Effects of direct glare and interaction between the visual system and the musculoskeletal system during computer work

Effekter av direkte blending
og interaksjon mellom det visuelle systemet og
muskelskjelettsystemet ved dataarbeid

Philosophiae Doctor (PhD) Thesis

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Notodden, August 2019
Randi Mork

Contents

Abbreviations and definitions

Abduction	Movement of shoulder joint with arm outward in the sagittal plane
Arcmin	Minutes of arc
D	Dioptres
EMG	Electromyography
Extension	To bend backward (head and back) or movement of shoulder joint with arm backward in the frontal plane
FD	Fixation disparity
Flexion	To bend forward (head and back) or movement of shoulder joint with arm forward in the frontal plane
Glare	Condition with glare exposure (paper I)
HPA axis	Hypothalamus–pituitary–adrenal axis
ipRGCs	Intrinsically photosensitive retinal ganglion cells
KVM	Kongsberg Vision Meeting
Lateral flexion	Side bending
LED	Light-emitting diode
LS	Low stress (condition in papers II and III)
MmHg	Millimetre of mercury
MIFs	Felderstruktur fibres/multiply innervated small muscle fibres (found in extraocular muscles)
MVC	Maximal voluntary contraction
NES	Nordic Ergonomics and Human Factors Society
Optimal	Condition with optimal lighting (paper I)
PPG	Photoplethysmography
PS	Psychological stress (condition in papers II and III)
RMS	root mean square
SCN	suprachiasmatic nucleus
SD	Standard deviation
SEM	Standard error of the mean
SIFs	Fibrillenstruktur fibres or single innervated large muscle fibres (found in extraocular muscles)
TBF	trapezius muscle blood flow
Test leader	PhD-candidate and author of the thesis
USN	University of South-Eastern Norway (before May 2018: University College of Southeast Norway)
VAS	Visual analogue scale
VPS	Visual and psychological stress (condition in papers II and III)
VS	Visual stress (condition papers II and III)

Abstract

This thesis presents results from two within-subject laboratory experiments that investigated how young, healthy subjects with normal binocular vision are affected by exposure to direct glare (visual stress) during computer work. In addition to investigating responses due to glare, the thesis explored possible functional interactions between the visual and the musculoskeletal systems during glare. More precisely: if eye and vision related factors affect the neck area, or vice versa, during computer work in the presence of glare.

The experiments used a counterbalanced, repeated design where all participants performed different computer work conditions at the same ergonomically optimized workstation but with different stress exposure requirements: appropriate lighting conditions (minimal stress; projects 1 and 2), direct glare (visual stress; projects 1 and 2), psychological stress (project 2), and combined visual and psychological stress (project 2). Muscle activity and muscle blood flow in the neck muscle trapezius and in the orbicularis oculi muscle around the eye, postural angles, heart rate, blood pressure, productivity, and blink rate were continuously recorded during work and rest sessions. Development of eye-related symptoms, neck pain, positive and negative state moods, and perceived workstation lighting were recorded using VAS-questionnaires. Fixation disparity was additionally measured in project 2.

The results from the current thesis revealed that glare during computer work result in increased eyelid squinting (increased activity of orbicularis oculi), eyestrain, head flexion, blink rate, and trapezius muscle blood flow, compared to optimal lighting. The participants also perceived the lighting worse with glare, and they felt more uncomfortable. Furthermore, during glare there were observed significant positive associations between perceiving the lighting worse and more perceived stress.

As glare exposure during computer work was observed to cause a significantly rise in trapezius muscle blood flow, this result suggested a direct effect of glare on the neck area and thus indicated an interaction between the visual system and the musculoskeletal system. This glare response could not be explained entirely by changes in posture and was seemingly induced by other mechanisms than those active during psychological stress. This proposed interaction between the eyes and the neck was suggested to occur

due to increased demands for gaze stabilization and/or a centrally mediated alertness response triggered by the induced visual stress (glare). This interaction may also be reflected in positive correlations between eyelid squinting, trapezius muscle blood flow and neck pain. Eyelid squinting is previously suggested to be an objective measure of discomfort glare, suggesting that the subjects who experienced the most annoyance and discomfort related to glare, probably also exhibited the strongest eyelid squinting response. Thus, the more glare-sensitive, the more increased eyelid squinting, trapezius muscle blood flow, and neck pain. This proposed interaction between the visual system and the musculoskeletal system require further research as the underlying mechanisms remain unclear.

Furthermore, the orbicularis oculi appears to be a muscle activated both by glare, with eyelid squinting to reduce incoming light to the retina and/or reflecting discomfort glare, and during computer work as such, possibly activated by the need for increased attention and concentration.

The results presented in this thesis revealed the importance of reducing glare conditions and visual stress during computer work, even for young, healthy subjects. From a public health and preventive perspective, the awareness of work lighting without glare should be highlighted among professionals working in the field, as exposure to glare may have negative consequences for several important health factors in the workplace, such as the development of symptoms, increased discomfort and stress, and generally reduced well-being.

Keywords

Glare, computer work, trapezius muscle blood flow, eyelid squinting, eyestrain, neck pain

Sammendrag (Norwegian abstract)

Denne avhandlingen presenterer resultater fra to laboratorieeksperimenter som undersøker hvordan unge, friske personer med normalt binokulært syn påvirkes av direkte blending (visuelt stress) under dataarbeid. I tillegg til å studere effekter av blendingseksponering, ble mulige funksjonelle interaksjoner mellom det visuelle systemet og muskelskjelettsystemet ved blending undersøkt. Mer presist fortalt; om øye- og synsrelaterte faktorer påvirker nakkeområdet, eller omvendt, under dataarbeid med blending.

Eksperimentene brukte et balansert og gjentatt design der alle deltakerne utførte flere forskjellige dataarbeidsøkter på den samme ergonomisk optimaliserte arbeidsstasjonen, men med ulike stresseksponeringskrav: gode belysningsforhold (minimalt stress, prosjekt 1 og 2), direkte blending (visuelt stress; prosjekt 1 og 2), psykologisk stress (prosjekt 2), og samtidig visuelt og psykologisk stress (prosjekt 2). Muskelaktivitet og muskel blodstrøm i nakkemuskelen trapezius og i orbicularis oculi muskelen rundt øyet, posturale vinkler, hjertefrekvens, blodtrykk, produktivitet og blunkefrekvens ble kontinuerlig registrert både under arbeid og i hvile. Utvikling av øyerelaterte symptomer, nakkesmerte, positive og negative følelser og opplevd belysning på arbeidsstasjonen ble registrert ved hjelp av et VAS-spørreskjema. I tillegg ble fiksasjonsdisparitet målt i prosjekt 2.

Resultatene fra denne forskningen viste at blending ved dataarbeid førte til økt mysing (økt aktivitet i orbicularis oculi), rapportering av mer øyesymptomer, økt hodefleksjon, økt blunkefrekvens og økt trapezius blodstrøm sammenlignet med ikke-blendende belysning. Deltakerne opplevde også belysningen på arbeidsplassen verre ved blending, samt mer ubehag. Videre, ved blending ble det også observert signifikante sammenhenger mellom det å oppleve belysningen ubehagelig og det å føle seg stresset.

