day on glare based on the project results and allowing for more expert input as well as practical implementation guidelines is planned for the autumn of 2017.
- The International Commission of Illumination (CIE) will be informed of this work during the session held in Seoul 23-26 october 2017: the board of the Indoor Lighting Division (Division 3) will be informed during their plenary meeting, as well as the Chair of the JTC 7 (D3/D1): Discomfort caused by glare from luminaires with a non-uniform source luminance - Naoya Hara (JP).
- A paper is on preparation to be published in Lighting Researh and Technology in 2018.

7. Future Work

In a future experiment, it would be extremely interesting to examine what happens to the pupil area if the vertical illuminance at the eye (adaptation luminance) stays fixed, i.e. to design an experiment where the downlights and/or wallwashers are dimmed when increasing the luminance of the glare sources to form a constant overall illuminance at the eye. Such an experiment could confirm which lighting design scenarios would provide the highest visual comfort. Measurements of the respective electricity use for the different lighting scenarios could also ascertain which lighting design scenarios would provide opportunities for electricity savings alongside providing good visual comfort.

In addition, further analysis work might look at the massive data sets collected in this experiment to better digest the information provided by the eye traking devices for both gaze and pupil size behaviour. Data provided in this report, for example, do not show detailed information on the differences in gaze patterns of observers with respect to the presence of glare sources in the field of vision.

It will also be necessary to provide better descriptions of the spatial and photometric characteristics of the experimental setup in order to allow for repetition of the experiment by other researchers.

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Appendix I Questionaire

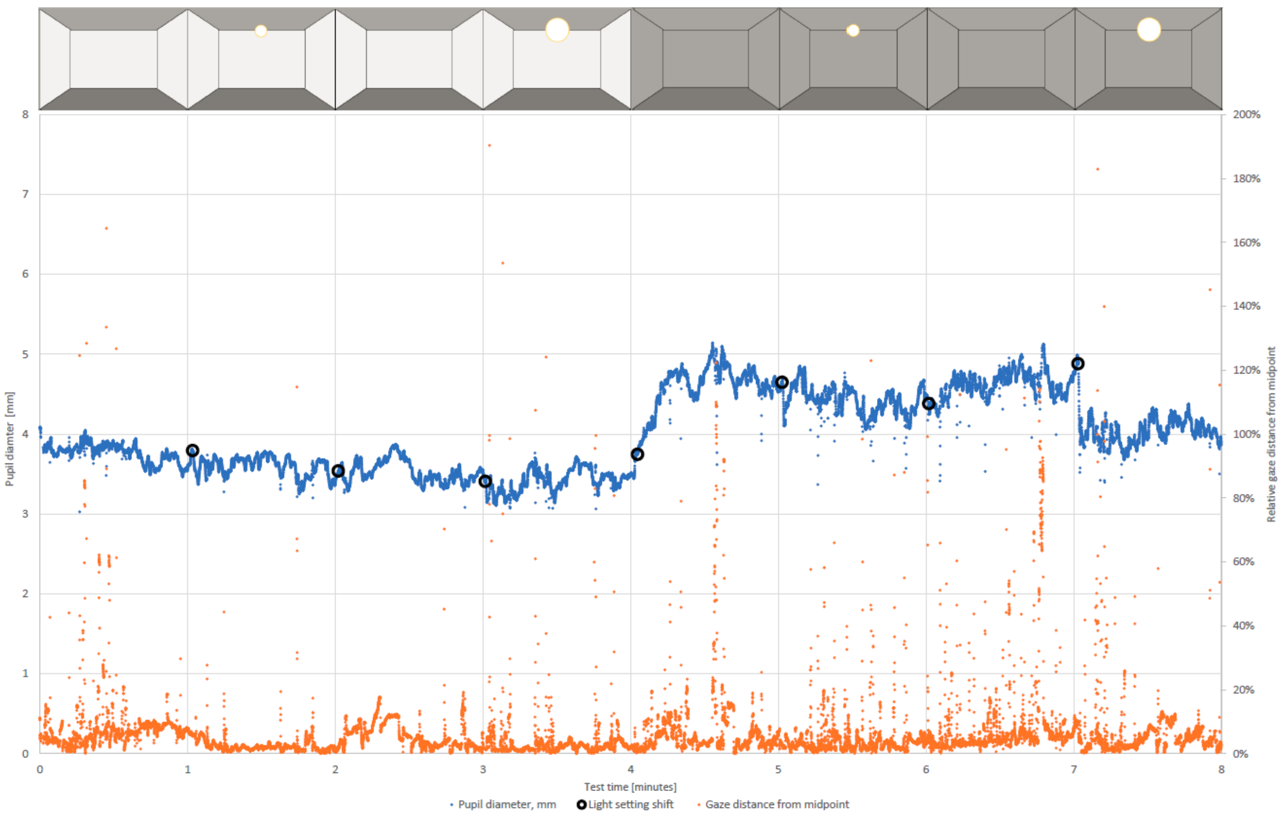
#	Question	Scale	
	Gender	Male/female	
	Age	#	
	Du you have normal (or corrected to normal) eyesight?	Yes (1) /no (0)	
Questions 1 through 8 concerns both working and non-working time			
1	Are you bothered by glare in general?	1-10	(1) No, never – (10) Yes, often
2	How serious are these glare problems?	1-10	(1) I don’t feel them – (10) They prevent me from doing tasks
3	Are you bothered by glare from cars travelling in the opposite direction at night?	1-10	(1) No, never – (10) Yes, often
4	Du you find it hard to read road names or the like because of headlights on cars travelling in the opposite direction?	1-10	(1) No, never – (10) Yes, often
5	Is your eyesight poorer in sharp light (as a on sunny day with blue sky)?	1-10	(1) No, never – (10) Yes, often
6	Is your eyesight poorer in dim light?	1-10	(1) No, never – (10) Yes, often
7	Do you experience problems with focussing on object close to you?	1-10	(1) No, never – (10) Yes, often
8	How bothered are you by focussing problems?	1-10	(1) I don’t feel them – (10) They prevent me from doing tasks
The following questions concern the study you have just participated in			
9	In which of he two configurations did you find the glare least bothering?	1-3	1: With lighting on walls 2: Without lighting on walls 3: There was no difference
10	To which degree was the glare bothering when there was light on the walls	1-10	(1) Not bothering at all – (10) Very bothering
11	To which degree was the glare bothering when there **wasn’t** light on the walls	1-10	(1) Not bothering at all – (10) Very bothering
12	How bothered were you by the test glasses	1-10	(1) Not bothering at all – (10) Very bothering
13	To which degree were you able to follow the film on the TV screen	1-10	(1) Could not follow at all – (10) Could easily follow

Questionnaire responses

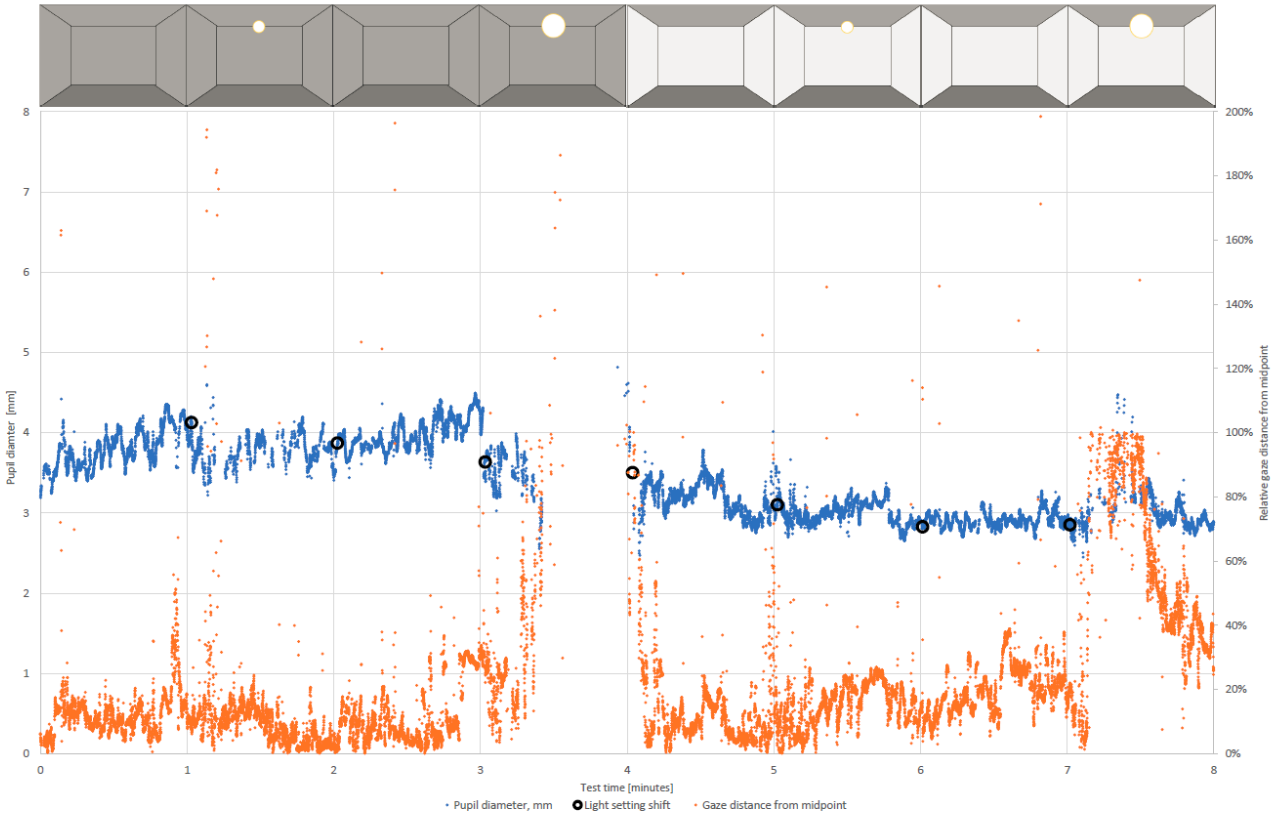
Questionnaire responses	Rotation	Time	Gender	Vision	Age	Q 01	Q 02	Q 03	Q 04	Q 05	Q 06	Q 07	Q 08	Q 09	Q 10	Q 11	Q 12	Q 13	Average of Q1:8
Participant 01	A-B	09:33	m	1	27	5	7	8	4	7	7	3	4	1	7	9	4	3	5,6
Participant 02	B-A	10:00	f	1	36	10	8	10	6	4	8	3	7	1	3	10	1	1	7,0
Participant 03	B-A	10:45	f	1	52	6	6	10	1	1	10	1	1	1	6	10	1	1	4,5
Participant 04	A-B	11:45	f	1	53	2	2	3	3	6	9	9	7	1	7	9	6	3	5,1
Participant 05	A-B	12:50	m	1	39	2	3	5	5	7	7	5	2	1	5	7	2	3	4,5
Participant 06	B-A	13:20	m	1	28	4	7	3	2	2	4	1	1	2	6	4	3	2	3,0
Participant 07	A-B	14:10	m	1	33	7	4	3	4	3	1	1	1	1	3	9	1	1	3,0
Participant 08	B-A	14:40	f	1	27	4	2	7	6	2	2	3	3	1	7	9	6	3	3,6
Participant 09	A-B	10:00	f	1	33	3	3	8	4	1	7	1	1	3	7	7	4	1	3,5
Participant 10	B-A	12:45	m	1	38	6	4	9	7	3	7	7	8	1	6	9	2	1	6,4
Participant 11	A-B	13:00	f	1	32	2	3	4	4	7	2	8	3	2	3	5	8	1	4,1
Participant 12	B-A	10:45	f	1	29	7	7	8	8	8	9	3	4	1	4	7	4	4	6,8
Participant 13	A-B	11:20	f	1	22	1	1	2	1	2	4	1	1	2	3	2	4	2	1,6
Participant 14	B-A	12:00	m	1	31	8	2	7	7	8	8	1	2	2	8	6	8	1	5,4
Participant 15	A-B	14:15	m	1		2	2	2	2	5	6	9	7	2	7	5	1	1	4,4
Participant 16	B-A	14:30	f	1	62	3	3	7	7	7	9	7	3	1	5	3	1	1	5,8
Mean					36,1	4,5	4,0	6,0	4,4	4,6	6,3	3,9	3,4	1,4	5,4	6,9	3,5	1,8	
Variance					117,6	6,4	4,8	7,5	4,7	6,2	7,4	8,9	5,9	0,4	2,9	6,1	5,6	1,0	
Standard deviation					10,8	2,5	2,2	2,7	2,2	2,5	2,7	3,0	2,4	0,6	1,7	2,5	2,4	1,0	