Da blending under dataarbeid forårsaket en signifikant økning i trapezius muskel blodstrøm, kan det tyde på en effekt av blending på nakkemuskelen, samt indikere en mulig interaksjon mellom det visuelle systemet og muskelskjelettsystemet. Denne blendingsresponsen i trapezius kunne ikke forklares utelukkende av endringer i sittestilling og ble tilsynelatende forårsaket av andre mekanismer enn de som var aktive under psykologisk stress. Denne foreslåtte interaksjonen mellom øynene og nakken, ble foreslått å oppstå på grunn av økt krav til blikkstabilisering og / eller en sentralt mediert

stressrespons utløst av det visuelle stresset (blendingen). Denne interaksjonen kan også være reflektert i de positive korrelasjonene mellom mysing, trapezius blodstrøm og nakke-smerte. Mysing er tidligere antydet å være et objektivt mål på ubehagsblending, noe som tyder på at deltakerne som opplevde mest irritasjon og ubehag relatert til blendingen, også antakelig hadde den sterkeste myseresponsen. Videre tyder det derfor på at mer følsomhet for blending, kan føre til mer mysing, trapezius blodstrøm og nakkesmerte. Denne foreslåtte interaksjonen mellom det visuelle systemet og muskelskjelett systemet krever videre forskning, da de underliggende mekanismene fremdeles er uklare.

Videre synes orbicularis oculi å være en ansiktsmuskel som blir aktivert både ved blending, med mysing for å redusere innkommende lys på retina og/eller som en respons som reflekterer ubehagsblending, og ved dataarbeid som sådan, muligens aktivert av behovet for økt oppmerksomhet og konsentrasjon.

Resultatene som presenteres i denne avhandlingen viser betydningen av å redusere forekomst av blending og visuelt stress under dataarbeid, selv for unge, friske mennesker. Fra et folkehelse- og forebyggende perspektiv bør oppmerksomhet om arbeidsplass-belysning uten blending økes blant fagfolk som arbeider ute i feltet, da eksponering for blending tilsynelatende kan ha negative konsekvenser for flere viktige helsemessige faktorer i arbeidslivet, som utvikling av symptomer, ubehag, stress og generelt redusert velvære.

Nøkkelord

Blending, dataarbeid, trapezius blodstrøm, mysing, øyesymptomer, nakke-smerte

List of papers

Paper I reports results from the experiment and data collected in Project 1, whereas paper II and paper III deals with different parts of the experiment and data collected in project 2.

Paper I

Mork, R., Bruenech, J.R., & Thorud, H-M.S. (2016). Effect of Direct Glare on Orbicularis Oculi and Trapezius During Computer Reading. *Optometry and Vision Science*, 93(7), p 738-749. doi: 10.1097/opx.0000000000000855

Paper II

Mork, R., Falkenberg, H.K., Fostervold, K.I., & Thorud, H-M.S. (2018). Visual and psychological stress during computer work in healthy, young females – physiological responses. *International Archives of Occupational and Environmental Health*, 91(7), p 811-830. doi: 10.1007/s00420-018-1324-5

Paper III

Mork, R., Falkenberg, H.K., Fostervold, K.I., & Thorud, H-M.S. (2019). Discomfort glare and psychological stress during computer work: subjective responses and associations between neck pain and trapezius muscle blood flow*. International Archives of Occupational and Environmental Health*, p 1–14. doi: https://doi.org/10.1007/s00420-019-01457-w

1. Introduction

In recent decades, the use of computers and other electronic devices has increased enormously. In Norway, 27% of the population used the internet on an average day in 2000; by 2015, that figure reached 87%. In today's society, people spend several hours a day performing tasks on digital screens, both at work and in their spare time, and computer work often consists of both visual, ergonomic, and psychological demands.

Because of rapidly evolving technology and the visual requirements of near work on digital devices, the term 'digital eye strain', also called 'computer vision syndrome', has become a pressing health issue. The syndrome is a collection of ocular and visual symptoms experienced during or related to prolonged use of digital screens, and musculoskeletal symptoms (including neck pain) are also included in these complaints (Blehm et al. 2005; Coles-Brennan et al. 2019; Gowrisankaran and Sheedy 2015; Rosenfield 2016; Sheppard and Wolffsohn 2018). Eyestrain and visual complaints are prevalent among computer workers, with the main visual symptoms reported include tired eyes, headaches, dry eye, blurred vision and double vision (Coles-Brennan et al. 2019; Ranasinghe et al. 2016; Rosenfield 2011). In line with this, visual discomfort are reported to be associated with reduced work capacity both in small offices and in office landscapes (Helland et al. 2011). Near visual work, like computer work, places a high demand on the human visual system and requires the involvement of both smooth and cross-striated muscles in and around the eyes to keep the near object clear and single (Levin et al. 2011; Lie and Watten 1994). Accordingly, optimal visual conditions, like the lighting, are essential during computer work, as the need for appropriate focused retinal images is crucial to perform work tasks efficiently and comfortably (Anshel 2005; Boyce 2014; Helland et al. 2011).

Computer workers also generally report a high prevalence of musculoskeletal pain and the most frequently reported symptoms are pain or discomfort in the neck and shoulder area (Côté et al. 2008; Gerr et al. 2002; Larsson et al. 2007; Mohanty et al. 2017). Côté et al. (2008) reported that office and computer workers had the highest incidence of neck pain of all occupations, with the one-year prevalence varying from 17.7% to 61.5% across different studies. Furthermore, women more often than men experience neck and shoulder pain (Larsson et al. 2007; Nordander et al. 2016; Paksaichol et al. 2012).

A number of studies report that visual demands, often investigated as induced refractive errors or stress on the binocular visual system, affect muscles in the neck area (Domkin et al. 2016; Lie and Watten 1994; Lie et al. 2000; Richter et al. 2011a; Richter et al. 2010; Richter et al. 2011b; Sánchez-González et al. 2018; Zetterberg et al. 2013). Furthermore, eyestrain and visual discomfort often occurs along with musculoskeletal symptoms in the neck area during computer work (Hayes et al. 2007; Helland et al. 2008; Richter et al. 2011b; Wiholm et al. 2007; Zetterberg et al. 2017). One proposed mechanism for the connection between poor visual conditions and musculoskeletal discomfort suggests that the muscle tonus in the neck region increases relative to the insufficiency of the visual conditions (Richter et al. 2011b; Wiholm et al. 2007). In line with this, it has also been reported that subjects with neck pain often correspondingly experience visual disturbances like visual fatigue and light sensitivity (Treleaven and Takasaki 2014), highlighting the existence of a close relationship between the visual system and musculoskeletal system.

Glare exposure is a major issue for lighting design of the work environment and is often experienced during computer work. Too intense or inappropriate distribution of lighting within the visual field may give rise to glare conditions, and the effect of glare may vary from being hardly noticeable to detrimental to functional vision for the worker. Glare exposure is known to aggravate eyelid squinting undertaken in an effort to reduce the amount of light from the environment that enters the eyes (Sheedy et al. 2003b). Moreover, glare may also provoke musculoskeletal pain, discomfort, eyestrain and annoyance (Berman et al. 1994; Boyce 2014; Gowrisankaran et al. 2007; Helland et al. 2011; Helland et al. 2008; Juul-Kristensen et al. 2004; Nahar et al. 2007). In the office environment, technological developments have resulted in a dramatic shift in visual tasks from writing and reading on paper placed on the desktop with a downward viewing angle to working at a display with gaze angles often close to the primary position, straight ahead or slightly downward. With a higher gaze, the visual field of the workers covers more of the office environment and thus the presence of various artificial light sources, surfaces with high specular reflection, and windows. Hence, computer workers in today's offices are exposed to multiple potential glare conditions during their work hours.

Further, from a public health perspective, preventive work to avoid neck pain is very important, as such problems cause great personal distress and are an economic burden on society (Cohen and Hooten 2017; NAV 2018). Today, prevention of the first episode or a recurrence of neck pain is the common focus at computer-driven workplaces (Jun et al. 2017); preventive actions often include adjustment of work postures, exercise, physiotherapy, and psychosocial interventions (Jun et al. 2017; Ortego et al. 2016; Verhagen et al. 2006). Along with this, as optimal visual ergonomics among computer workers appears to be essential to prevent neck pain and to increase the well-being of workers (Aaras et al. 1998; Helland et al. 2008; Richter et al. 2011b), the lighting conditions have traditionally received less attention in preventive work in this area. Concerning this, no one have, to the best knowledge of the author, previously investigated how exposure to glare conditions during computer work affect neck muscles and symptom development in the neck area.

In this thesis, the main aim are therefore to explore both subjective and objective responses in healthy, young subjects with normal binocular vision due to exposure to direct glare while working on a computer screen. Another aim are to investigate possible functional links between the visual system (eyes) and the musculoskeletal system (neck) during computer work with glare.

2. Background

This chapter outlines the key elements and background of the topics discussed in this thesis. The main emphasis is on lighting in the work environment, including glare conditions, work-related symptoms during visual demanding work, the visual system, and the current knowledge regarding potential interactions between the visual system and the musculoskeletal system.

Below, the term ‘eyestrain’ is used as a general description for all relevant eye symptoms and visual discomfort and is roughly synonymous with the formal diagnostic term asthenopia. Pain and discomfort in the neck area are referred to as simply ‘neck pain’ and the term ‘glare’ refers to direct glare conditions unless otherwise is described.

2.1 Lighting in the computer work environment

Lighting at the workstation is an important issue in a work environment and may influence employees’ task performance, comfort, well-being, and overall health (Aaras et al. 1998; Anshel 2007; Duijnhoven et al. 2017; Hemphälä and Eklund 2012; Osterhaus and Bailey 1992). According to Anshel (2007), lighting is one of the most underemphasized components in today’s workplaces. Appropriate lighting is essential while working, and light adequate for seeing the visual objects clearly is crucial. In addition, lighting must be of proper quality to prevent visual discomfort; for instance, it should avoid reflections and sources of glare (Anshel 2007). Optimal lighting quality and visual comfort are achieved when the visual field has a relatively uniform distribution of luminance (Duijnhoven et al. 2017).

The visual environment for computer work must enable the worker to see and perform the work task properly, without causing unnecessary eyestrain or discomfort in other parts of the body. The main factors related to lighting in the work environment are: illuminance, luminance, direction of light, glare, correlated colour temperature of the light source, colour rendering of the light source, and possible non-visual effects (such as non-visual flicker) (Osterhaus et al. 2015). Illuminance, measured as lumens per square metre (lm/m^2) and abbreviated as lux, is the total luminous flux falling onto a point of a surface from all directions of a hemisphere over the surface measured (Bjørset 1994; Boyce 2014). Luminance (measured as candela per square metre, cd/m^2) is the luminous intensity per unit area emitted in a given direction. It is an expression of the measured brightness of a light source or illuminated surface, and reflects the lighting affecting the eye when measured from that point of view.

In order to produce a work environment that provides visual satisfaction, comfort, and performance, the luminance distribution within the visual field needs to be balanced. The distribution of light at a workstation is recommended to have a maximal luminance ratio of 5:3:1 between the working area, the immediate surrounding area and the background area (Anshel 2007), with the highest luminance located in the working field. Because this ratio may be difficult to achieve in many real-life situations, Bjørset (1994) recommends a maximum ratio of 10:3:1. The working field will be defined somewhat different according to the work achieved at the particular workstation, e.g. if the work is performed at the computer screen only, that will be defined as the working field. When the worker has to shift the gaze from the screen, to the keyboard and papers at the desk, the luminance in the working field are the mean luminance of all areas. However, the working area should be the brightest area in the field of view, and the immediate surrounding area and the background area should ideally have slightly lower luminance. According to the illuminance at the workstation, the European standard EN-12464-1 for lighting in office recommend illuminance for computer work 500 lx at working task, 300 lx at nearest surrounding area and 100 lx in the room (European-Standard 2011).

Boyce (2014) states that lighting conditions may affect human performance through three different routes: the visual system, the non-image-forming system, and mood and motivation (Boyce 2014, p. 116, figure 4.1). As to the first, the visual system is an image-processing system and depends on light for humans to see the outside world and carry out work tasks. Visible light, the optical spectrum, is electromagnetic radiation with wavelengths between 380 and 780 nm that stimulates the rods and cones on the retina of the human visual system. Five parameters are important when determining the degree to which the visual system can detect and identify a stimulus: visual size, luminance contrast, colour difference, retinal image quality, and retinal illuminance (Boyce 2014). Four out of five of these parameters may be affected by lighting conditions, for instance in an office environment, which can either facilitate or inhibit visual performance.

Secondly, lighting may affect task performance through the non-image-forming system. However, the effect of light through this route is not yet fully understood, but it probably involve the intrinsically photosensitive retinal ganglion cells, or ipRGCs, that send signals directly to the part of the brain that controls the circadian timing system and other biological rhythms: the suprachiasmatic nucleus (SCN) of the hypothalamus (Berson et al. 2002; Westland et al. 2017). IpRGCs will be further explained under the section ‘2.3.1 Anatomy of the eyes’. Phase shifts of the circadian rhythms, cortisol affection, and alerting effects are all aspects that may be involved in this route of lighting effects. Furthermore, ipRGCs contribute to the pupillary light reflex, as discussed later in this chapter (Markwell et al. 2010).

The third route through which lighting may impact human performance is by affecting a subject’s moods and motivation (Boyce 2014), as by the presence of glare or flicker during work. The visual system may produce emotional responses due to the surrounding visual world; this might occur during poor lighting conditions under which the worker develops a sense of visual discomfort. In line with this, workers who perceive their office lighting as being of higher quality rate the room as more attractive, enjoy more pleasant moods, and show greater well-being at the end of a working day (Veitch et al. 2008).