Appendix II Individual Result Graphs

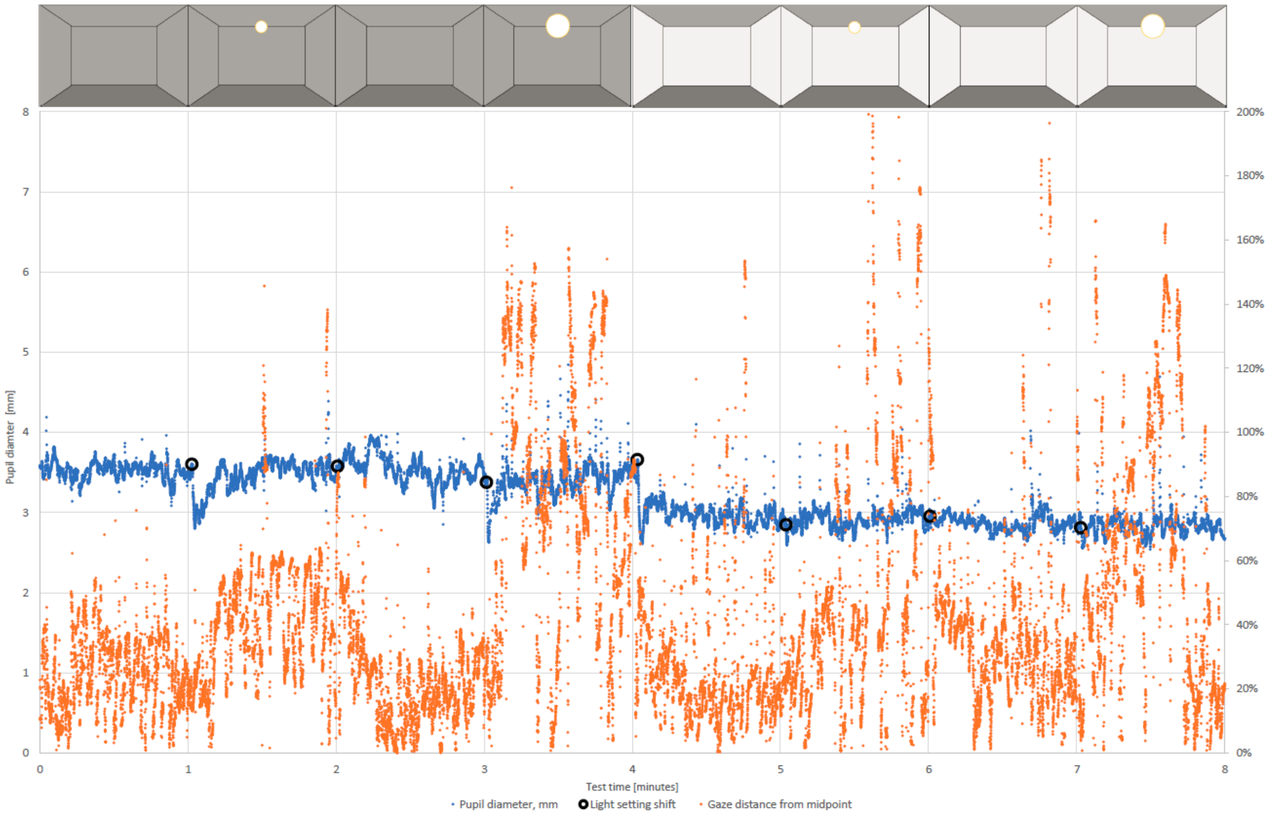
Participant 1



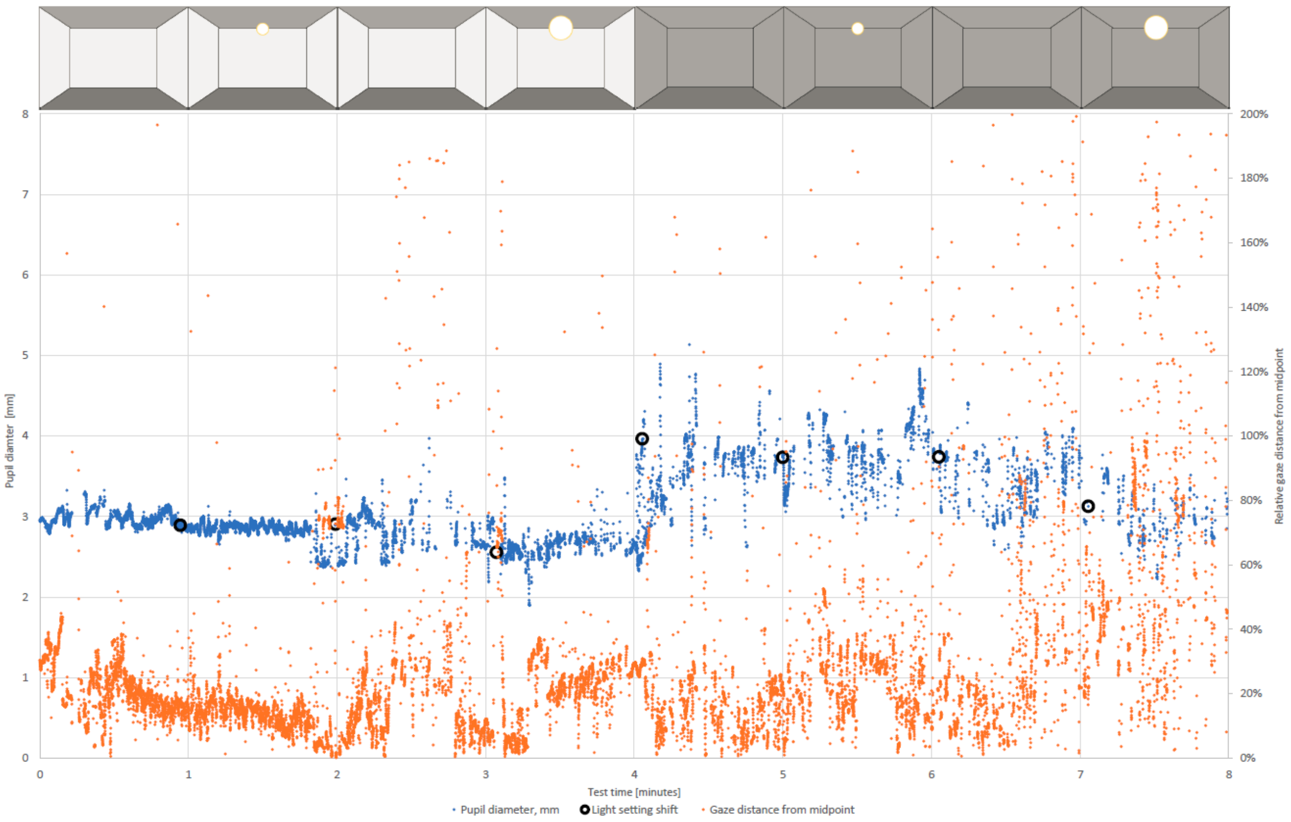
Participant 2

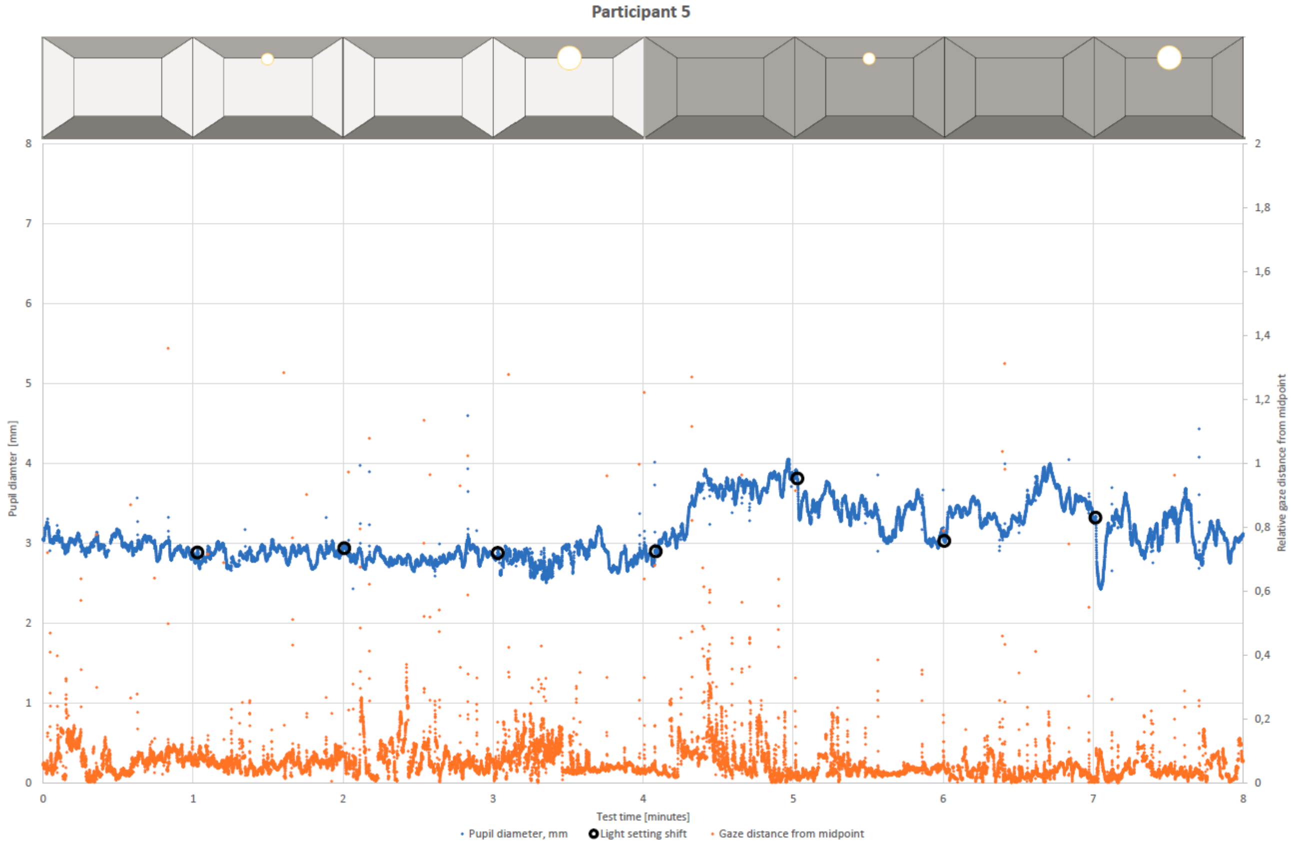


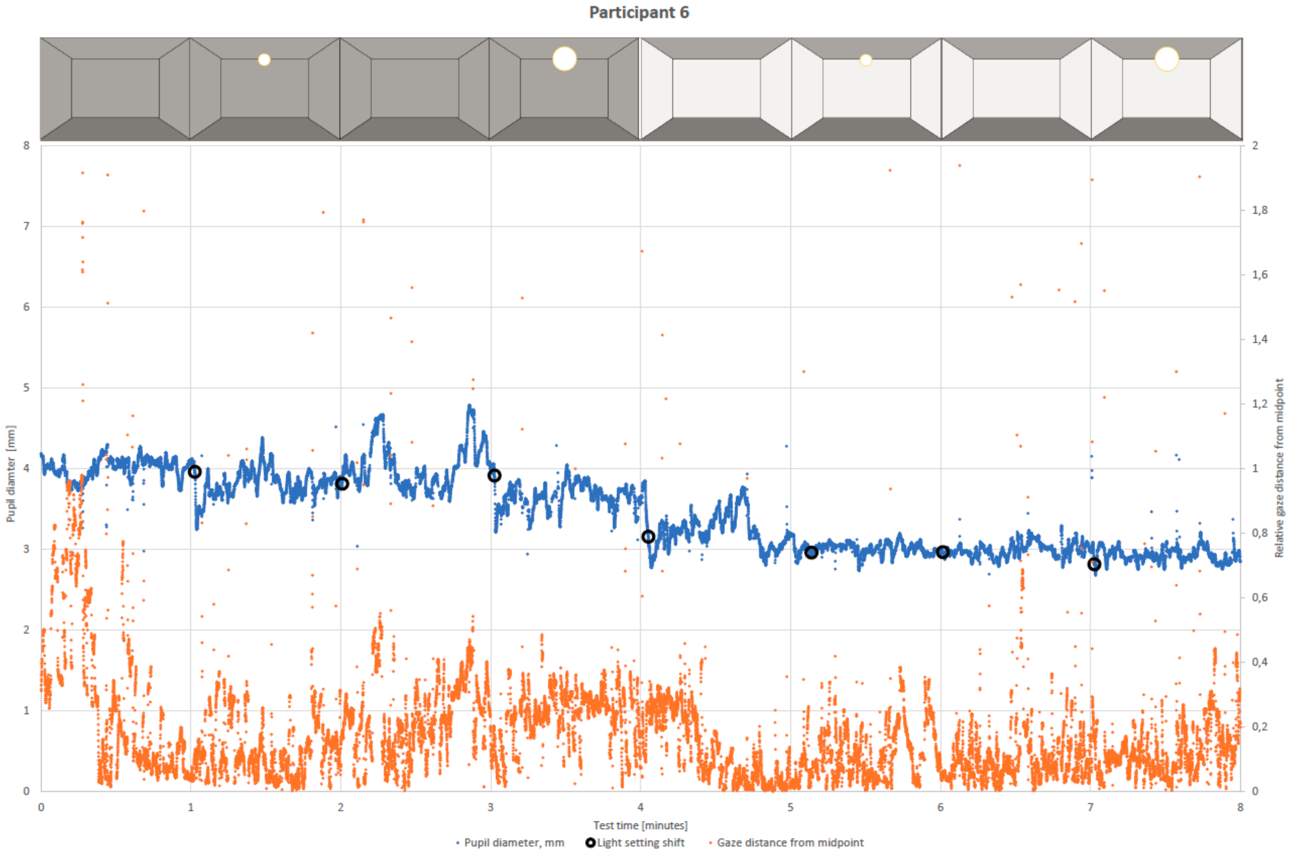
Participant 3

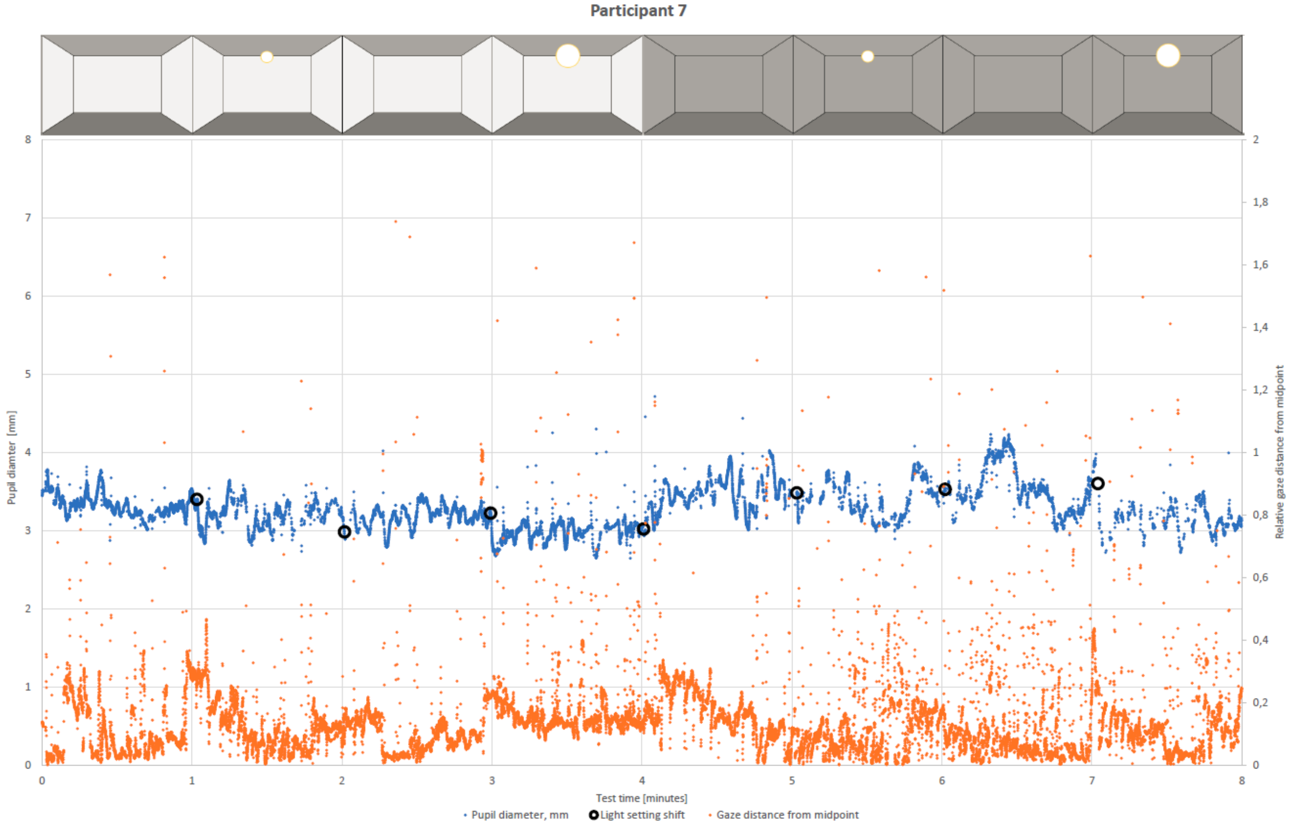


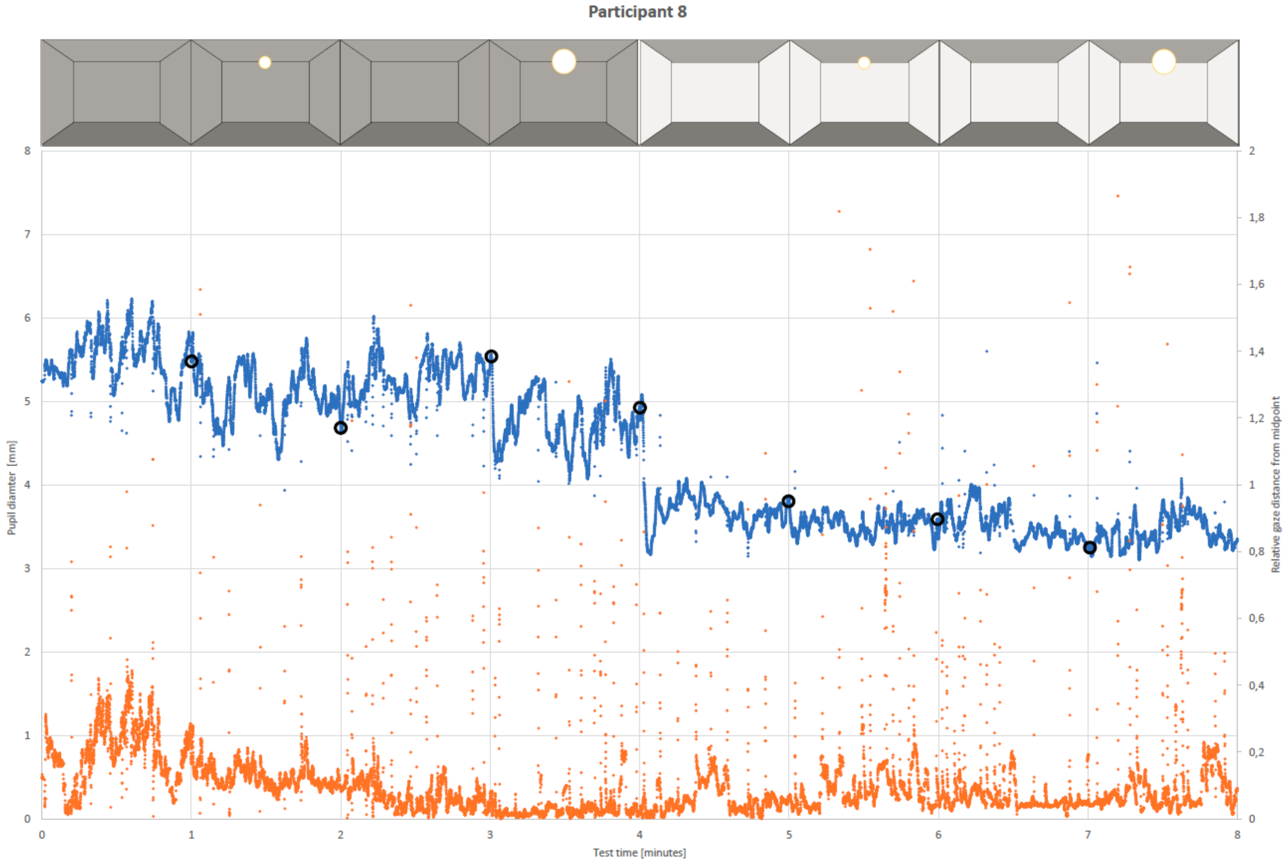
Participant 4

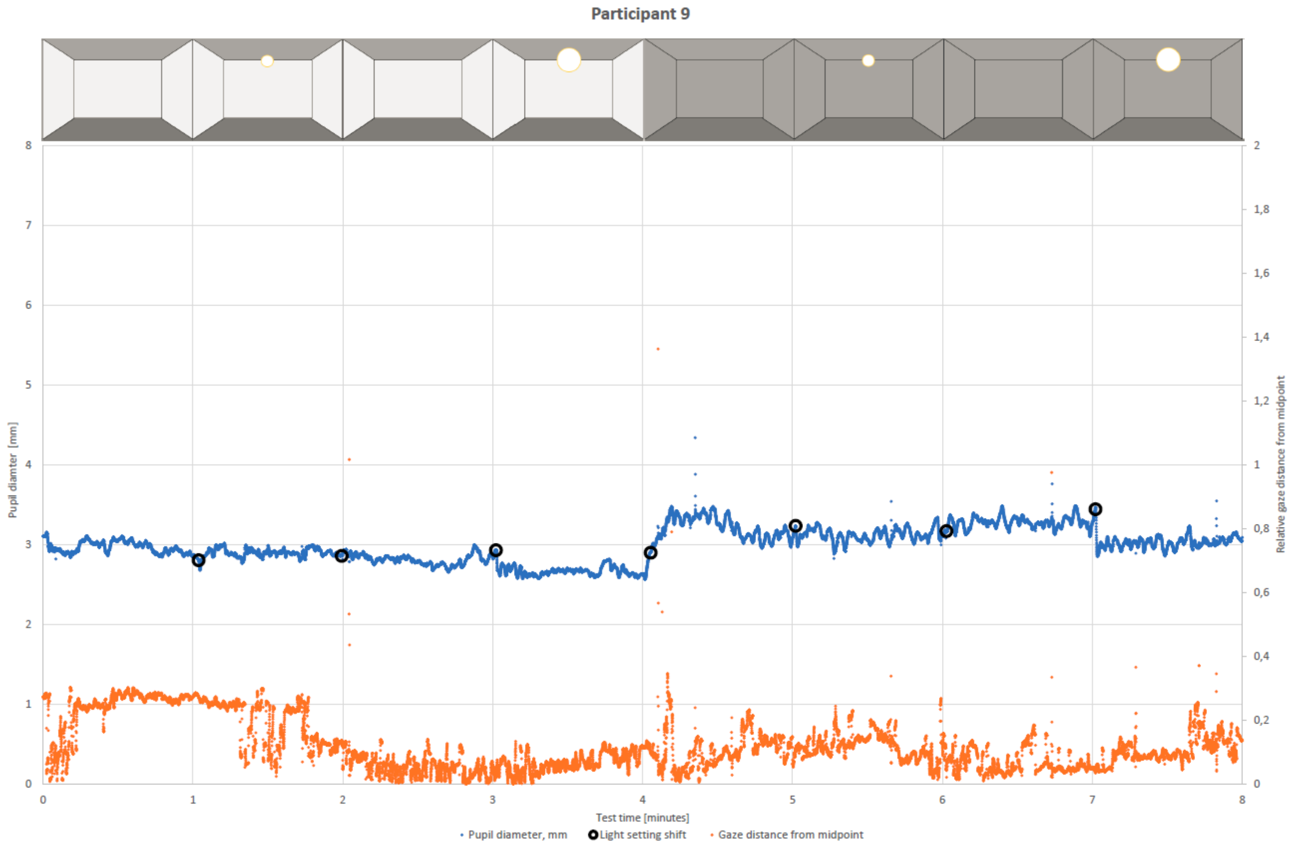


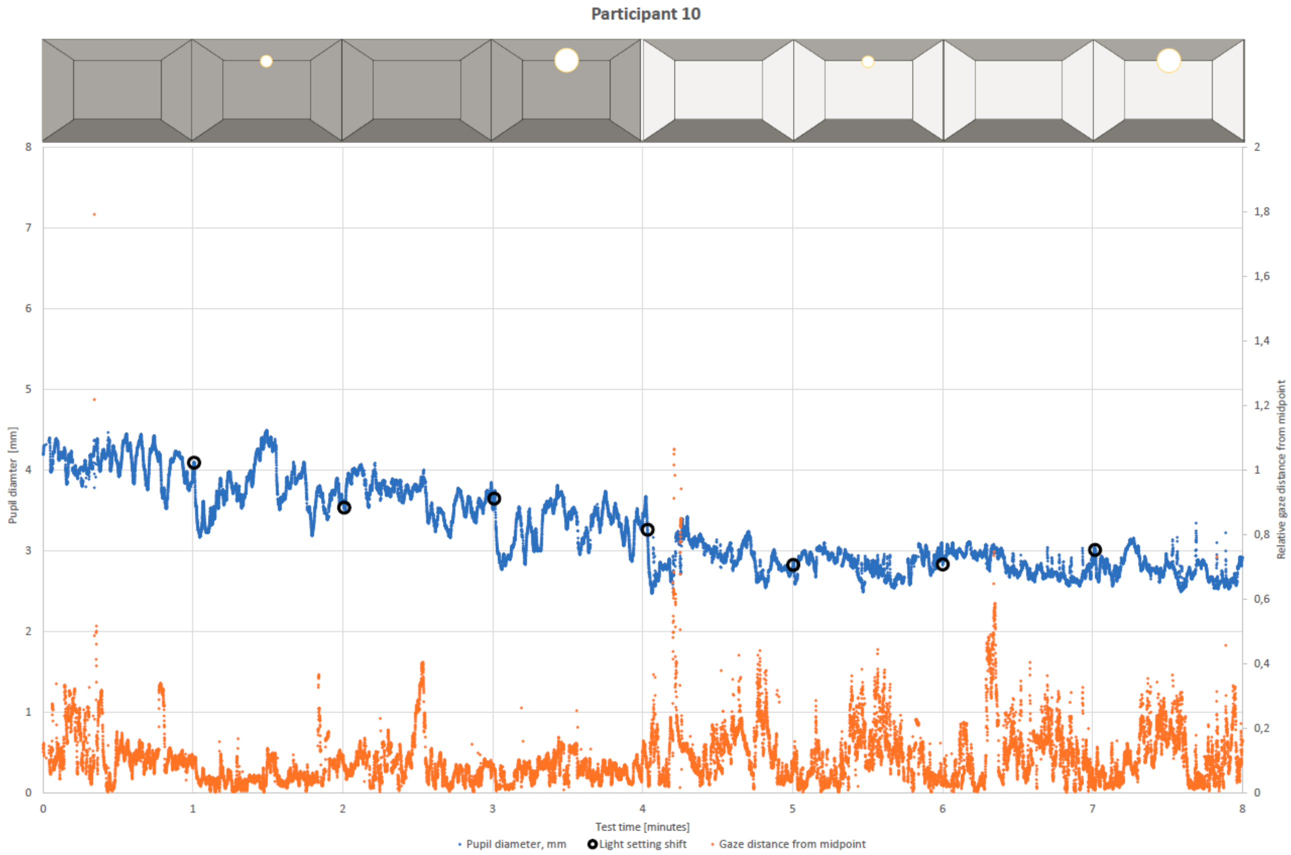

Participant 5
Pupil diamter [mm]
Relative gaze distance from midpoint
Test time [minutes]
0
1
2
3
4
5
6
7
8
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
Pupil diameter, mm
Light setting shift
Gaze distance from midpoint

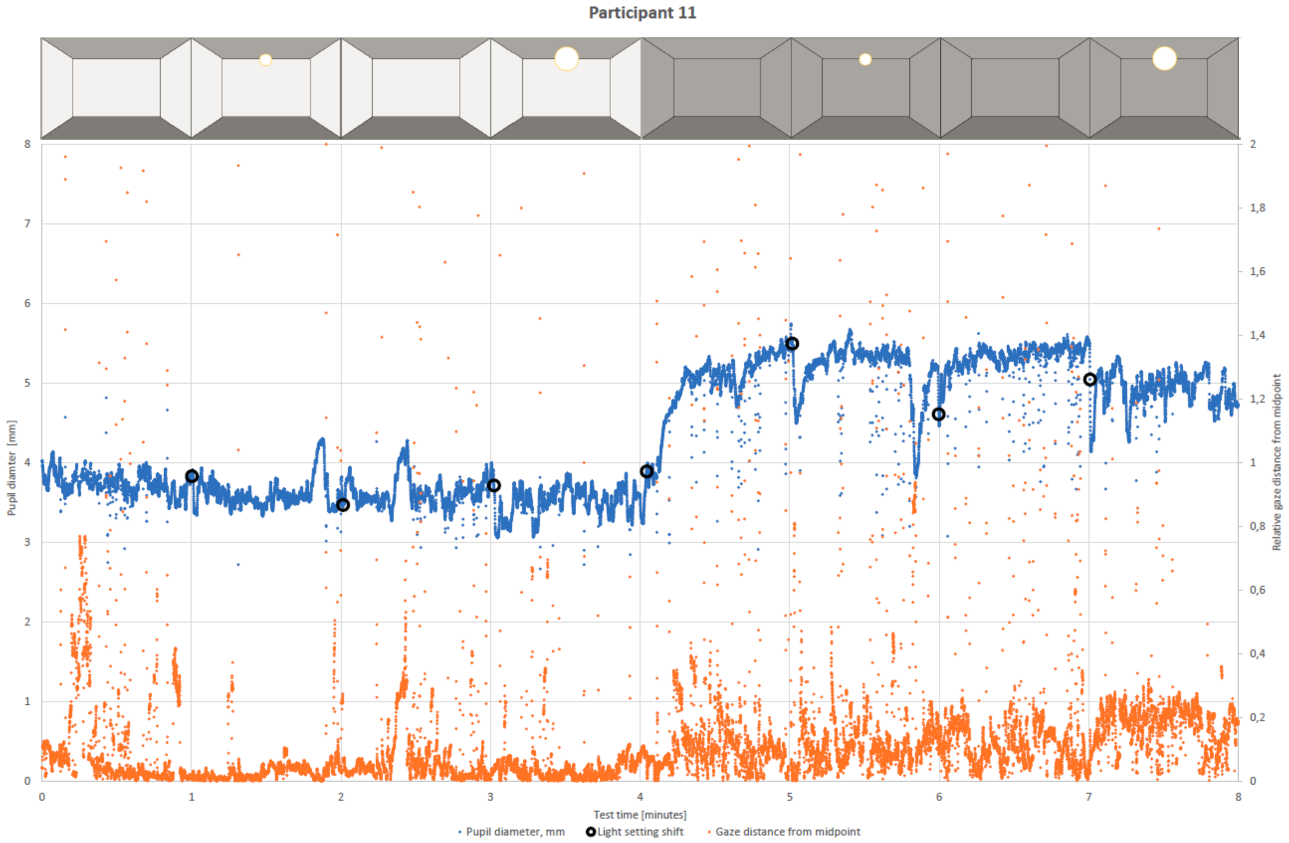

Participant 6
Pupil diamter [mm]
Relative gaze distance from midpoint
Test time [minutes]
0
1
2
3
4
5
6
7
8
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