2.1.1 Glare

Glare has been said to be light entering the eyes that does not aid vision; it is typically caused by environmental luminance that is too intense or variable across the field of view for a particular person or task (Mainster and Turner 2012). Direct glare conditions exists when the glare sources are placed within the field of view sending light directly towards the eyes, whereas indirect or reflection glare occurs if light from a glare source reflects from a glossy surface and hits the eyes of the worker. Furthermore, excessive light within the peripheral visual field is easily detected by the human visual system and may attract attention, be distracting, and cause stress when the subject tries to ignore it while working (Boyce 2014; Boyce and Wilkins 2018). Hence, glare may lead to visual discomfort and reduced well-being.

The two most common forms of glare are disability glare and discomfort glare. Disability glare, also called physiological glare, is glare that impairs vision; it leads to an actual reduction in visual performance due to intraocular stray light resulting in a veiling luminance on the retina, which decreases image contrast and reduces visibility in the field of view (Mainster and Turner 2012). Discomfort glare, also known as psychological glare, is glare that causes visual annoyance, discomfort, and distraction. It occurs because of high luminance or unsuitable distributions of luminance in the field of view that are significantly higher than the luminance to which the visual system is adapted (Boyce and Wilkins 2018; Mainster and Turner 2012; Pierson et al. 2018). Disability glare is reasonably well understood, whereas there are deficiencies in our understanding of the causes behind discomfort glare (Boyce 2014).

The visual system in human may operate within a wide range of luminance levels, from starlight (3×10^{-2} cd/m2) to a clear sky (5×10^{4} cd/m2), as long as those luminance conditions are not present in the visual field at the same time. In line with this, increased luminance of the glare source, decreased luminance of the background, the contrast effect, increased vertical illuminance at eye level, position of glare source, and size of the glare source are all factors proposed to increase the level of discomfort glare (Boyce and Wilkins 2018; Pierson et al. 2018). The contrast effect refers to that the contrast between the viewing direction (for example the visual task) and a bright spot in the field of view is too strong (Pierson et al. 2018).

The annoyance in discomfort glare conditions may arise because information from the excessive light is transmitted from the retina to important thalamic, somatosensory, visual, and other associated brain centres (Mainster and Turner 2012). Furthermore, the level of discomfort felt during glare is differing considerably between different subjects (Bargary et al. 2015; Berman et al. 1994; Karlsen et al. 2015; Stone and Harker 1973).

Responses to glare exposure

A variety of responses are reported due to glare exposure in humans. Glare are related to increased visual discomfort and eyestrain (Berman et al. 1994; Gowrisankaran et al. 2007; Helland et al. 2011; Helland et al. 2008; Lin et al. 2019; Nahar et al. 2007), shoulder pain (Juul-Kristensen et al. 2004), and behavioural countermeasures like changing posture, looking away, or shielding the eyes from the bright light (Boyce 2014; Ko et al. 2014). Increased eyelid squinting performed by the orbicularis oculi (Gowrisankaran et al. 2007; Sheedy et al. 2003b) and a reduction in pupil size (Ellis 1981; Hopkinson 1956), both of which are aimed at reducing retinal illumination, are also shown due to glare conditions. Additionally, glare has been reported to induce other visual responses, such as increased blink rate (Gowrisankaran et al. 2007; Nahar et al. 2007), blurred vision (Helland et al. 2011), and affection of the accommodation response (Kruger and Pola 1986; Shahnavaz and Hedman 1984; Wolska and Switula 1999).

Exposure to glare are moreover reported to have negative effects on reading performance and eye movements (Glimne et al. 2015; Glimne et al. 2013; Lin et al. 2015). Glimne et al. (2015) reported reduced reading speed and increased fixation durations due to both direct and indirect glare while reading. Direct glare has also been reported to decrease binocular coordination by significantly increasing the fixation disparity variation, which further has been proposed as an indicator of visual discomfort and fatigue (Glimne et al. 2013; Glimne and Österman 2019). Lin and co-workers (2015) examined the relationship between glare exposure, perceived discomfort, relative pupil size (pupil constriction caused by glare after adaption of the eyes to the background illumination), and vertical eye movements (given as average eyeball movement speed). They reported that increased subjectively reported discomfort glare was related to larger pupil constriction and increased vertical eye movement speed in both young and older subjects. In this study, relative pupil size was suggested to be a better measure for discomfort glare than actual pupil size. In line with pupil responses due to glare, exaggerated pupillary unrest has also been observed during glare exposure and has been proposed as a factor involved in generating eyestrain and discomfort with glare (Fry and King 1975; Hopkinson 1956; Nakamura 1997).

Moreover, external light exposure are previously reported to result in altered autonomic responses of the nervous system (Abrahams et al. 1964; Belkić 1986; Fan et al. 2018; Niijima et al. 1993; Niijima et al. 1992; Noseda et al. 2017; Saito et al. 1996). Along these lines, Saito et al. (1996) showed a significantly enhanced muscle sympathetic nerve activity in the peroneal nerve in healthy humans during 20 minutes of exposure to excessive light with an intensity of 5000 lux, whereas Niijima et al. (1992) reported increased sympathetic activity in rats due to bright light exposure for 10 minutes (2000 lux).

2.2 Discomfort during computer work

As noted in the introduction, both eyestrain and neck pain are frequently reported among computer workers, and these symptoms appear to co-exist (Gerr et al. 2002; Helland et al. 2008; Ranasinghe et al. 2016; Richter et al. 2011b; Wiholm et al. 2007). Development of symptoms seems to be dose-dependent; symptoms increases as time spent on the computer screen increases (Chang et al. 2007; Portello et al. 2012). Furthermore, both eye and neck symptoms are reported to affect the quality of life among computer workers (Hayes et al. 2007).

2.2.1 Work-related eyestrain

Various causes have been discussed in the literature to explain the development of eyestrain in computer workers, including different environmental factors, the users' visual abilities, and the demands placed on the visual system by the computer work (Blehm et al. 2005; Gowrisankaran and Sheedy 2015; Rosenfield 2011; Sheppard and Wolffsohn 2018).

A variety of environmental factors, such as lighting, glare, workstation design, and relative humidity, may put extra stress on the visual system during computer work and may thus encourage the development of eyestrain (Aaras et al. 1998; Boyce 2014; Fostervold et al. 2006; Gowrisankaran and Sheedy 2015; Hemphälä and Eklund 2012; Rosenfield 2011; Wolkoff 2008). Dry eyes are common in people working at computer screens and have been cited as a major contributor to computer-related eyestrain (Blehm et al. 2005; Rosenfield 2011; Wolkoff 2008). Computer work requires increased attention by the worker, and high gaze angles induce decreased blink rate, increased number of incomplete blinks, and a greater corneal exposure (Rosenfield 2011; Wolkoff 2008; Wolkoff et al. 2005). All these factors are assumed to be involved in the development of dry eyes among computer workers, possibly in relation to affection of the precorneal tear film stability (Wolkoff 2008). During visually demanding computer work, the involvement of the orbicularis oculi muscle in the development of extraocular symptoms like eye tiredness and pain has also been suggested (Berman et al. 1994; Thorud et al. 2012).

If a subjects visual abilities are reduced, that may also cause eyestrain during computer work (Rosenfield et al. 2012; Sheedy 1980; Sheppard and Wolffsohn 2018; Wiggins and Daum 1991). Increased eyestrain due to visual capabilities may result from reduced visual acuity and increased target blur, making task performance more difficult due to the increased demands on the visual system (Jenkins et al. 1994; Rosenfield 2011). Furthermore, stress put on the binocular vision during computer work are also reported to increase eye-related symptoms even in young adults with normal binocular vision (Yekta et al. 1987). Blurred vision is another visual symptom often experienced by computer users; common causes may be uncorrected refractive errors, accommodative dysfunction, presbyopia (diminished age-related ability to focus at closer distances), and binocular vision disorders (Rosenfield 2011; Rosenfield et al. 2012). Blurred vision may also occur during glare conditions (Blehm et al. 2005; Helland et al. 2011).

Computer work, places a high demand on the visual system. During natural viewing conditions, the visual system works dynamically with visual scanning performance shifting between near and far distances. However, during computer work the demands of the visual system are replaced with static, intensive, and often long-lasting focusing at near within a restricted two-dimensional area of the visual field. Accordingly, this implies that the same demands should be present during near work tasks at paper as well, not only during computer work. In line with this, Köpper et al. (2016) conducted four experiments to investigate eye symptom development during reading on a computer screen compared to reading on paper. In the three first experiments, they found that symptoms of eyestrain were more pronounced during prolonged proofreading tasks (25, 45, and 60 minutes) on a computer than on paper, even though the viewing distance was shorter under the paper conditions and thus required more accommodation. Further, the difference in reported symptoms was still present even when the luminance on the computer screen was reduced, suggesting that screen luminance may not be the sole cause of eye complaints during computer work. However, in the fourth experiment, the same task was performed, but the viewing angles of the screen (an iPad) and paper conditions were similar. The paper-like positioning of the screen equalized the chosen viewing distance in the two conditions, and there were no longer any differences in eyestrain symptoms between the screen and paper conditions. These results indicate that the positioning of the screen and high gaze angles may be crucial factors in the occurrence of eyestrain during computer work, a result that accords with other work (Fostervold et al. 2006; Nielsen et al. 2008). Conversely, Chu et al. (2011) reported that computer work differs from near work performed on printed material. They also compared these two conditions but used a computer-like position for the reading material. Reading from a computer screen compared to the printed material was reported to give rise to higher symptom scores for both blurred near vision and mean ocular symptom scores.

2.2.2 Work-related neck pain

Several risk factors and exposures, both physical and psychological, have been proposed for the development of work-related neck pain. These factors include, among others, posture and ergonomic demands, poor workstation arrangement, stress, repetitive movements, prolonged static muscle activity, and psychosocial work environments (Cohen and Hooten 2017; da Costa and Vieira 2010; Hagberg 1984; Hanvold et al. 2013; Jun et al. 2017; Keown and Tuchin 2018; Kim et al. 2018; Larsson et al. 2007; Linton 2000; Malchaire et al. 2001; Wahlström 2005). Yet, the cause for the high prevalence of neck pain among computer users seems to be complex, and the underlying mechanisms for the development of occupational neck pain remain unclear.

During computer work, the muscle loads of the active muscles are of low intensity but follow a repetitive and largely static pattern. There is shown significantly less variation in both posture and muscle activity than occurs when performing the same task on paper (Wærsted and Westgaard 1997), which demonstrates the static muscle pattern of computer workers. As to posture and the development of neck pain during computer work, the scientific literature indicates that posture may indeed be a contributing factor, but the evidence is limited and remains inconclusive (Chen et al. 2017; Jun et al. 2017; Malchaire et al. 2001; Mayer et al. 2012; Richards et al. 2016). Both forward bending (Ariens et al. 2001) and backward bending (Lau et al. 2010) of the neck have previously been reported to be related to the development of neck pain. Even though the connection between postural factors and neck pain is not yet fully understood, there is strong evidence of a relationship between pain development and extreme or awkward postures (da Costa and Vieira 2010; Larsson et al. 2007; Malchaire et al. 2001). Sustained postures have also been identified as a commonly reported risk factor for neck pain (Kim et al. 2018).

In addition to visual and postural demands, computer work often also involves mental effort and high attention requirements. Psychological factors have been suggested as playing a significant role in both chronic pain and the aetiology of acute pain (Linton 2000). Kim et al. (2018) sought to identify risk factors for experiencing a first episode of neck pain, an important issue from the public health perspective because neck pain often becomes a chronic issue. They found that most risk factors detected for neck pain were related to psychosocial rather than physical characteristics, and the strongest psychosocial risk factors were depressed mood, high role conflict, and perceived muscular tension. Visser and van Dieën (2006) concluded in their review that there are multiple possible pathophysiological mechanisms for upper extremity muscle disorders, but that none of the hypotheses forms a complete explanation for pain development. They further suggested that the pathophysiological processes appear to be influenced by different effect modifiers that range from individual to psychosocial factors.

Different factors are suggested to play a role in the pathogenesis of muscle pain. Among others, these include sustained muscle activity and overloading of type I motor units, intra-cellular accumulation of metabolites, and changes in skeletal muscle morphology and muscle blood flow (De Meulemeester et al. 2017; Hägg 1991; Johansson and Sojka 1991; Knardahl 2002; Larsson et al. 2007; Larsson et al. 1999; Lund et al. 1991; Sjøgaard et al. 2000; Travell et al. 1942; Visser and van Dieën 2006). When investigating the causes of work-related neck and shoulder pain, several studies have focused on the static low-level muscle contractions of the involved skeletal muscles. However, previous research has found limited evidence of a causal association between work-related pain and muscle contractions measured by using electromyography (EMG) (Knardahl 2002; Larsson et al. 2008; Strøm et al. 2009a; Strøm et al. 2009b; Vasseljen and Westgaard 1996).

One of the other proposed hypotheses regarding the pathogenesis of muscle pain during low-intensity work is the blood vessel–nociceptor interaction hypothesis, which involves skeletal muscle microcirculation (Knardahl 2002). Knardahl (2002) suggested that the development of muscle pain has to involve activation of the nociceptors, the sensory receptors sending pain signals into the central nerve system. Muscle pain was proposed to originate from these nociceptors in the connective tissue and/or blood vessels in the muscle by mechanical activation caused by vasodilation. In addition to the vasodilation, Knardahl suggested that other factors that contribute to nociception have to be present in the tissue to produce pain, for instance released prostaglandins and nitric oxide (Knardahl 2002).

In line with this hypothesis, several studies have investigated muscle blood flow responses and the presence of muscle nociceptive substances both in subjects exhibiting muscle pain (myalgia) and in pain-free subjects (Cagnie et al. 2012; De Meulemeester et al. 2017; Elvin et al. 2006; Gerdle et al. 2014; Gold et al. 2017; Hallman et al. 2011; Larsson et al. 2008; Larsson et al. 1999; Larsson et al. 1993; Larsson et al. 1995; Rosendal et al. 2004; Sandberg et al. 2005a; Sjogaard et al. 1986; Sjogaard et al. 2010; Strøm et al. 2009a; Strøm et al. 2009b). However, the literature is contradictory and regarding muscle blood flow and the effect on pain development, and both elevated and reduced TBF have been linked to neck pain development.