Pupil diameter, mm
Light setting shift
Gaze distance from midpoint

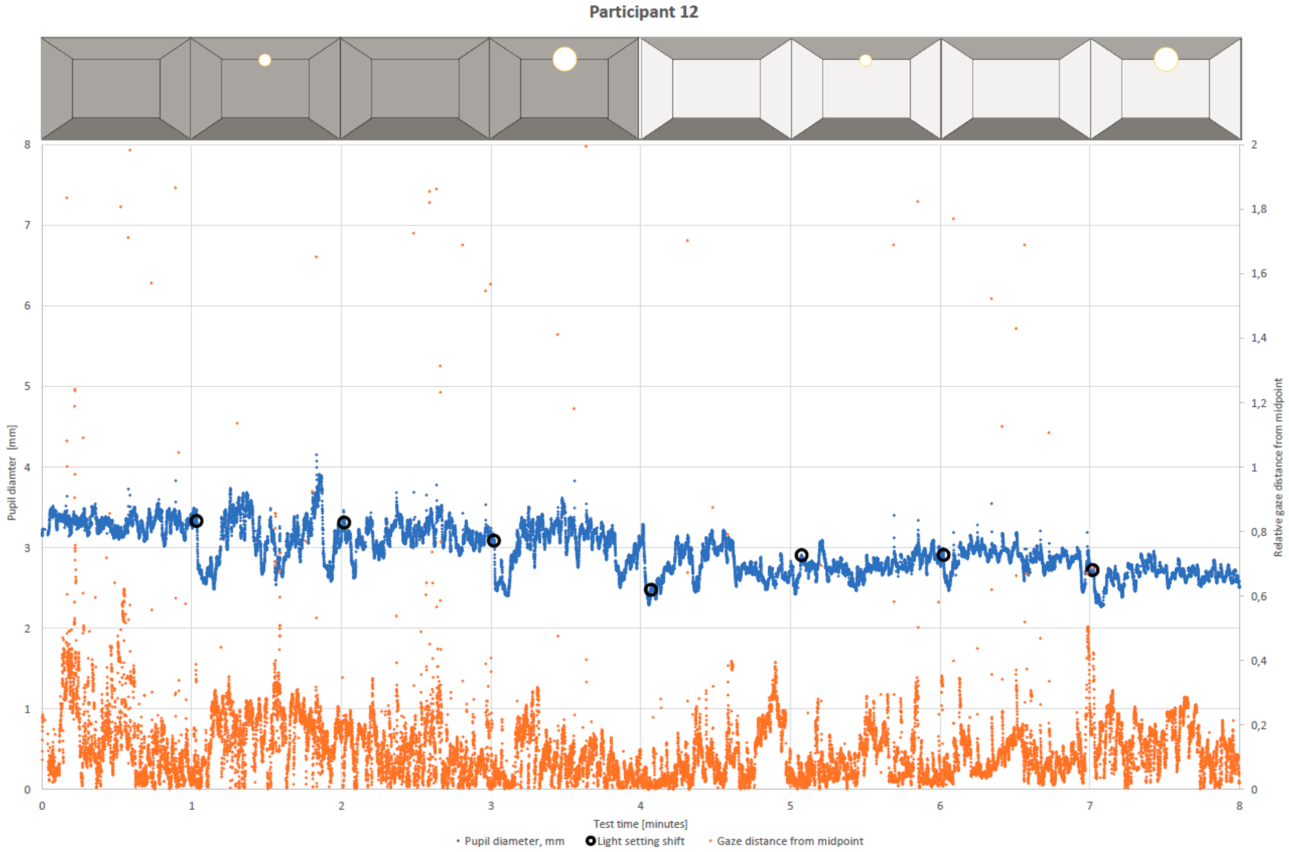

Participant 7
Pupil diamter [mm]
0
1
2
3
4
5
6
7
8
Relative gaze distance from midpoint
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
2
Test time [minutes]
0
1
2
3
4
5
6
7
8
Pupil diameter, mm
Light setting shift
Gaze distance from midpoint

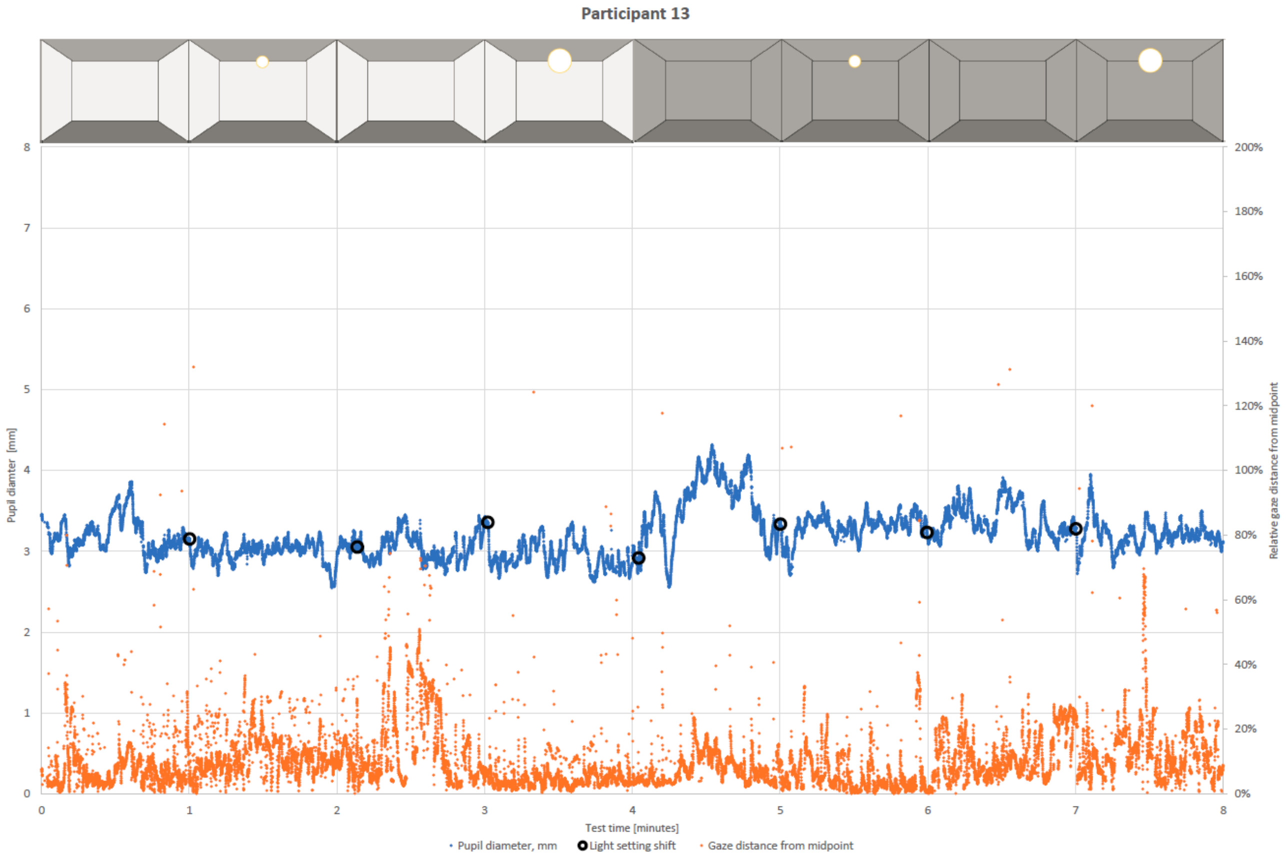

Participant 8
Pupil diamter [mm]
0
1
2
3
4
5
6
7
8
Relative gaze distance from midpoint
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
2
Test time [minutes]
0
1
2
3
4
5
6
7
8

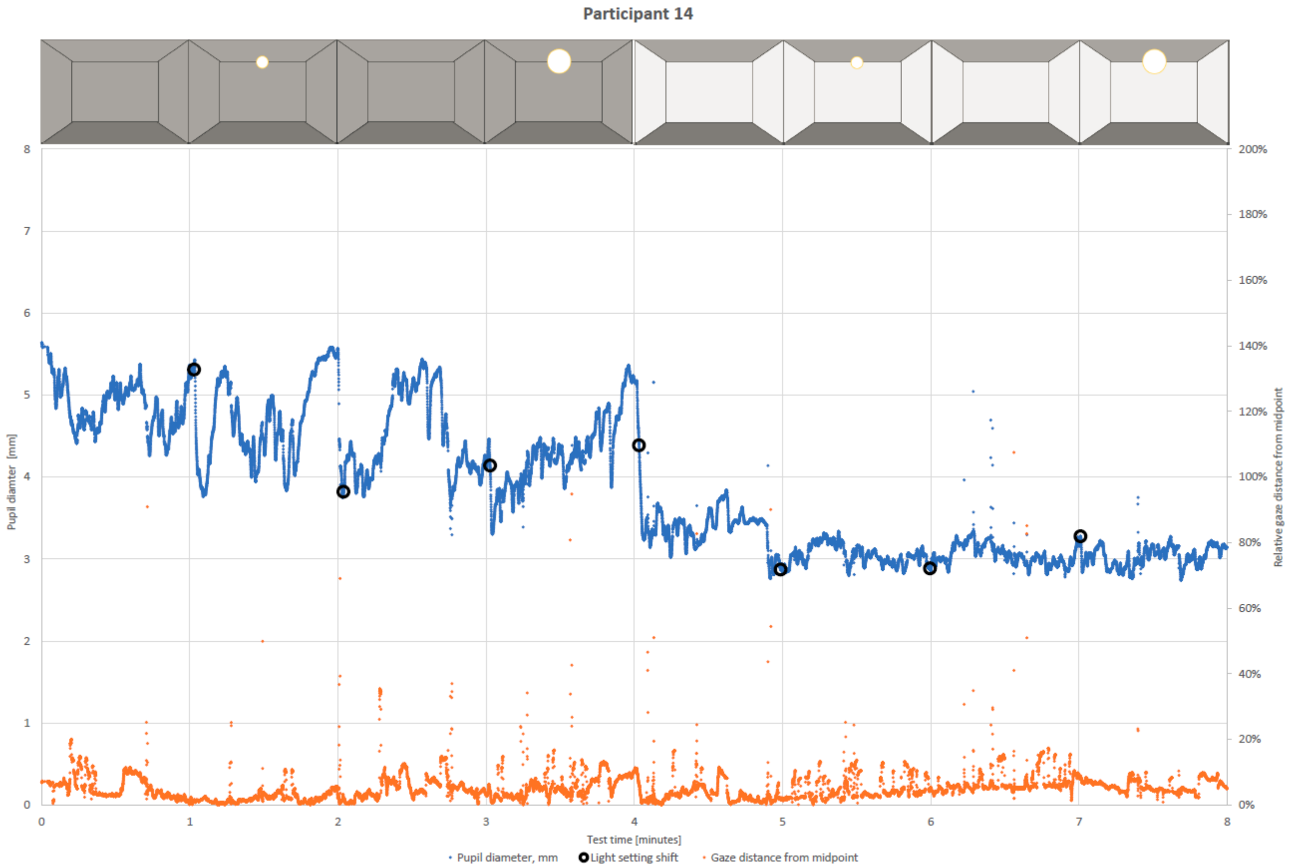

Participant 9
Pupil diamter [mm]
0
1
2
3
4
5
6
7
8
Relative gaze distance from midpoint
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
2
Test time [minutes]
0
1
2
3
4
5
6
7
8
Pupil diameter, mm
Light setting shift
Gaze distance from midpoint

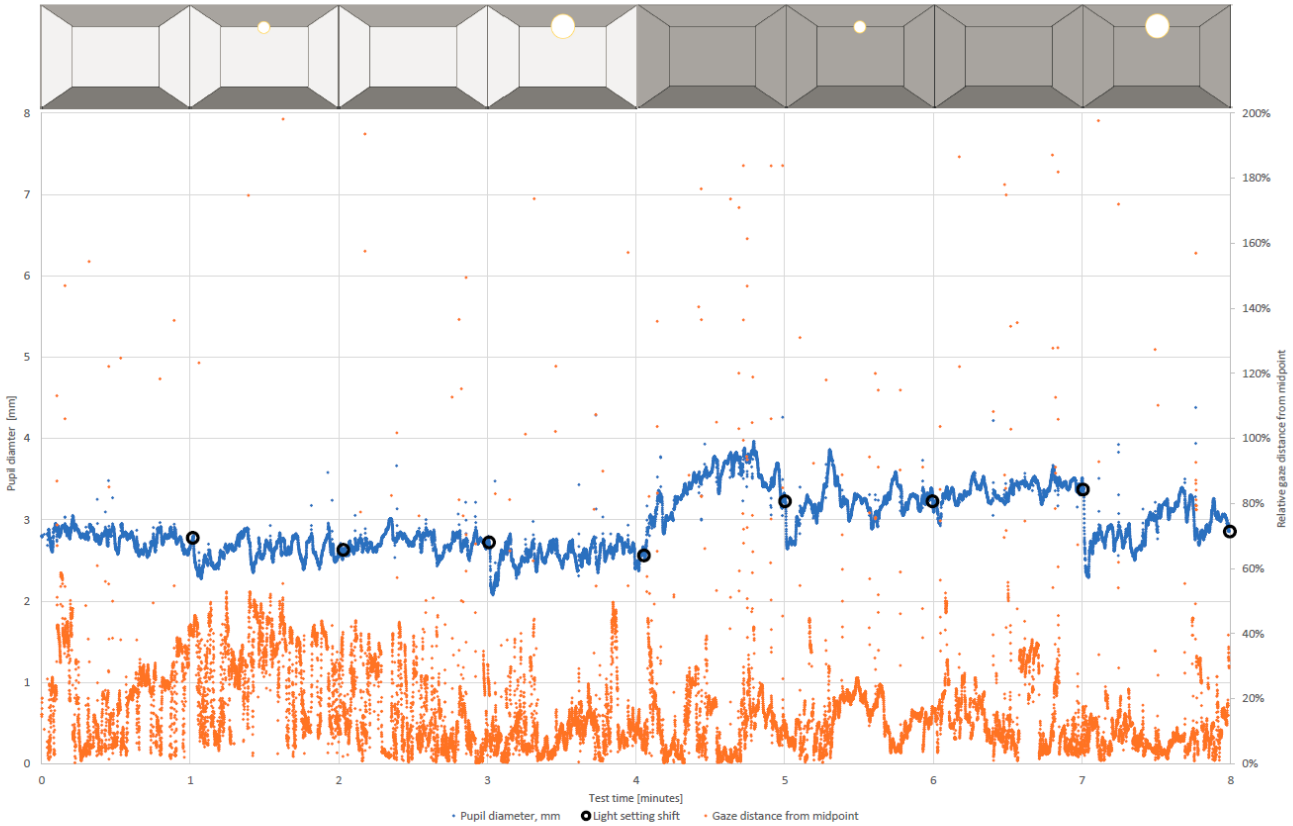

Participant 10
Pupil diamter [mm]
0
1
2
3
4
5
6
7
8
Relative gaze distance from midpoint
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
2
Test time [minutes]
0
1
2
3
4
5
6
7
8
Pupil diameter, mm
Light setting shift
Gaze distance from midpoint


Participant 11
Pupil diamter [mm]
0
1
2
3
4
5
6
7
8
Relative gaze distance from midpoint
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
2
Test time [minutes]
0
1
2
3
4
5
6
7
8
Pupil diameter, mm
Light setting shift
Gaze distance from midpoint

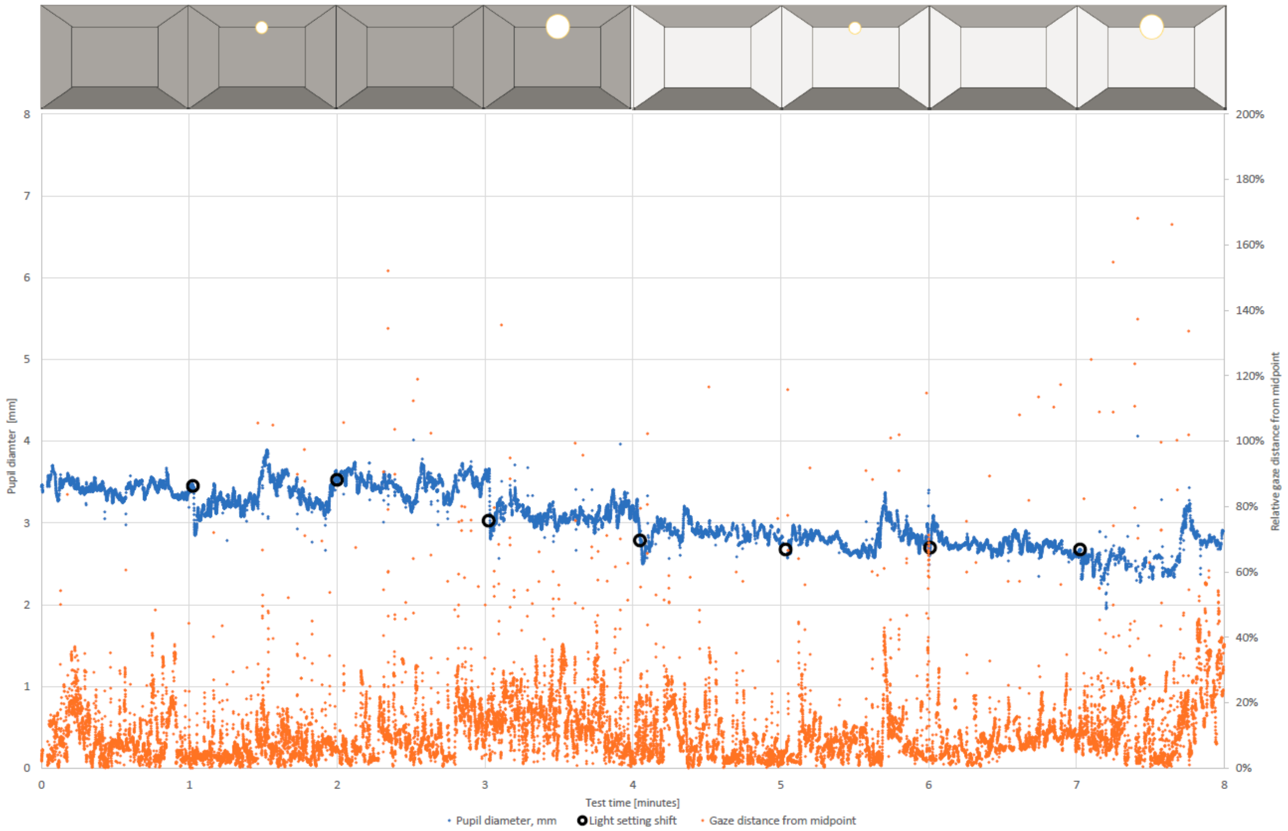

Participant 12
Pupil diamter [mm]
0
1
2
3
4
5
6
7
8
Relative gaze distance from midpoint
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
2
Test time [minutes]
0
1
2
3
4
5
6
7
8
Pupil diameter, mm
Light setting shift
Gaze distance from midpoint


Participant 13
Pupil diamter [mm]
8
7
6
5
4
3
2
1
0
Relative gaze distance from midpoint
200%
180%
160%
140%
120%
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6
7
8
Test time [minutes]
Pupil diameter, mm
Light setting shift
Gaze distance from midpoint


Participant 14
Pupil diamter [mm]
8
7
6
5
4
3
2
1
0
Relative gaze distance from midpoint
200%
180%
160%
140%
120%
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6
7
8
Test time [minutes]
Pupil diameter, mm
Light setting shift
Gaze distance from midpoint

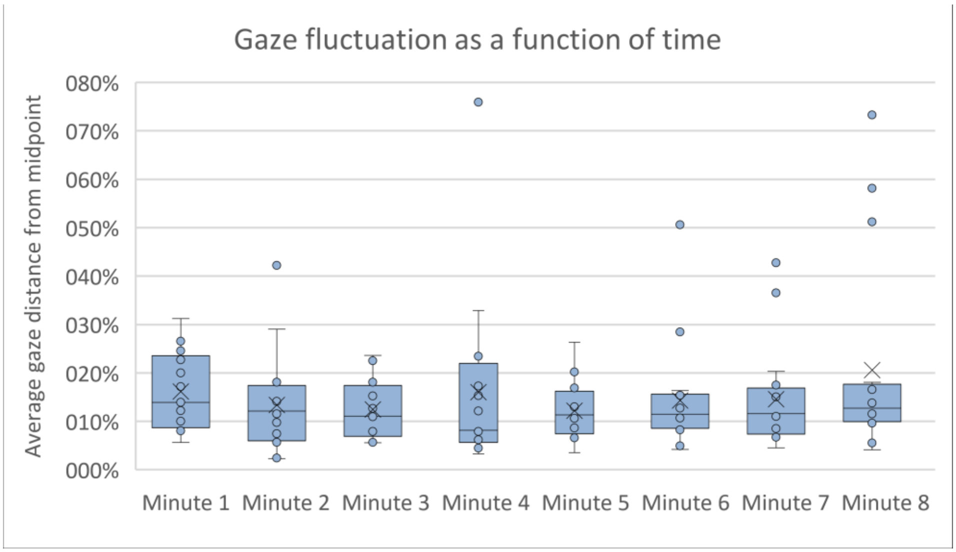


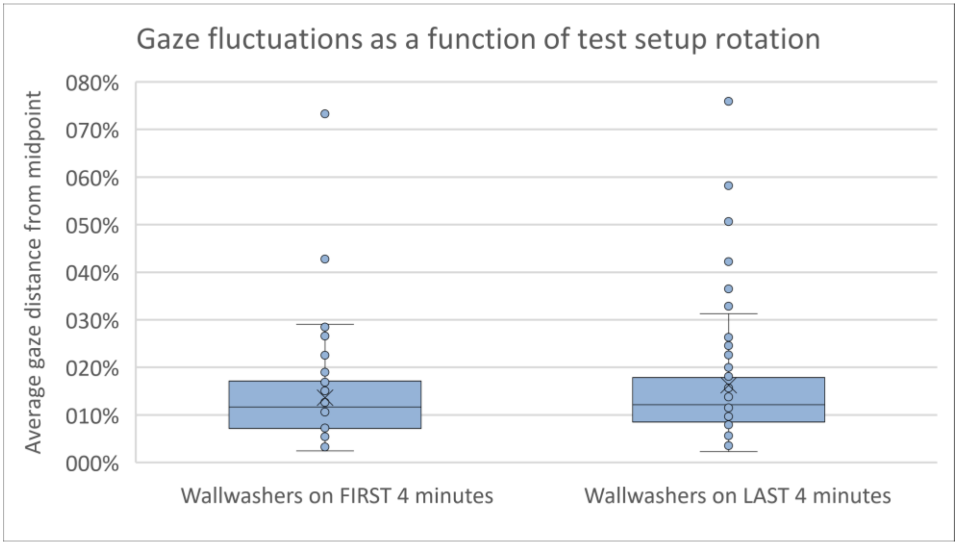
Participant 15

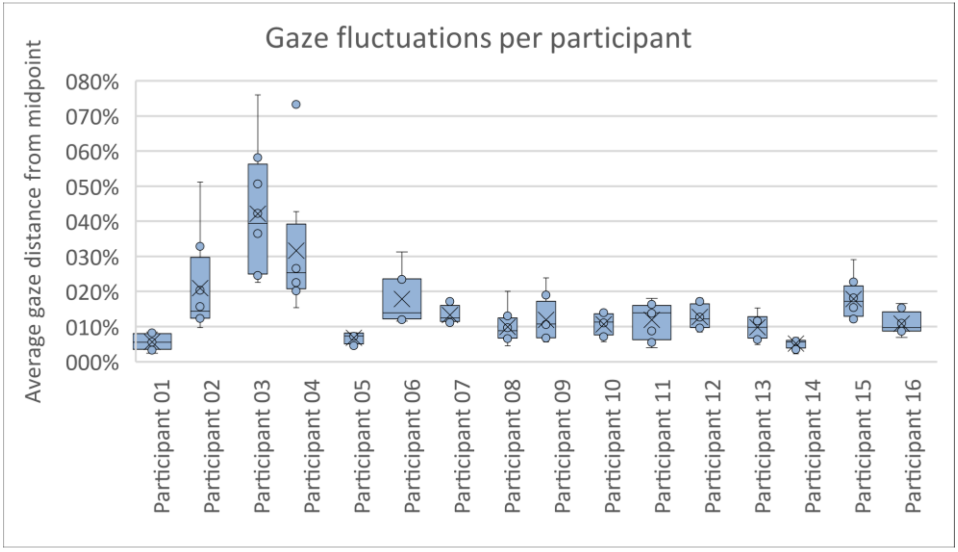


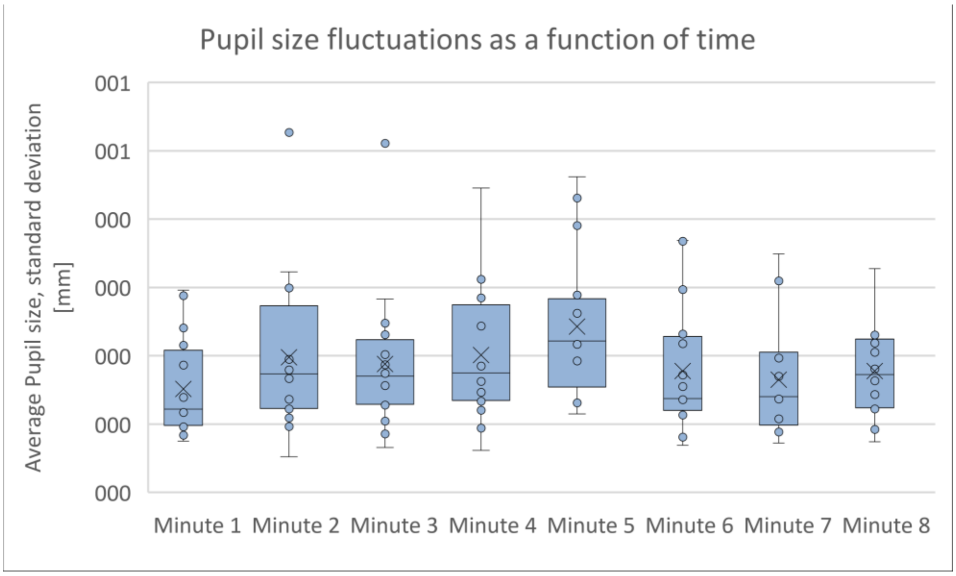
Participant 16

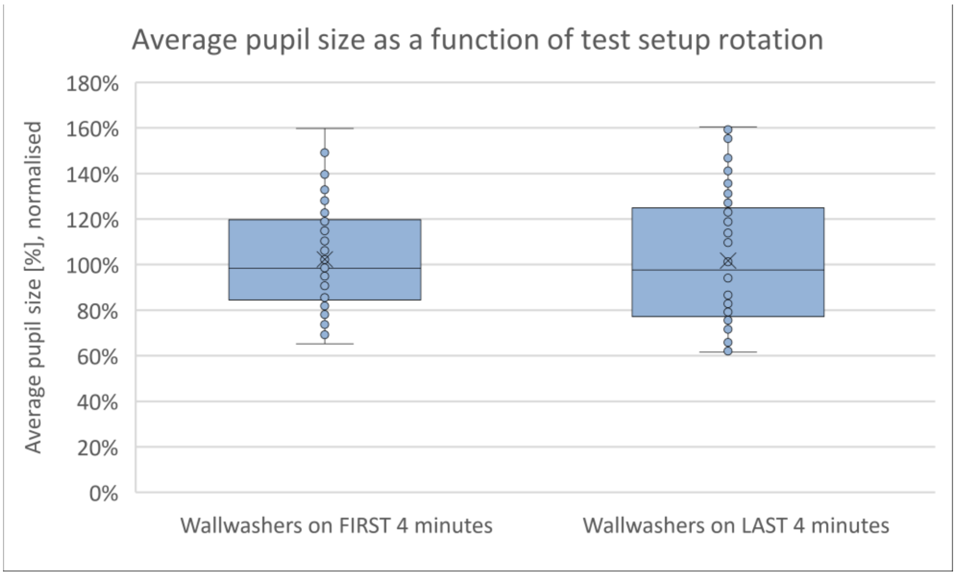
Appendix III Investigating Test Participant Fatigue