Larsson et al. (1999) reported that during fatiguing series of stepwise-increased contractions of the trapezius muscle, subjects with myalgia showed reduced trapezius muscle blood flow (TBF) in the painful side compared to pain-free subjects. The myalgia patients also revealed lower local TBF in the painful trapezius compared to the non-painful side, indicating that decreased TBF was related to pain, at least in myalgic muscles.

Further, subjects both with and without chronic work-related trapezius myalgia have shown increased TBF during repetitive low-force exercise and computer work, whereas the muscle blood flow remained significantly higher in the subjects with myalgia during the following recovery compared to in the controls (Rosendal et al. 2004; Strøm et al. 2009b). In Rosendal et al.'s (2004) study, the subjects with trapezius myalgia also exhibited increased anaerobic metabolism in the form of increased lactate and pyruvate during the low-force exercise, as well as higher concentrations of muscle nociceptive substances which were positively associated with pain intensity. Strøm et al. (2009b) showed that pain in the active side during computer work correlated positively with muscle blood flow (measured by laser-Doppler flowmetry) in subjects with chronic pain, whereas it correlated negatively with pain in the pain-free reference group.

Larsson et al. (2008) reported higher TBF throughout a working day consisting of highly repetitive work tasks in subjects with chronic neck and shoulder pain compared to a group of healthy controls. Further, they reported higher concentrations of glutamate and pyruvate, as well as higher levels of interstitial serotonin in the muscle tissue of the subjects with myalgia. No signs of simultaneously increased mental stress or muscle activity measured with electromyography (EMG) were found in the myalgia group (Larsson et al. 2008).

The different responses in muscle blood flow seen in the literature reflect the fact that different experimental tasks, along with the presence of myalgia or not, may affect TBF. Moreover, the studies indicate that muscle metabolism and circulation may be involved in relation to the development of neck pain, even though the underlying mechanism is still unclear.

2.2.3 Psychological stress

Various physiological responses due to psychological stress and mental loads have been found to be induced in human beings. Increased muscle activation of the trapezius muscle has been suggested to occur as a response to mental demands (Iwanaga et al. 2000; Lundberg et al. 2002; Wærsted 2000). Furthermore, mental stress has been reported to increase the muscle blood flow in skeletal muscles, both with (Larsson et al. 1995) and without (Dietz et al. 1994) additional static contractions of the muscles.

In addition to the effects on the trapezius muscle, other responses shown with mental loads include increased muscle activity and blood flow in different facial muscles, activated neuroendocrine and autonomic stress systems, increased cardiovascular responses, such as heart rate and blood pressure, and decreased blink rate (Hidaka et al. 2004; Larsson et al. 1995; Lundberg et al. 2002; Nilsen et al. 2007; Nimbarte et al. 2012; Rodriguez et al. 2018; Skoluda et al. 2015; Ulrich-Lai and Herman 2009).

Stimuli that act as mental stressors evoke a complex, centrally co-ordinated response involving autonomic, hormonal, and behavioural responses (Dampney 2015; Dayas et al. 2001). The two most prominent physiological stress response systems are the autonomic nervous system, which is activated first, and the hypothalamus—pituitary—adrenal axis (HPA axis) which responds after a certain amount of time (Ulrich-Lai and Herman 2009).

2.3 The visual system

To see clearly while working, a well-functioning visual system and the presence of an appropriate amount and quality of light are both required. The light from the surroundings enters the eyes and the visual system through the cornea, the pupil, and the lens before finally reaching the retina, where the light energy is transformed into nerve impulses that are sent through the optical nerve into the central nerve system. Figure 2.1 shows the main structures of the human eye.

In front of the eye, the coloured iris forms a circular opening, the pupil, which regulates the light entering the eyes (Bron et al. 1997). The pupil's diameter is adjusted by two sets of smooth muscles in the iris. The diameter can either be decreased by contraction of the sphincter pupillae, a ring muscle located around the pupil aperture, or increased by contraction of the dilator pupillae, a thin muscle sheet radiating from the sphincter muscle to the ciliary body (Markwell et al. 2010).

The ciliary body is a ring-shaped thickening of tissue inside the eye consisting of the ciliary muscle, which controls the shape of the crystalline lens of the eye, and the ciliary epithelium, which produces the aqueous humour that provides oxygen and nutrients to

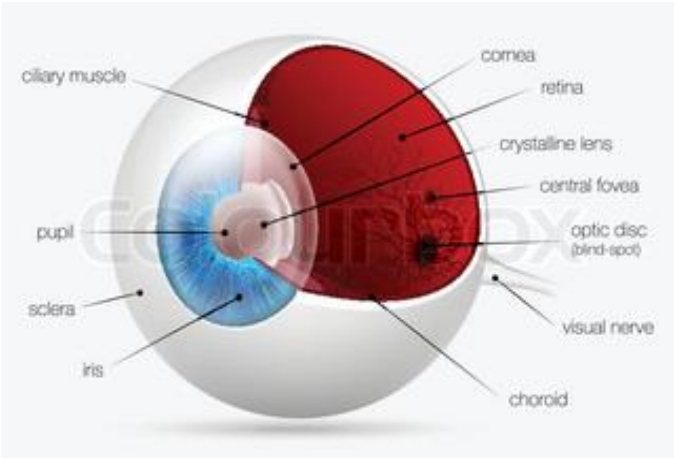


Figure 2.1
Illustration of main structures of the human eye. The figure is captured with permission from colourbox.com: https://d2gg9evh47fn9z.cloudfront.net/thumb_COLOURBOX10352467.jpg.

the cornea and the lens (Bron et al. 1997). The crystalline lens is transparent and has a biconvex structure; its sole function is to refract light rays onto the retina, along with the cornea. The shape of the lens is altered by relaxation and contraction of the ciliary muscle surrounding it, thus changing the optical power of the eye to focus clearly on objects at varying distances (the process known as accommodation) (Levin et al. 2011).

The retina

While the retina is a complex structure, in simple terms it consists of three different layers: visual photoreceptors (rods and cones), collector cells (links between multiple photoreceptors), and ganglion cells, such as bipolar cells and horizontal cells (Levin et al. 2011). The axons from the ganglion cells form the optical nerve that sends the visual information as electrical impulses into the brain.

The cone photoreceptors are able to perceive fine details and are responsible for colour vision; they function best when an appropriate amount of light is available. Cones contain photopigments based on the protein photopsin and can be divided into three subgroups according to the wavelengths to which they are most sensitive: S-cones (short wavelengths; ~440 nm), M-cones (medium wave-lengths; ~543 nm), and L-cones (long wavelengths; ~566 nm) (Markwell et al. 2010). The cones are concentrated within the fovea, but low densities of cones are also found across the entire retina. The rod photoreceptors are more sensitive and require less light to function than the cones, so rods are responsible for night vision and vision in the peripheral field; they all contain the same photopigment, rhodopsin (Levin et al. 2011). Rods have peak sensitivity to the green-blue wavelengths of light around 498 nm.