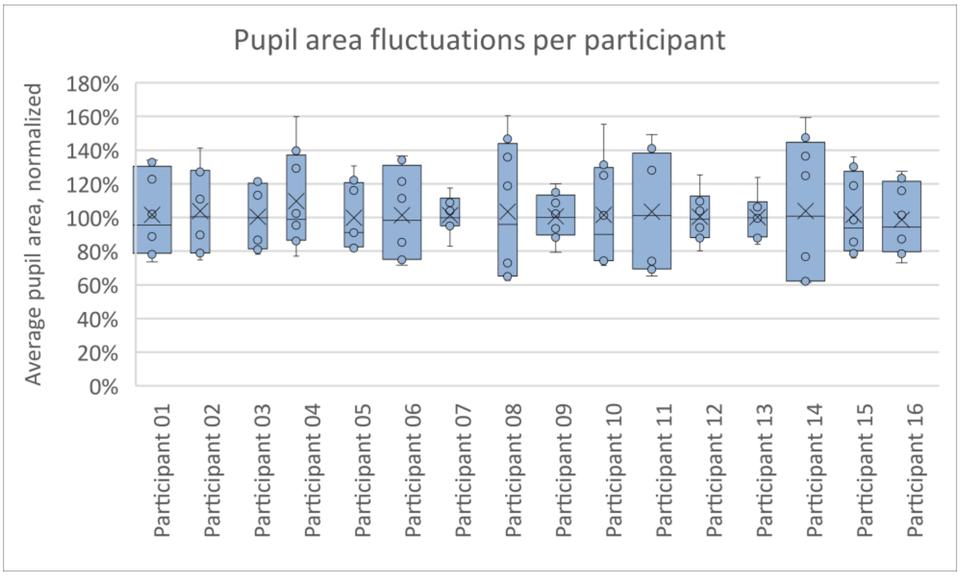







Pupil size fluctuations as a function of time
Average Pupil size, standard deviation [mm]
001
001
000
000
000
000
000
Minute 1
Minute 2
Minute 3
Minute 4
Minute 5
Minute 6
Minute 7
Minute 8

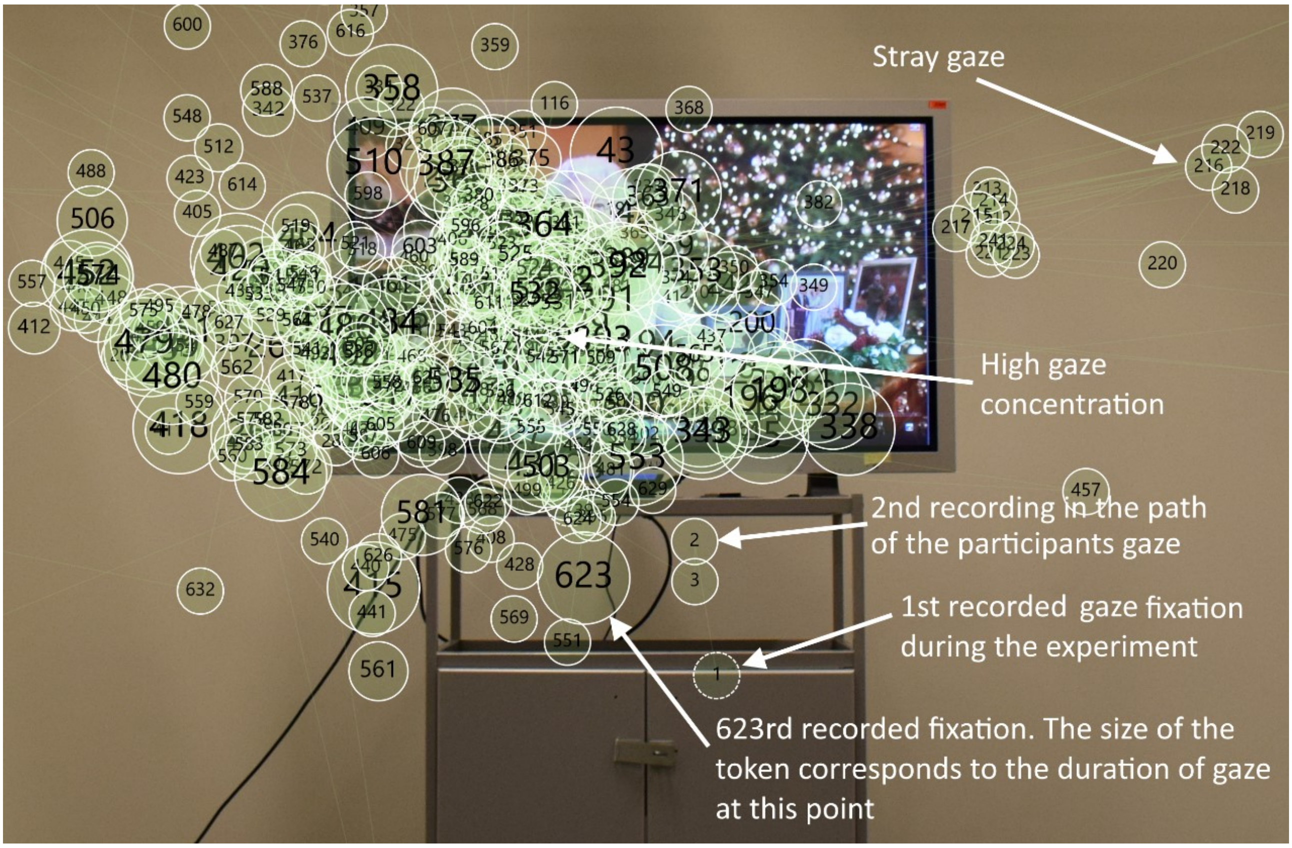

Average pupil size as a function of test setup rotation
Average pupil size [%], normalised
180%
160%
140%
120%
100%
80%
60%
40%
20%
0%
Wallwashers on FIRST 4 minutes
Wallwashers on LAST 4 minutes


Pupil area fluctuations per participant
Average pupil area, normalized
180%
160%
140%
120%
100%
80%
60%
40%
20%
0%
Participant 01
Participant 02
Participant 03
Participant 04
Participant 05
Participant 06
Participant 07
Participant 08
Participant 09
Participant 10
Participant 11
Participant 12
Participant 13
Participant 14
Participant 15
Participant 16

Appendix IV Gaze Patterns

Gaze Plots

Gaze plots are created, from datasets recorded using the Tobii glasses, to illustrate the gaze pattern of each test participant throughout the entire experimental session. The gaze plots display the measured position and sequence of fixations (tokens) projected onto a snapshot during the experimental session. Snapshots are statics images of the real-world environment, and is used to aggregate data from the recording. The snapshot selected for the gaze analysis, corresponds to the typical field of view of the test subject. The Tobii Pro Lab software uses an automatic gaze mapping feature using real world mapping algorithms to program gaze plots from the datasets (Tobii AB. 2017. *Tobii Pro Lab User Manual*. Retrieved from https://www.tobiipro.com/siteassets/tobii-pro/user-manuals/tobii-pro-lab-user-manual.pdf/?v=1.70). This automatically codes data from the recording onto the snapshot. The size of tokens indicates the duration of gaze at a recorded fixation point. The numbers within each token indicate the path order of the participant gaze over the recording period.



Stray gaze

High gaze concentration

2nd recording in the path of the participants gaze

1st recorded gaze fixation during the experiment

623rd recorded fixation. The size of the token corresponds to the duration of gaze at this point

Figure 8-1 Example of a gaze plot. The plot displays where the gaze fixates during experiment. Each token (circle) represents the position of a visual fixation. The path and order of fixations is marked in a numerical sequence, (“1” = first recorded fixation; “highest number” = last recorded fixation). The size of the token indicates the relative duration of the fixation.