Among the ganglion cells, we find another photoreceptor, the intrinsically photosensitive retinal ganglion cells, or ipRGCs (Berson et al. 2002). This photoreceptor does not aid vision directly like rods and cones do; rather, it sends signals through the non-image-forming system. The ipRGCs contain the photopigment melanopsin, which has a peak sensitivity at about 480 nm (Markwell et al. 2010). In contrast to the cones that respond to variations in luminance very quickly (100–200 ms), the response of the ipRGCs has a slow onset (Westland et al. 2017).

Extraocular muscles

There are six highly specialized extraocular muscles distributed in three antagonistic pairs of muscles that control the eye movements. Figure 2.2 shows the arrangement of the six extraocular muscles. The extraocular muscles are striated muscles, but compared to other somatic muscles, they differ in terms of both structural organisation and function (Bruenech et al. 2012; Porter et al. 1995). The extraocular muscles consist of two principal types of muscle fibres: the Fibrillenstruktur fibres or single innervated large muscle fibres

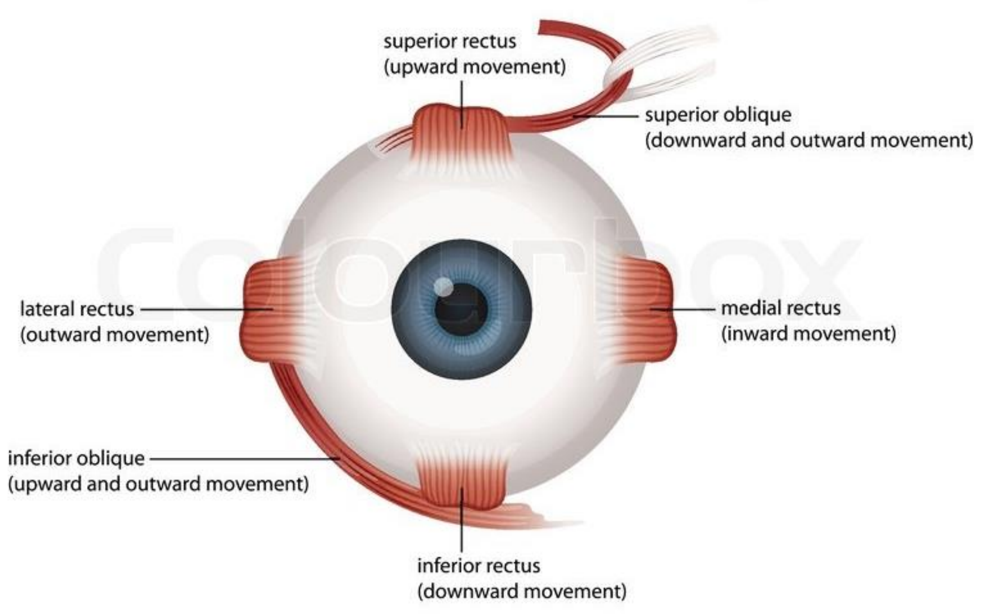


Figure 2.2
Illustration of the arrangement of the extraocular muscles of the right eye with names and the movements of the eyeball for which each muscle is responsible. The figure is captured with permission from colourbox.com: https://www.colourbox.com/preview/8814347-human-eye.jpg COLOURBOX 23333350.jpg.

(SIFs), and the Felderstruktur fibres or multiply innervated small muscle fibres (MIFs) responsible for rapid saccadic eye movements, while the MIFs contribute to stable fixation and slow-pursuit eye movements (Bruenech et al. 2012). Furthermore, nociceptors have (Siebeck and Krüger 1955; Yu Wai Man et al. 2005). The SIFs which constitute approximately 80 % of the fibre population in the extraocular muscles are primarily been reported to be present in large numbers in the collagenous distal insertions of the rectus muscles to the orbital wall; they are suggested to be capable of creating pain due to muscle contraction during visually demanding near work and convergence actions (Bruenech and Kjellevold Haugen 2007).

The horizontal rest position of the eyes and thus of the extraocular muscles is often referred to as the dark vergence (Owens 1984). Dark vergence differs reliably among subjects, with average convergence at a viewing distance of about one metre and a range among individuals from infinity to about 40 cm (Jaschinski et al. 2007). The extraocular muscles are innervated by three cranial nerves: N. oculomotorius (III), N. trochlearis (IV), and N. abducens (VI) (Spencer and Porter 1988). The abducens nerve innervates the lateral rectus muscle, the trochlear nerve innervates the superior oblique muscle, and the oculomotor nerve supplies the rest of the extraocular muscles.

2.3.1 Visual functions related to computer work and glare exposure

Uncorrected refractive errors and/or accommodative problems are previously shown to be related to both eyestrain and neck symptom development (Rosenfield et al. 2012; Sánchez-González et al. 2018; Zetterberg et al. 2017). Refractive errors may be myopia (nearsightedness), hypermetropia (farsightedness) and/or astigmatism (irregularly shaped cornea). Certain visual functions are especially important in connection with computer work and glare conditions, as outlined below.

The near response

In order to see clearly when viewing objects at near, such as the letters on a computer screen, human beings depend on three highly coordinated processes in the visual system through the near response: accommodation, convergence, and pupil constriction (miosis) (Atchison and Smith 2000).

When the gaze changes from a distant object to a nearer one, accommodation happens when the smooth ciliary muscle contracts to make the intraocular lens more spherical to focus the object clearly on each retina. Through accommodation, the refractive power of the lens is changed, with the response measured in dioptres (D), the measure of refractive power that is the reciprocal of the lens's focal length in metres (Owens 1984). The ciliary contraction conducting the focusing response is parasympathetically mediated (Loewenfeld 1993).

In accordance with accommodation, convergence occurs when the striated extraocular medial rectus muscles contract to rotate the eyes medially to maintain single vision (Atchison and Smith 2000). Binocular vergence movements (convergence and divergence) are primarily controlled by the medial and lateral recti muscles, which determine the visual axes' angle from the two eyes towards the visual target. Looking at near objects requires the eyes to converge at a relative large angle (Owens 1984). Thus, prolonged near work, for instance fixating on a computer screen, requires sustained convergence of the eyes and muscle contraction of the extraocular muscles. The accommodation and convergence responses may both be stimulated either by target blur (accommodation-driven) or by disparity cues (vergence-driven) (Toates 1972).

Additionally, the dark vergence of the eyes has been reported to shift to a more convergent (nearer) position with lowered gaze and to a more divergent (farther) direction with elevated gaze (Heuer and Owens 1989). In regard to near work, this means that convergence actions is facilitated with lowered viewing angles during computer work compared to working at near with a high gaze.

Simultaneously with accommodation and convergence, miosis take place when the pupil contracts while focusing at near, an action performed by the iris sphincter muscle. The small pupils increase the depth of focus of the eyes' optical system (often referred to as 'the pinhole effect') and help the vision better focus on objects during near work tasks (Levin et al. 2011). The pupil constriction due to the near reflex involves activation of cortical areas surrounding the visual cortex and areas within the frontal eye fields, as well as neurons in the ventral brainstem that transmit their signals along to Edinger-Westphal neurons (Levin et al. 2011; Remington 2012). From there, neurons sends para-sympathetic axons along the third cranial nerve – the oculomotor nerve – to the ciliary ganglion in each orbit (Remington 2012).