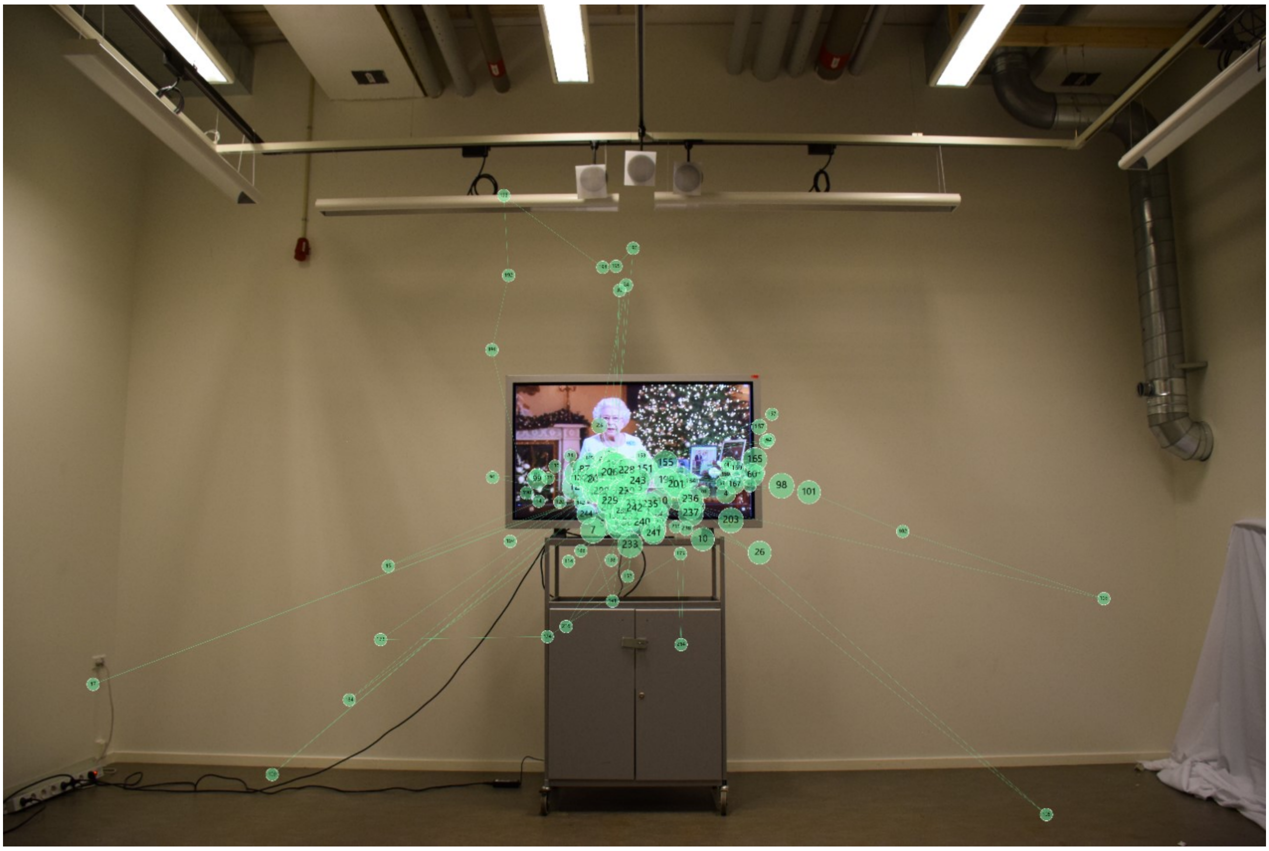


Figure 8-2 Participant 1

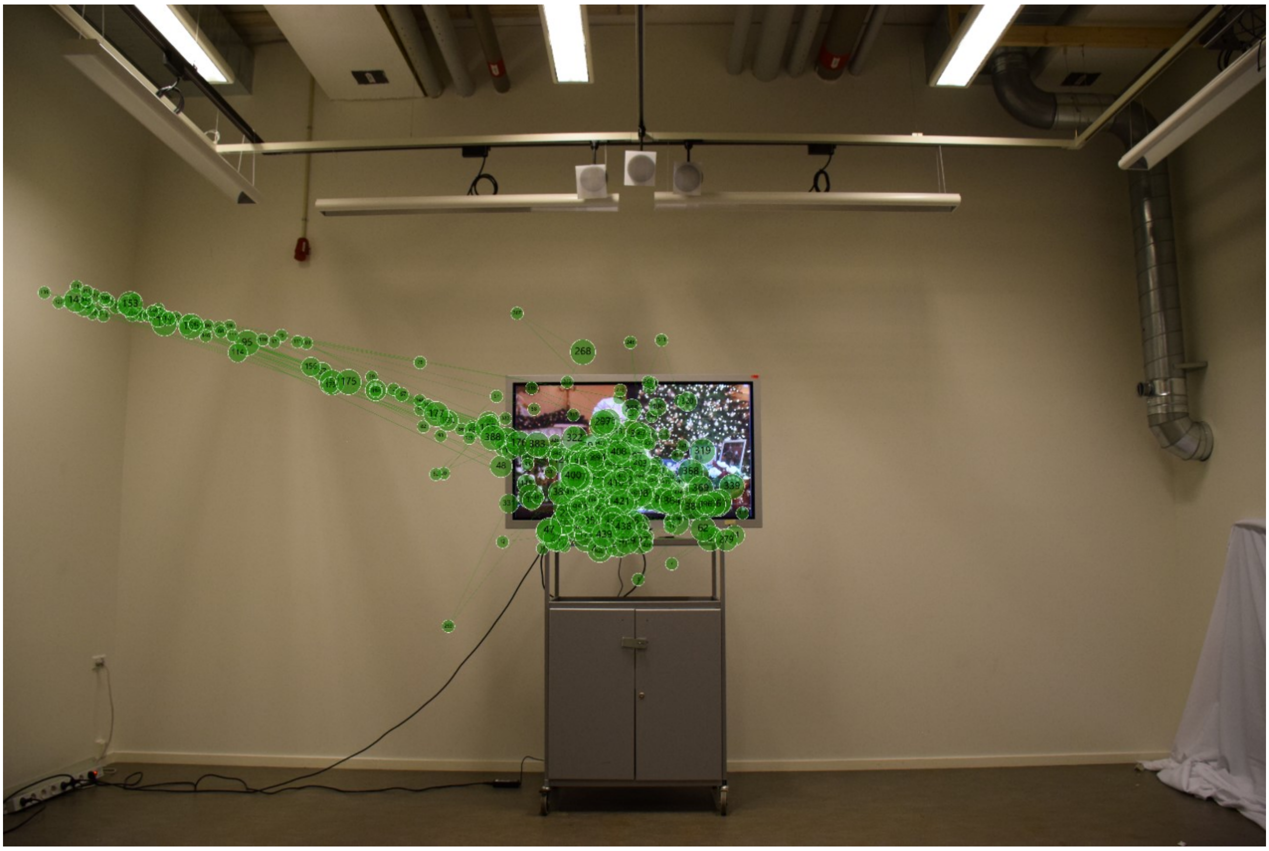


Figure 8-3 Participant 2

Figure 8-4 Participant 3

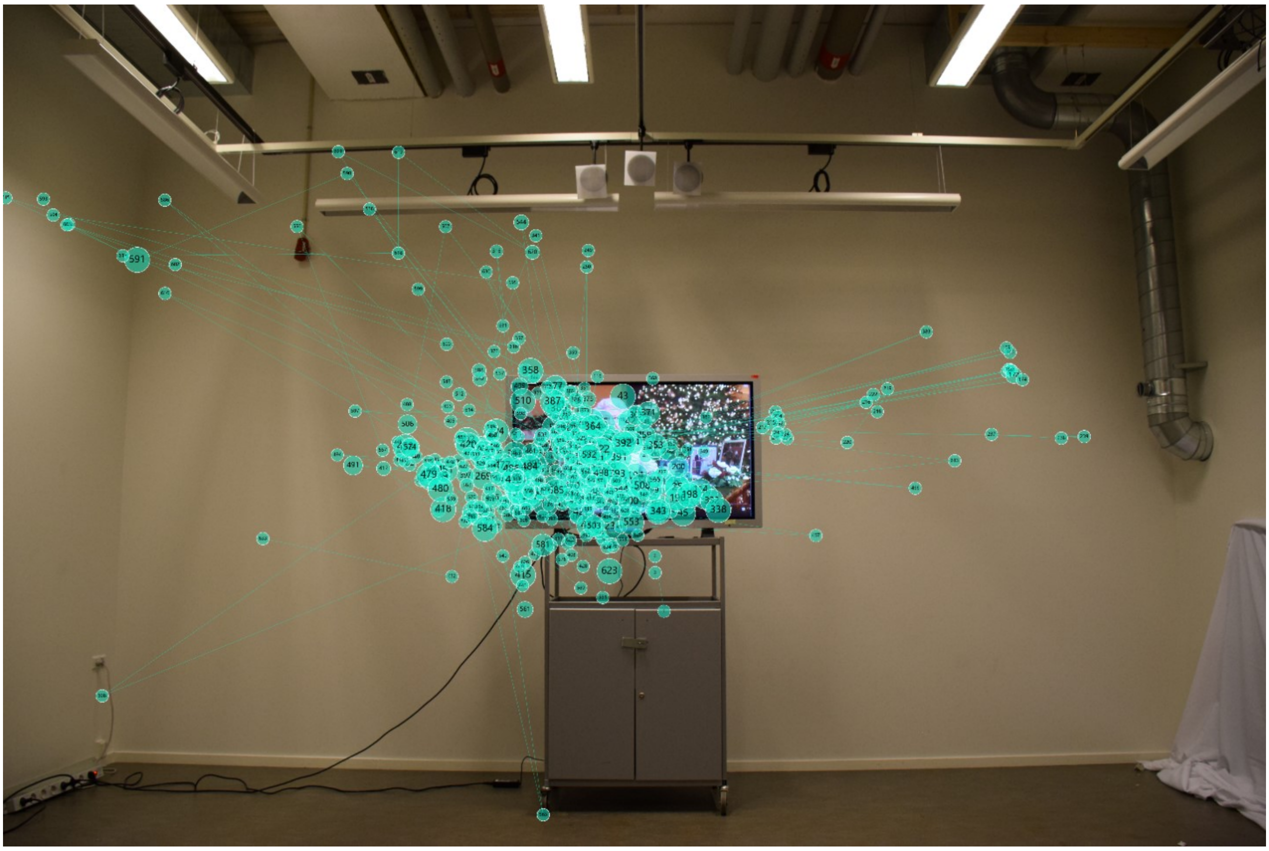


Figure 8-5 Participant 4

Figure 8-6 Participant 5

Figure 8-7 Participant 6

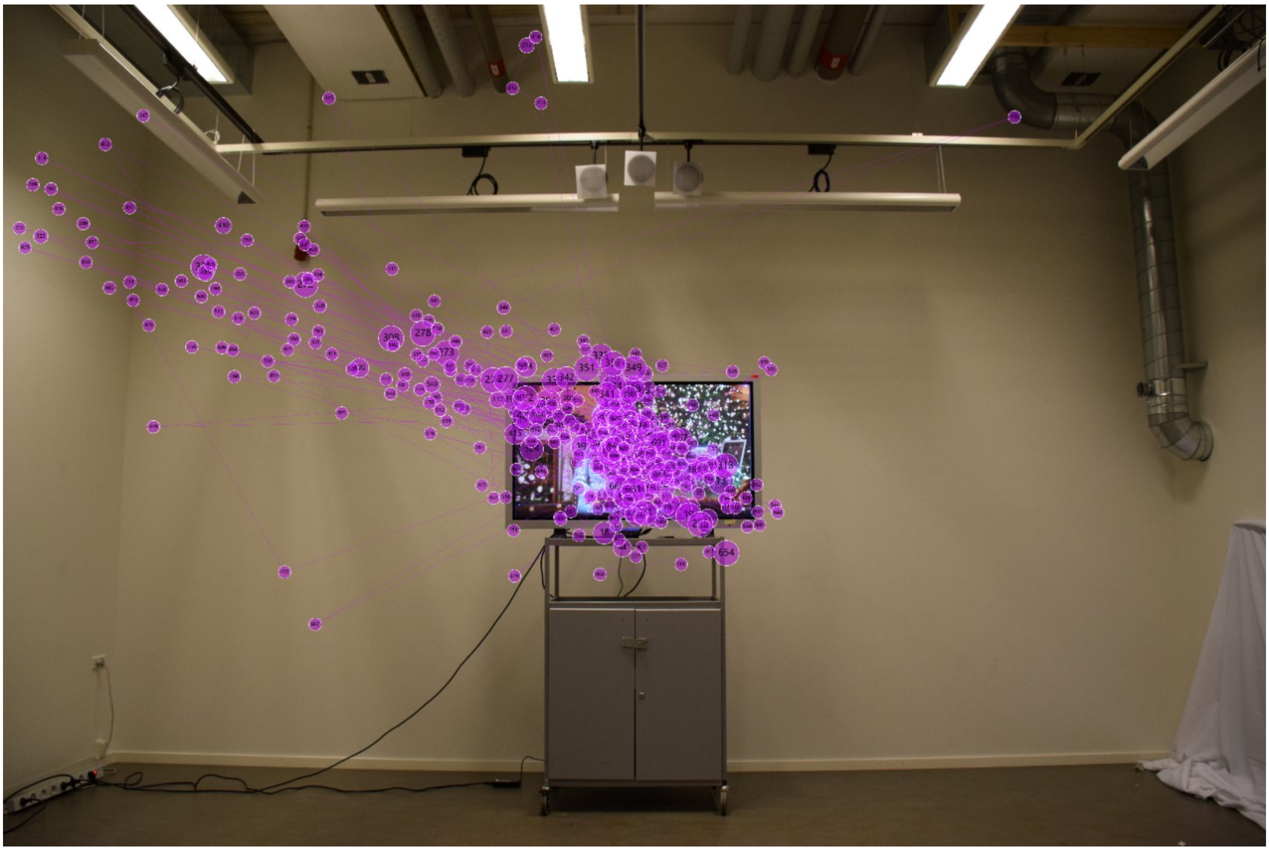


Figure 8-8 Participant 7

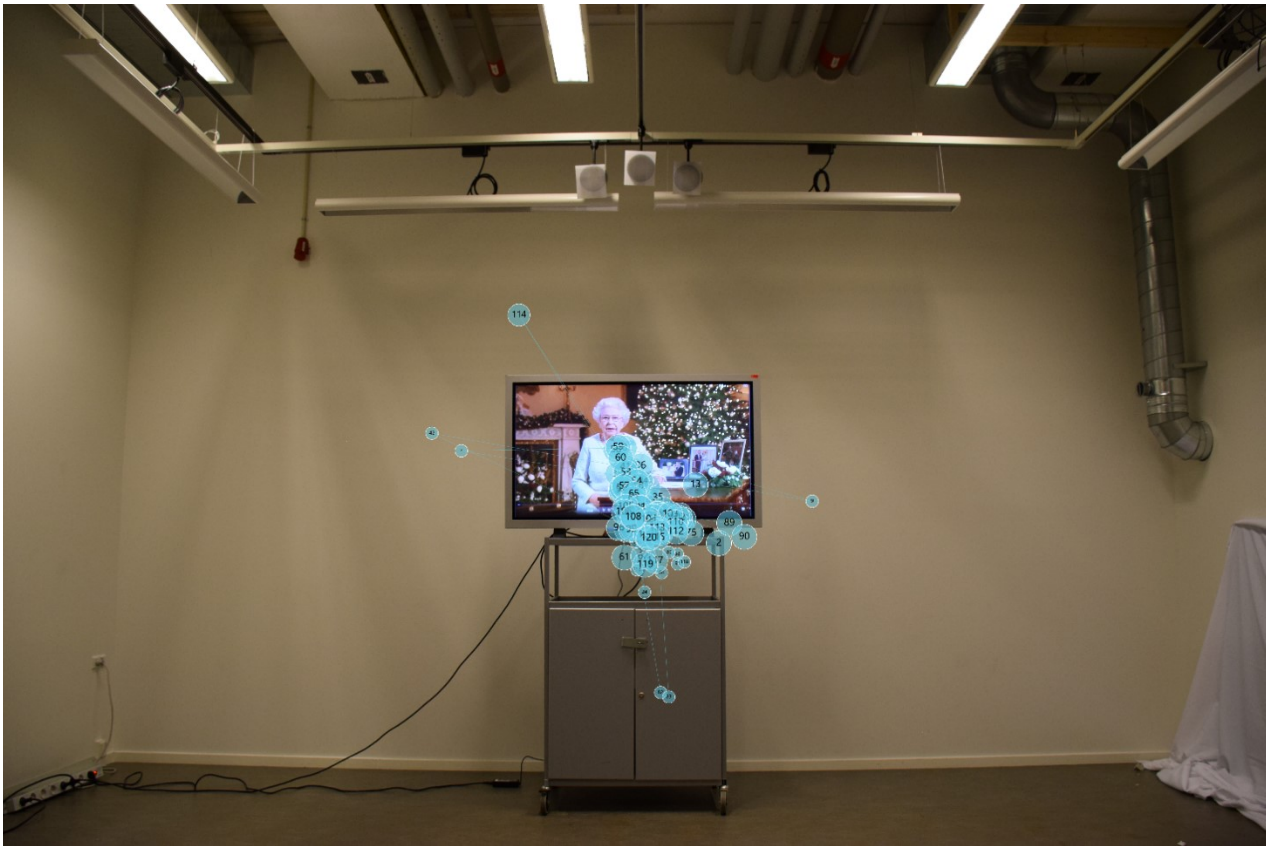


Figure 8-9 Participant 8

Figure 8-10 Participant 9

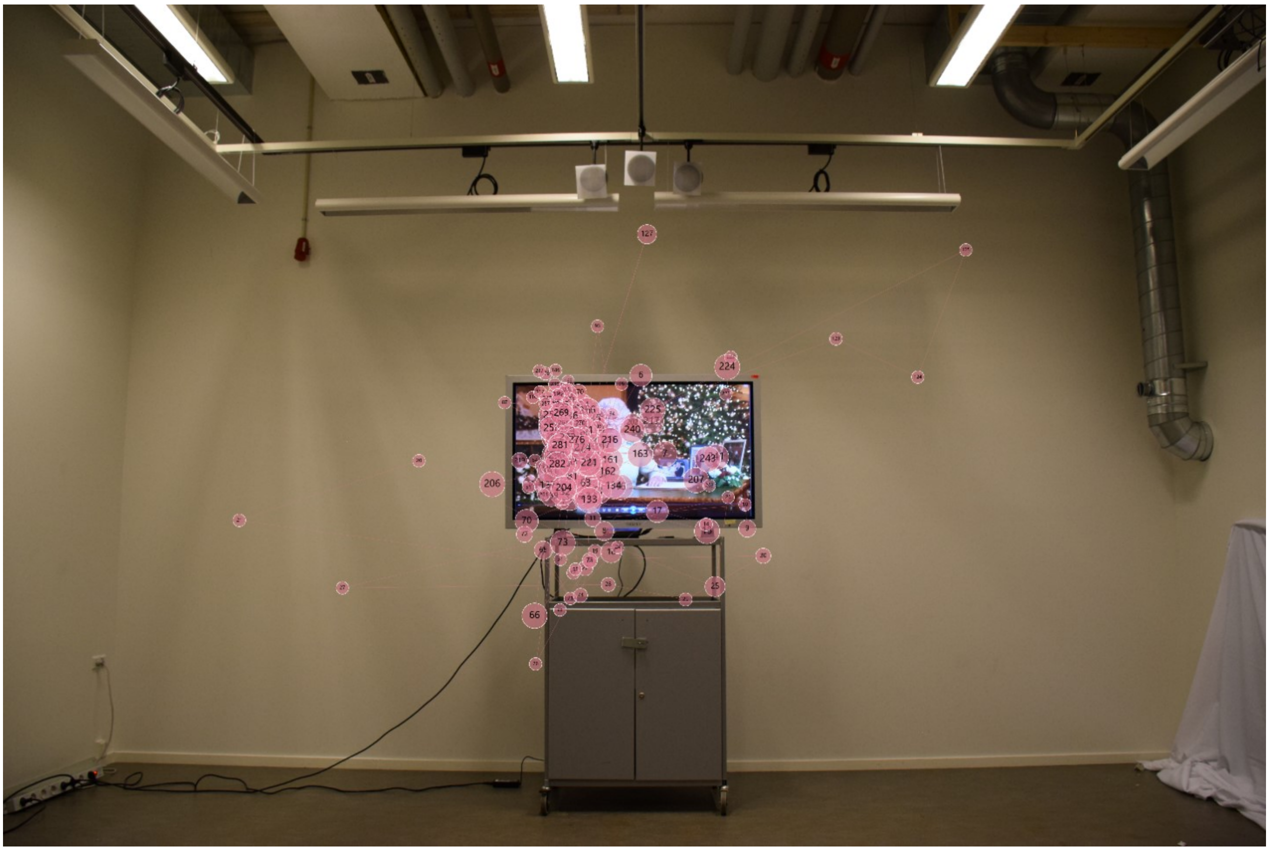


Figure 8-11 Participant 10

Figure 8-12 Participant 11

Figure 8-13 Participant 12

Figure 8-14 Participant 13

Figure 8-15 Participant 14

Figure 8-16 Participant 15

Figure 8-17 Participant 16

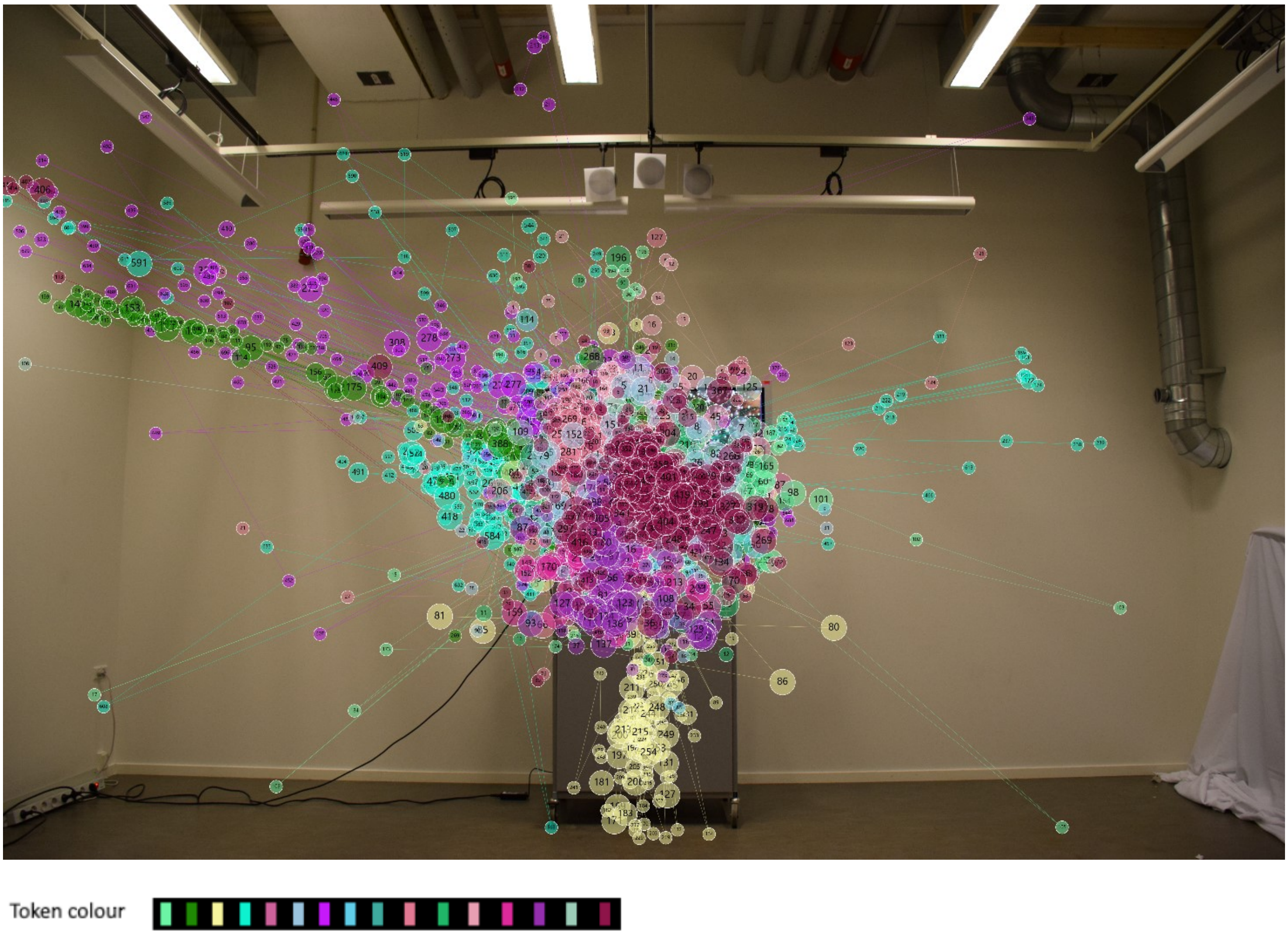
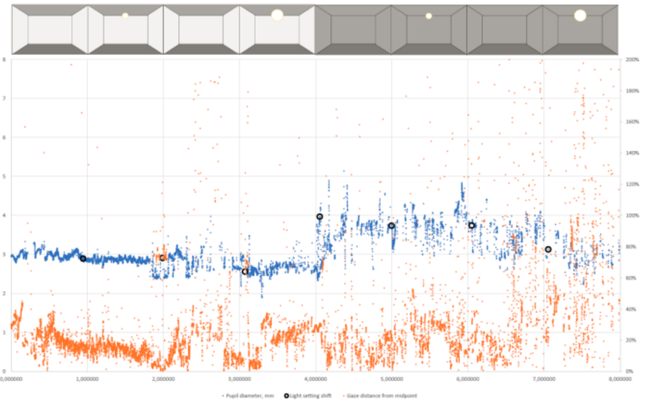
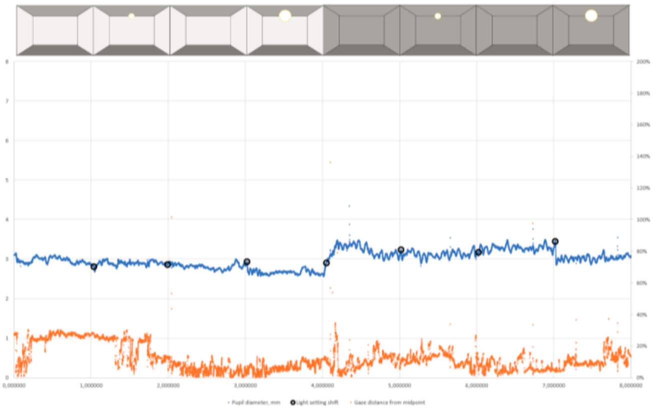
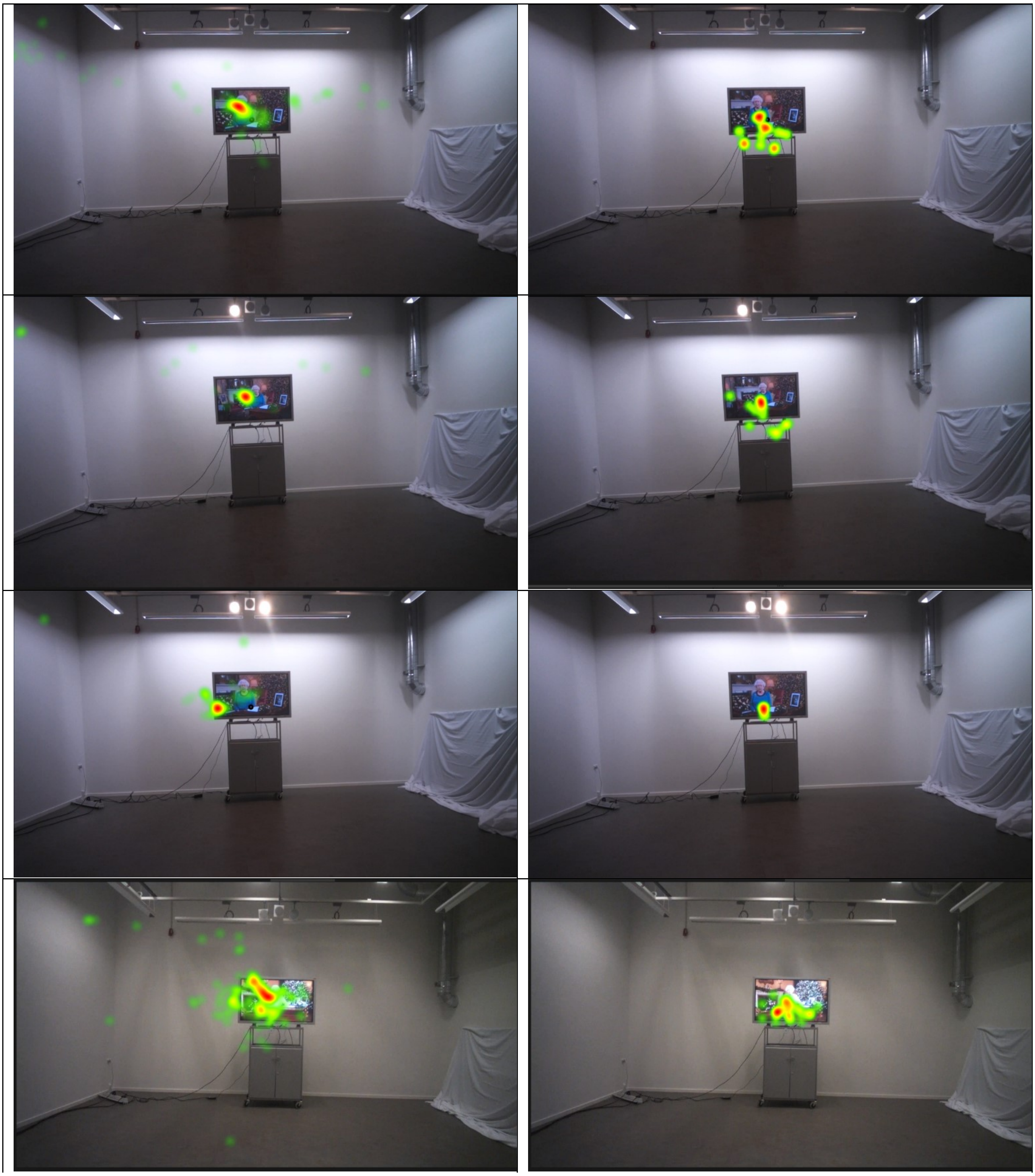


Figure 8-18 Combined gaze plot of all 16 participants.

Comparison of Two Participants

The gaze plot of two participants are compared in the 6 different settings during a session with the same rotation. Here the gaze plot is visualized as heat maps, to compare two different result graph patterns. Heat maps are created from an absolute count of fixations, calculated by the number of gaze data samples in the 6 scenarios. The same 6 snapshots are used for both participants. For the steps with no glare, the heatmap is made as a compilation of both step in in each sequence – 2 times with, and 2 times without wall wash.

Comparison	
Participant 4	**Participant 9**
	



Field of view and direction of view

The video of the queen was selected as the visual target for the experiment. It was chosen so that it would not stimulate efforts of vision (to avoid myosis), but stimulate interest (but no emotion) of the viewer. It is expected that the viewers gaze will fixate at the eyes of queen, on the parts of the video where she’s visible. There are however also various short scenes that narrate the content of the Queens speech. In these scenes at vision may fixate on anything of interest. It is also expected that while fixating at the video there will be some roaming motion of the eye within the vicinity of the visual target.

It is important to bear in mind that the snapshot is a graphical projection of gaze. The field of view of the participant is reasonably stable due to the structure of the experiment. Therefor it was possible to project almost all gaze recordings onto the same snapshot with an acceptable precision and accuracy. Only a few recordings are outside the snapshot image, when participants tilt their head and look in another direction. The only rare occurrences of this, are short duration fixation recordings on the floor and ceiling.

Gaze plot limitations

The tokens are recordings of the position of visual fixation projected onto a static image of the scene (a snapshot). The actual recordings are however relative to the time it was recorded and the state of the variable conditions at that time. The visual target is a film displayed on the monitor – i.e. that images are transient, and therefore the focal part of the images may also change during the film. So, the tokens variating position on the visual target, as seen on the gaze plot, must also be considered in relation to the changing conditions not visible on the static snapshot – the course of the film and experimental variables.

It appears from the gaze plot that, as expected, there is a much higher density of fixations on the monitor displaying the video. There are however often occurrences of stray gaze - fixations on other objects in the field of view than the visual task. No gaze was recorded directly on the glare sources. Some of the participants (3, 8, 10, 13, 14) have a high density of their gaze just beneath the visual target, on the TV-stand. So, the participants have been very focused on a certain area, but not one that would appear to be of any interest. This is found to be unlikely and is expected to be occurring because of recording errors. The gaze pattern is most likely precise, but inaccurate. When plotted, the data appears to be slightly offset either by the recording or by the gaze plot processing software. For some participant, the calibration was more difficult to conduct successfully - even though the calibration succeeded according to the software, it might still have caused some discrepancies.

Appendix V Pilot Test #4 Results

PSO 348-009 Energibesparelse gennem reduktion af blænding

Results of Pilot test #3

	Eik 1					**Eik 2**					**Anne 1**					**Anne 2**				
Minute	**1**	**2**	**3**	**4**	**Overall**	**1**	**2**	**3**	**4**	**Overall**	**1**	**2**	**3**	**4**	**Overall**	**1**	**2**	**3**	**4**	**Overall**
Wallwasher [0=Off, 1=on]	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Glare source [0=off, 1=L1, 2=L1+L2+L3]	0	1	0	2		0	1	0	2		0	1	0	2		0	1	0	2	
Vertical illuminace at eye [lux]	325	338	325	395		137	150	137	208		137	150	137	208		325	338	325	395	
Average gaze distance from midpoint	8,3%	7,9%	7,9%	8,0%	8,0%	9,7%	3,2%	5,0%	5,6%	5,9%	5,6%	6,5%	6,1%	6,5%	6,2%	6,5%	5,0%	4,1%	7,0%	5,6%
Gaze more than 10% away from midpoint, no. of events	688	634	328	703	2353	711	96	194	318	1319	248	147	259	198	852	182	114	139	313	748
Gaze more than 10% away from midpoint, no. of events, normalized	117%	108%	56%	120%		216%	29%	59%	96%		116%	69%	122%	93%		97%	61%	74%	167%	
Average Pupil diameter [mm]	3,84	3,74	3,81	3,67	3,77	5,31	4,89	4,78	4,35	4,77	3,51	3,43	3,51	3,33	3,44	2,88	2,89	2,89	2,84	2,88
Average Pupil size, standard deviation [mm]	0,12	0,11	0,19	0,12	0,15	0,19	0,22	0,22	0,58	0,53	0,15	0,15	0,15	0,14	0,16	0,09	0,11	0,15	0,10	0,11
Average pupil area, normalized	104%	99%	102%	95%	100%	124%	105%	100%	83%	100%	104%	99%	104%	94%	100%	100%	101%	101%	98%	100%

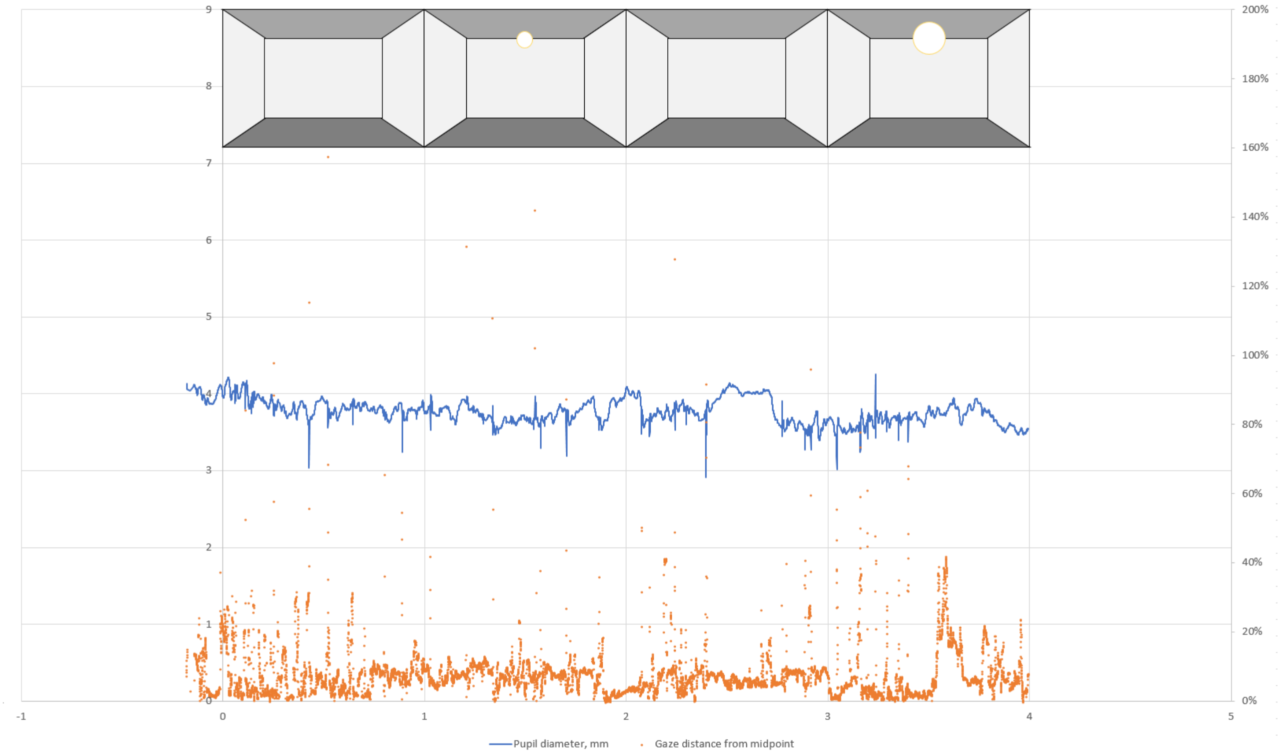


Figure 8-19 Pilot test 4 – Eik #1

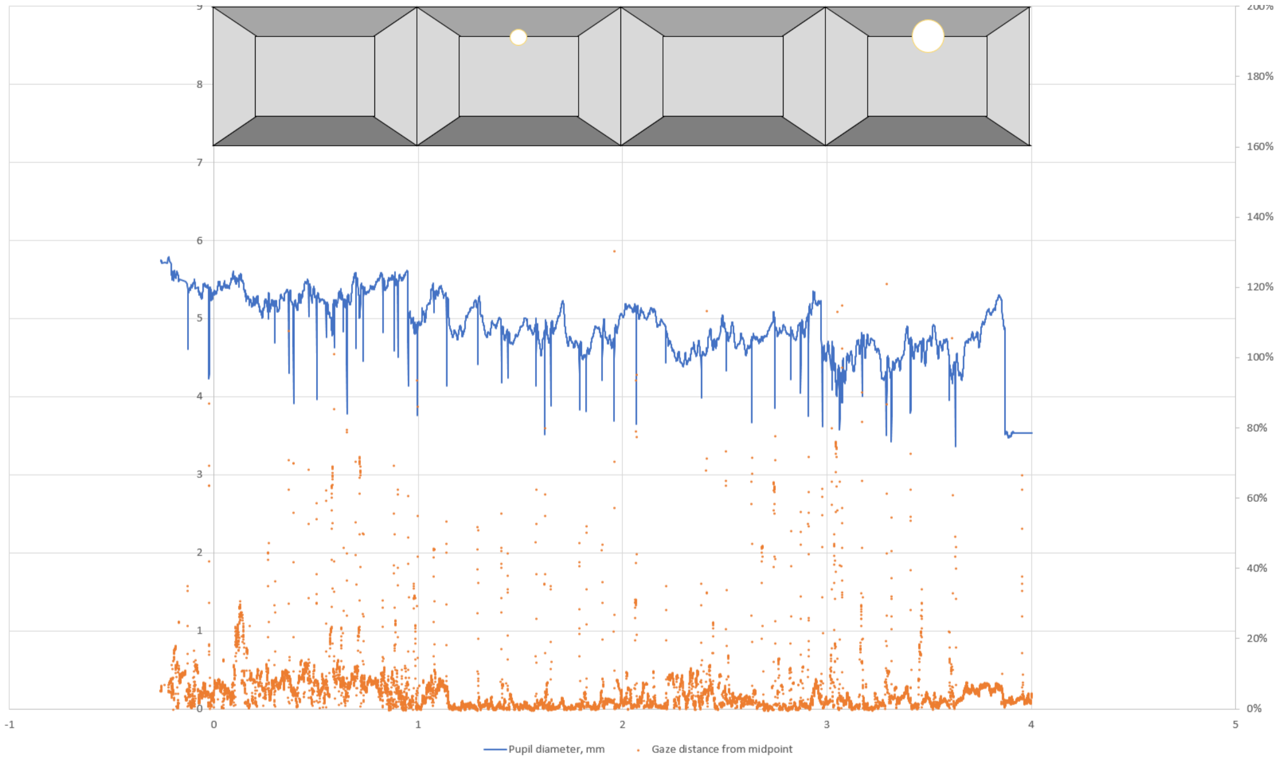


Figure 8-20 Pilot test 4 – Eik #2

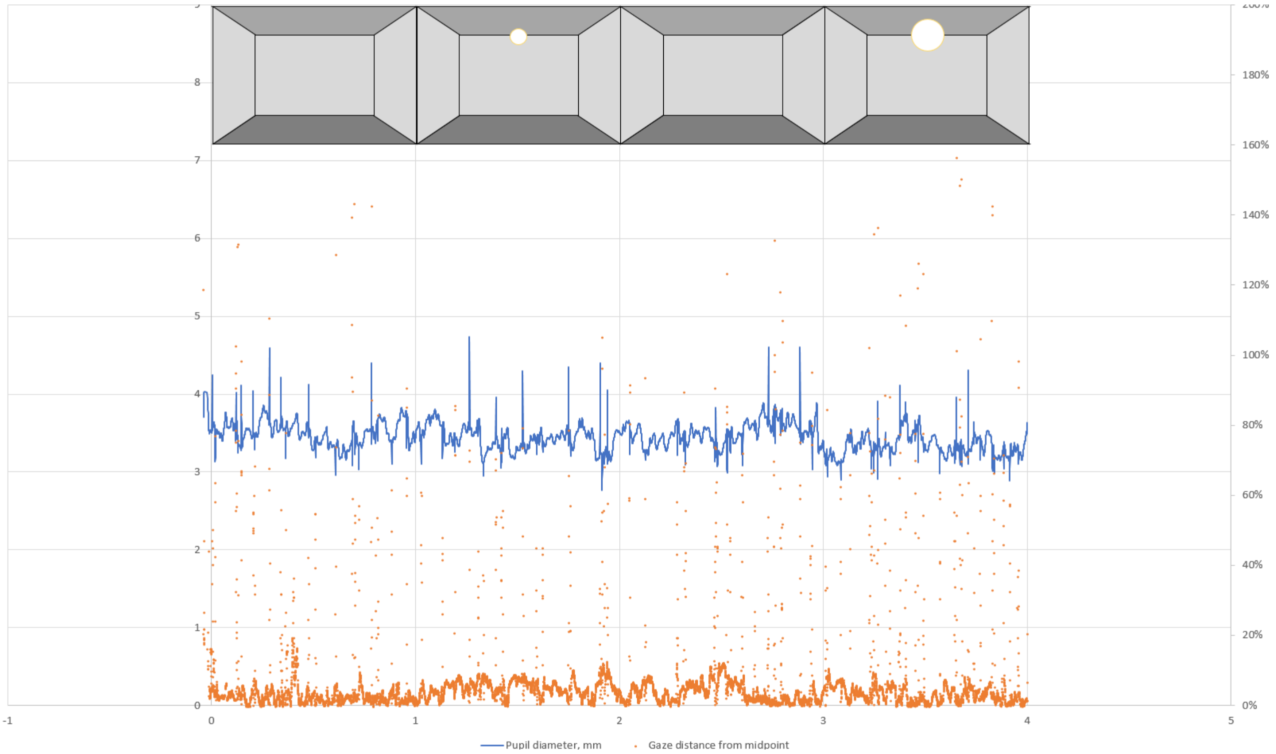


Figure 8-21 Pilot test 4 – Anne #1

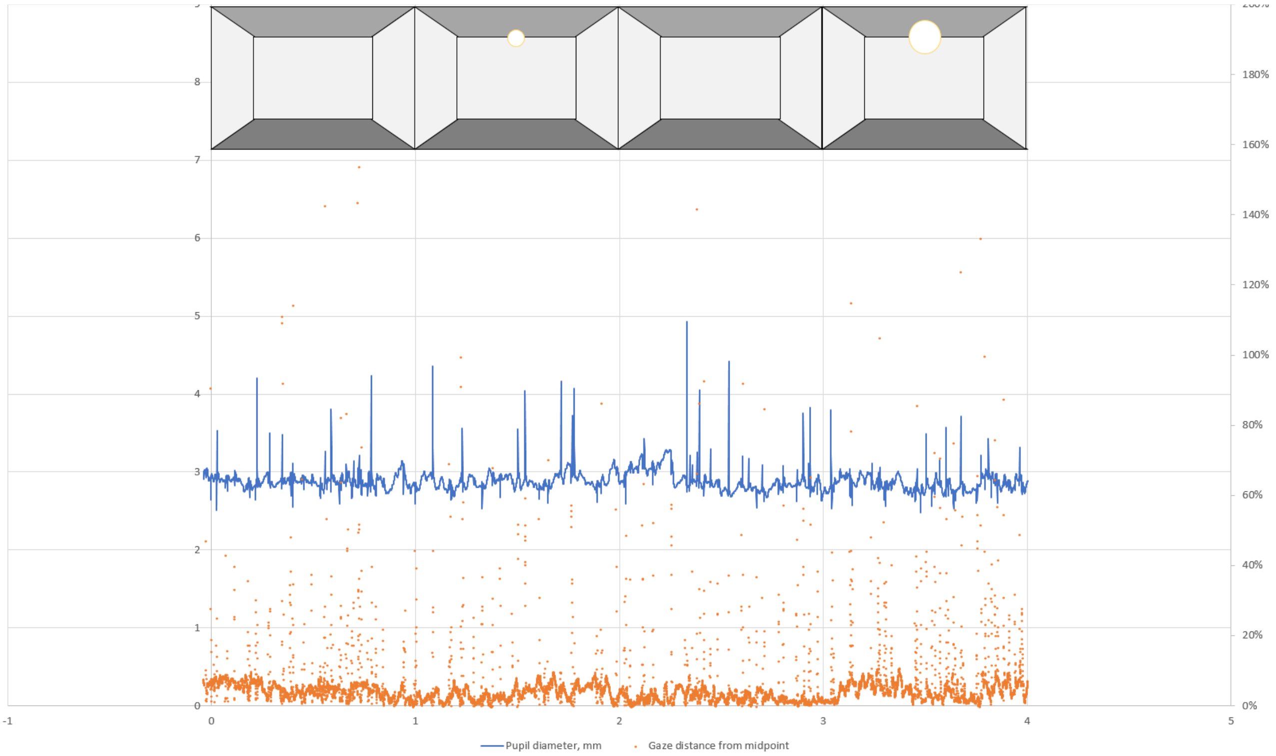
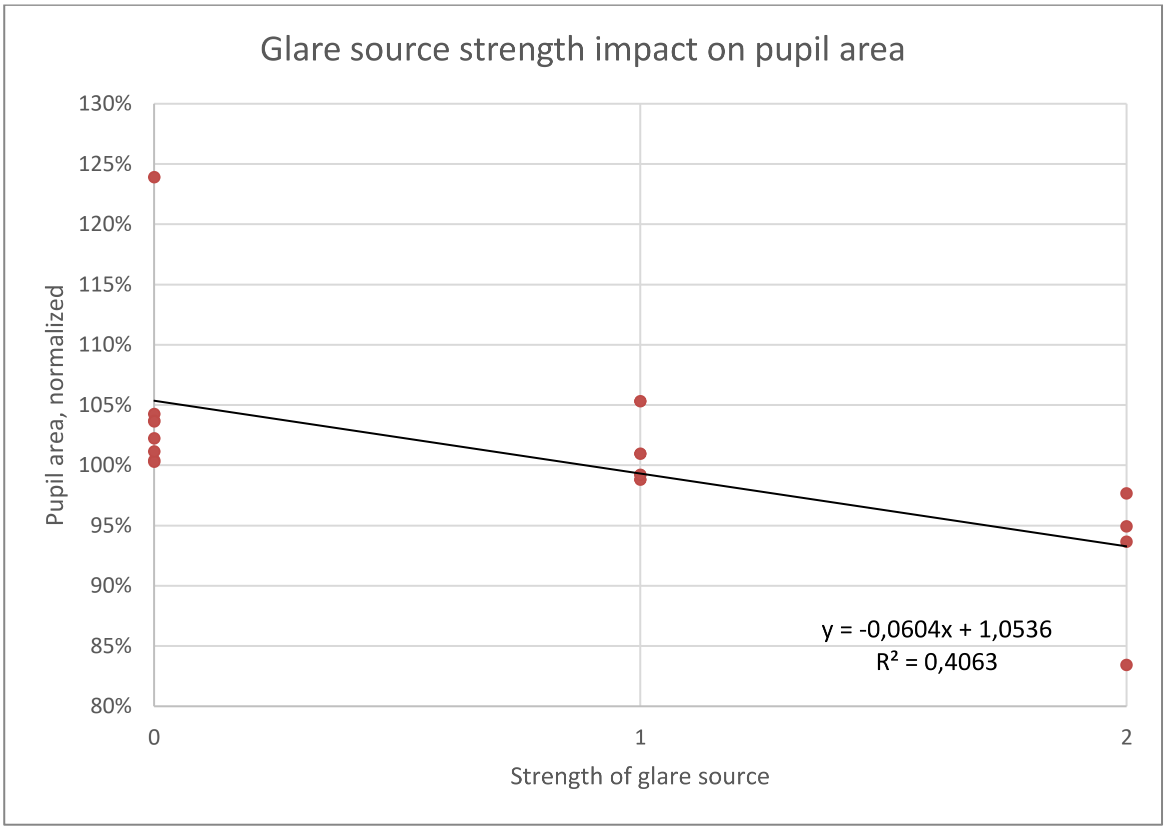
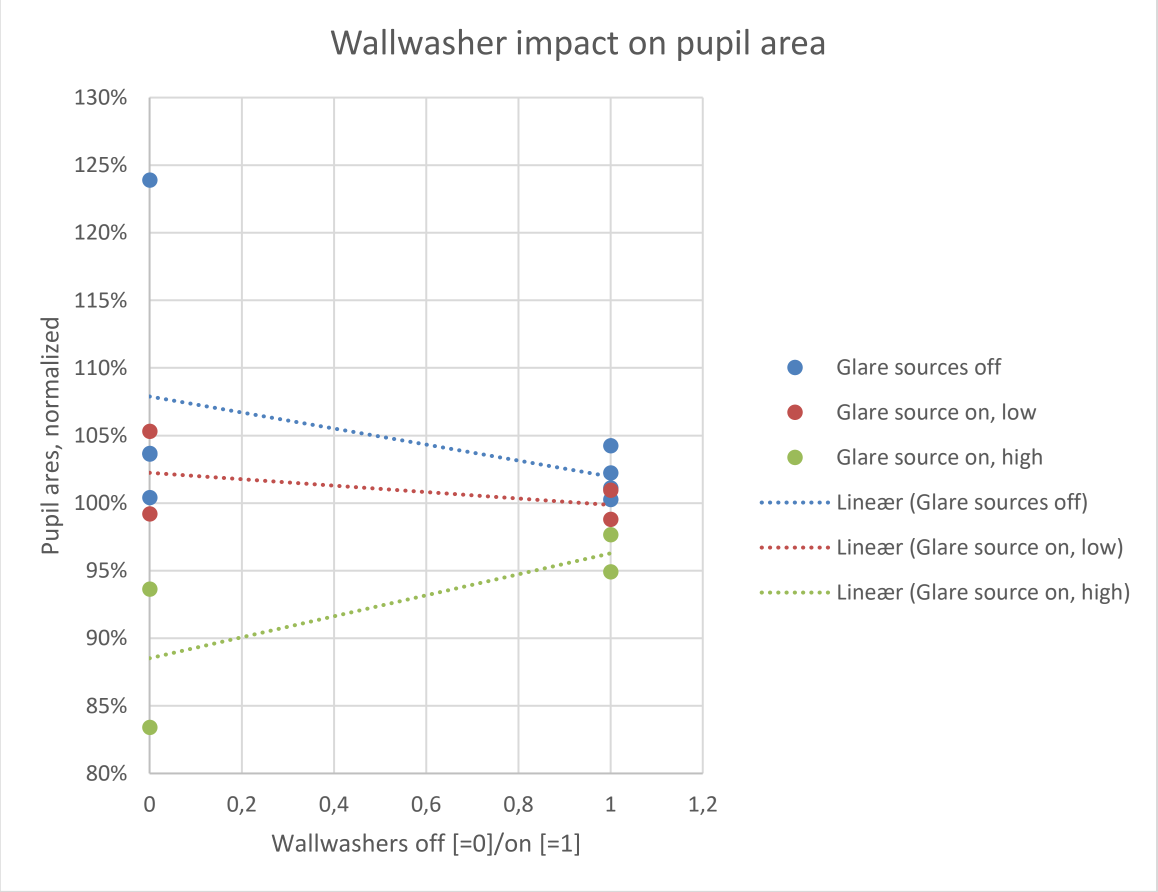
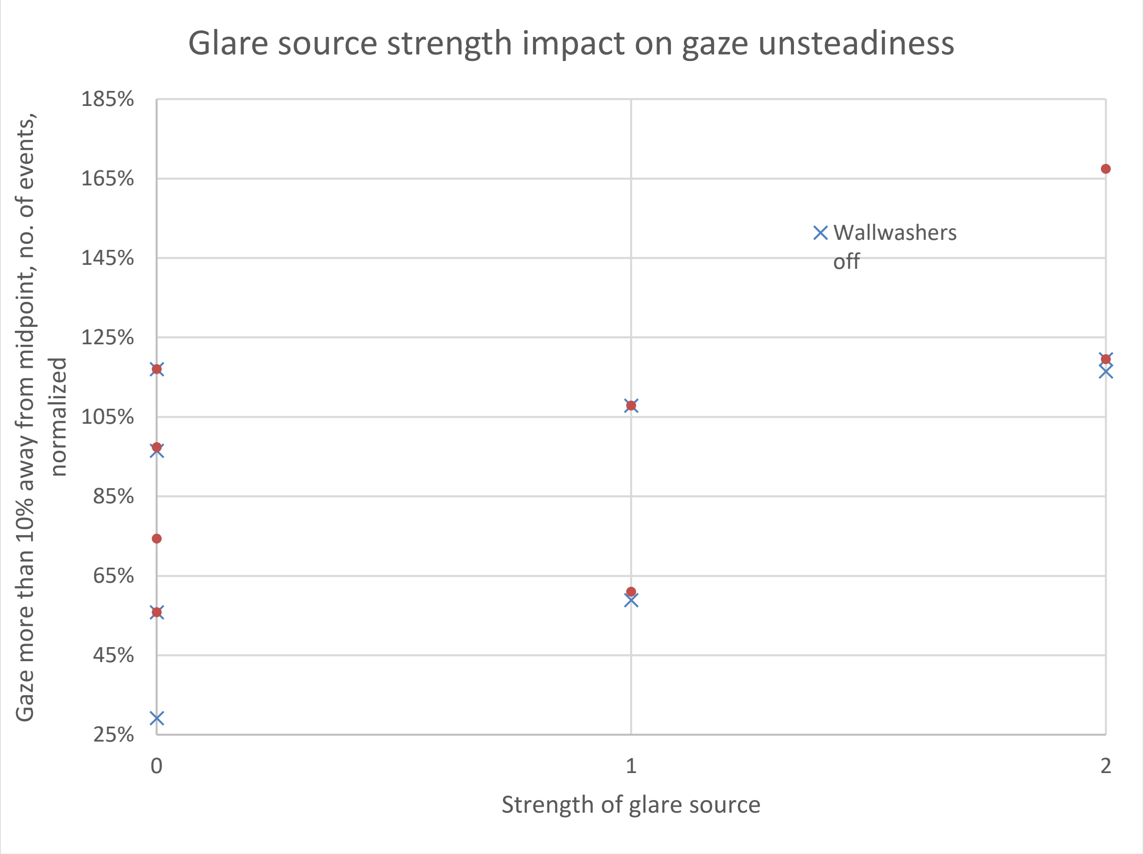
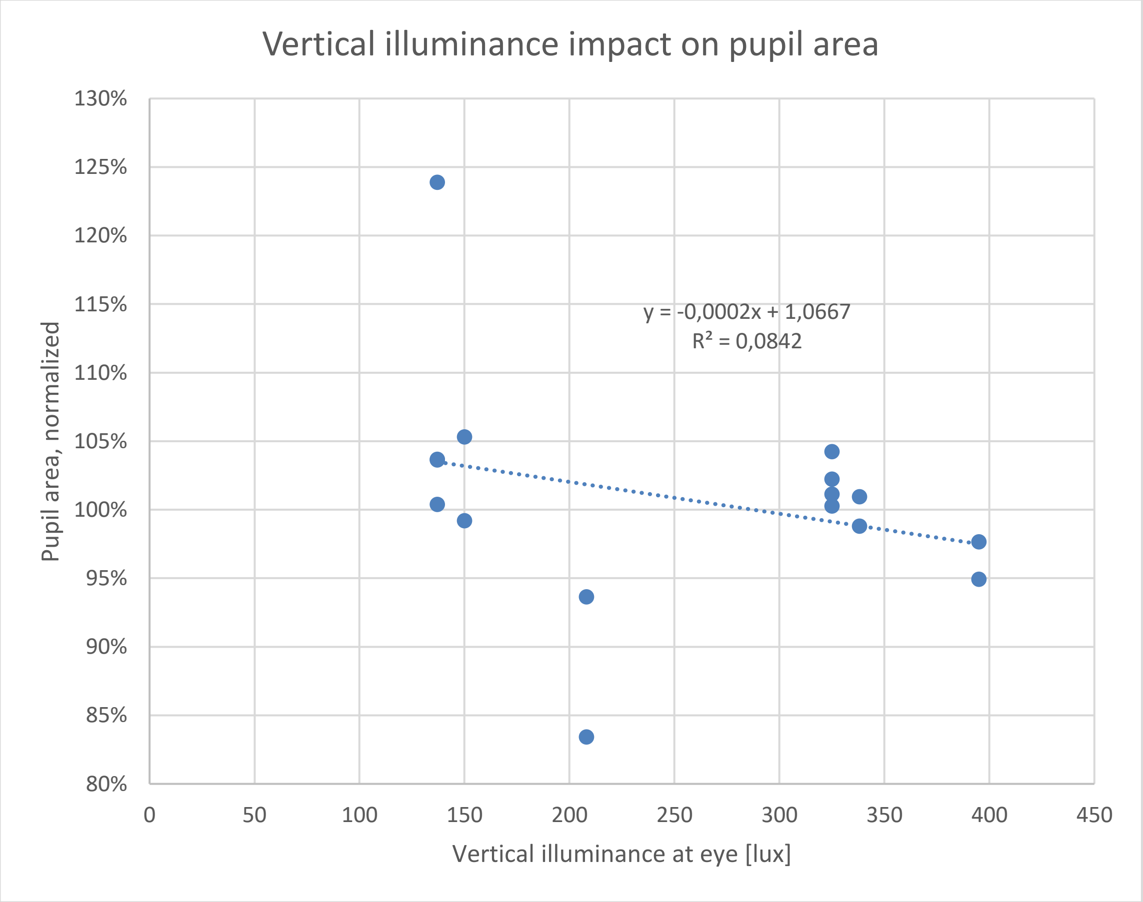


Figure 8-22 Pilot test 4 – Anne #2


Glare source strength impact on pupil area
Pupil area, normalized
130%
125%
120%
115%
110%
105%
100%
95%
90%
85%
80%
0
1
2
Strength of glare source
y = -0,0604x + 1,0536
R² = 0,4063


Wallwasher impact on pupil area
Pupil ares, normalized
130%
125%
120%
115%
110%
105%
100%
95%
90%
85%
80%
0
0,2
0,4
0,6
0,8
1
1,2
Wallwashers off [=0]/on [=1]
Glare sources off
Glare source on, low
Glare source on, high
Lineær (Glare sources off)
Lineær (Glare source on, low)
Lineær (Glare source on, high)


Glare source strength impact on gaze unsteadiness
Gaze more than 10% away from midpoint, no. of events, normalized
185%
165%
145%
125%
105%
85%
65%
45%
25%
0
1
2
Strength of glare source
Wallwashers off


Vertical illuminance impact on pupil area
Pupil area, normalized
130%
125%
120%
115%
110%
105%
100%
95%
90%
85%
80%
0
50
100
150
200
250
300
350
400
450
Vertical illuminance at eye [lux]
y = -0,0002x + 1,0667
R² = 0,0842

Appendix VI Pupil Fluctuations After Initial Adaptation

Light settings

Wallwasher	On	On	On	**On**	Off	Off	Off	**Off**	**Off/On**
Glare source	Off	Low	High		Off	Low	High		
UGR	6,4	24,2	28,5	**All**	9,4	30,0	31,4	**All**	
Pupil diameter std. dev. /average all participants	**Pupil diameter standard deviation [mm] - excl. 4 initial seconds after shift**								
	0,139	0,120	0,147	**0,135**	0,220	0,235	0,221	**0,228**	**1,689**
Participant 01	0,116 0,139	0,122	0,144	**0,130**	0,202 0,156	0,172	0,152	**0,170**	**1,309**
Participant 02	0,200 0,096	0,135	0,207	**0,160**	0,231 0,198	0,182	0,318	**0,232**	**1,453**
Participant 03	0,117 0,110	0,111	0,126	**0,116**	0,106 0,169	0,152	0,167	**0,149**	**1,281**
Participant 04	0,096 0,218	0,112	0,241	**0,167**	0,359 0,354	0,348	0,328	**0,347**	**2,082**
Participant 05	0,091 0,094	0,085	0,132	**0,101**	0,260 0,203	0,204	0,207	**0,219**	**2,169**
Participant 06	0,212 0,098	0,071	0,089	**0,118**	0,130 0,293	0,147	0,156	**0,182**	**1,543**
Participant 07	0,126 0,132	0,158	0,122	**0,135**	0,217 0,312	0,236	0,241	**0,251**	**1,867**
Participant 08	0,163 0,198	0,116	0,174	**0,163**	0,304 0,240	0,291	0,302	**0,284**	**1,747**
Participant 09	0,073 0,064	0,047	0,059	**0,061**	0,136 0,071	0,082	0,064	**0,088**	**1,458**
Participant 10	0,184 0,141	0,137	0,145	**0,152**	0,186 0,199	0,292	0,232	**0,227**	**1,496**
Participant 11	0,140 0,189	0,194	0,174	**0,174**	0,358 0,171	0,359	0,205	**0,273**	**1,567**
Participant 12	0,186 0,123	0,123	0,100	**0,133**	0,102 0,150	0,313	0,272	**0,209**	**1,574**
Participant 13	0,220 0,178	0,125	0,166	**0,172**	0,386 0,204	0,129	0,159	**0,219**	**1,274**
Participant 14	0,219 0,140	0,116	0,124	**0,150**	0,266 0,522	0,512	0,417	**0,429**	**2,862**
Participant 15	0,106 0,104	0,127	0,114	**0,113**	0,245 0,100	0,181	0,208	**0,183**	**1,627**
Participant 16	0,092 0,073	0,140	0,228	**0,133**	0,080 0,129	0,167	0,111	**0,122**	**0,916**