The pupillary light reflex

The pupillary light reflex refers to pupil diameter changes in response to altered retinal illumination, such as what occurs during changed lighting intensity and glare conditions. The pupillary light reflex is controlled by the autonomic nervous system, with para-sympathetically activated pupil contraction in response to increased lighting and sympathetically activated pupil dilation in response to decreased lighting (Markwell et al. 2010).

In the pupil light reflex, input from the rods and cones are mediated by the ipRGCs (Markwell et al. 2010). Additionally, as ipRGCs are directly sensitive to light, they are also responsible for sustainable pupil constriction due to light exposure (Markwell et al. 2010). However, pupil constriction is not a steady state action. Even in conditions of stable illumination, the size of the pupil changes constantly (Loewenfeld 1993). This fluctuation in pupil size is called pupillary unrest.

The afferent pathway of pupil constriction due to the pupillary light reflex starts with retinal input. However, the signals do not reach the visual cortex; they leave the visual pathway before lateral geniculate nucleus and are sent to interneurons in the midbrain. These interneurons further provide input to Edinger-Westphal nucleus (Markwell et al. 2010; Remington 2012). Accordingly, the final efferent pathway for pupil constriction due to the near reflex and the light reflex is similar – from the Edinger-Westphal nucleus to the sphincter pupillae – but the input pathways to the Edinger-Westphal nucleus are different.

In glare conditions, pupil constriction contributes to reducing the amount of light entering the eye. In addition to reduced retinal illumination, a small pupil also increases the depth of focus, as noted above, and improves the image quality of the retina by a reduction in optical aberrations (Levin et al. 2011). This is partly because a smaller pupil reduces the number of light rays entering the peripheral parts of the cornea and the lens, where aberrations are the greatest. Under bright light exposure, constriction of the pupil is capable of reducing retinal illumination by up to 1.5 log units within 0.5 seconds and is an important and immediate contributor to light adaptation (Levin et al. 2011).

Non-photic pupil effects

Dilation of the pupils also occurs due to many non-photic stimuli like cognitive processes, stress, emotions, noise, pain, surprise, and pleasure result in (Bradley et al. 2008;

Hahnemann and Beatty 1967; Loewenfeld 1993; van der Wel and van Steenbergen 2018). Pupil dilation may be caused by activation of the sympathetic nervous system, leading to the stimulation of the dilator muscle, or by a parallel inhibition of the parasympathetic pathway (Bradley et al. 2008; Loewenfeld 1993; Sirois and Brisson 2014; Steinhauer et al. 2004). Dilation increases together with the demand level and is sustained during continuous cognitive tasks (Laeng et al. 2012).

Fixation disparity

In optimal and precise binocular vision, the image from each eye projects centrally in the fovea, and the two visual axes interconnect at the fixation point. Fixation disparity (FD) refers to small misalignments of the visual axis during binocular vision, in which the fixation points of the two eyes are not projected onto exactly equivalent areas on the retina (Jaschinski 1998; Scheiman and Wick 2008). The FDs may be vertical, horizontal, or both. Horizontal FD, as measured in this thesis, is a vergence error that is defined as either exo disparity, where the visual axis crosses behind the fixation point, or eso disparity, where the visual axis crosses in front of the fixation point.

A given retinal region in one eye corresponds to a given retinal region in the other eye, and sensory input within these areas will result in a fused binocular image. The slightly different retinal areas lead to retinal disparity, which occurs due to lateral displacement of the eyes. The region in visual space over which we perceive single vision is known as Panum's fusional area (Fender and Julesz 1967). Objects in front or behind of the Panum’s area are projected to the brain in physiological diplopia (i.e., double vision), but the visual system suppresses this diplopia, so no double vision occur under normal viewing conditions (Kalloniatis and Luu 1995). If images fall without Panum's area, then diplopia arise.

FD can be measured using different methods. It can be quantified as the associated phoria, defined as the amount of prism needed to reduce FD to zero minutes of arc (arcmin) (Scheiman and Wick 2008). Associated phoria is usually measured clinically, and since one prism dioptre may compensate for either a small or a large misalignment in arcmin, they do not give an exact measure of the actual misalignment. An other method is to measure the actual misalignment between the two visual axes given as arcmin, as by using the Sheedy Disparometer (Dwyer 1982).

In persons with normal binocular vision under normal viewing conditions, we expect a result of zero on an associated phoria test. However, when measuring the actual visual axis misalignments, it is normal to detect minor disparities, even in in young subjects with normal binocular vision (Glimne et al. 2013; Jaschinski 2017; Scheiman and Wick 2008). For the purposes of comparing the outcome of the two methods, 12 arcmin is about 1/5 of a prism dioptres (Stidwill and Fletcher 2011).

Both glare exposure and computer work have previously been shown to alter the FD in subjects with normal binocular vision (Glimne et al. 2013; Glimne and Österman 2019; Jaschinski-Kruza 1993). Accordingly, FD variation has been considered to be an objective indicator of visual fatigue during glare conditions (Glimne et al. 2013). Individual differences in how much visual stress may affect the FD in a subject have also been reported (Jaschinski 1997).

2.4 M. orbicularis oculi and m. trapezius

Orbicularis oculi

The orbicularis oculi is a facial sphincter muscle that encircles the eyes and is involved in blinking, eyelid squinting (increased muscle activity in the orbicularis and reduced palpebral aperture size), and modulation of facial expression. See Figure 2.3. The muscle can be subdivided into an outer or orbital portion, and an inner or palpebral portion (Bron et al. 1997; Costin et al. 2015). The orbital portion is voluntarily controlled and can close the eyelids firmly during voluntary blinking. Contraction of the orbital portion draws the brows and cheeks closer to the eyes and depresses the eyebrows. Mild eyelid closure, such as what occurs in spontaneous or reflex blinking, engages only the inner palpebral part of the muscle. The orbicularis oculi muscle is responsible for eyelid squinting when the orbital part of the muscle contracts, while the relaxed palpebral part allows the lids to remain open.

The beneficial functions of eyelid squinting have been reported to be decreasing visual field sensitivity (as during glare exposure) by reducing the light entering the eye, especially from the superior visual field, and improving visual acuity for subjects with uncorrected refractive error (Sheedy et al. 2003b). The proposed mechanism for improved visual acuity with eyelid squint is the increased depth of focus due to the decreased palpebral aperture size.

The orbicularis oculi muscle is composed of striated skeletal muscle fibres exhibiting both slow-twitch type 1 and fast-twitch type 2 muscle fibres (Freilinger et al. 1990; Porter et al. 1989). Overall, the orbicularis oculi is a muscle with 'fast' properties, as it contains mostly type 2 fibres (Freilinger et al. 1990), but orbicularis oculi fibre types are not uniformly distributed, which indicates a functional subdivision within the muscle. The inner, palpebral portion of the orbicularis oculi closest to the eyelid margin consists predominantly of fast-twitch fibres, reflecting their function in reflex blinking (Cattaneo and Pavesi 2014; Goodmurphy and Ovalle 1999; McLoon and Wirtschafter 1991). The outer orbital part has a slightly larger portion of slow-twitch fibres, but the muscle overall is still one of the mimic muscles with the lowest composition of type 1 fibres (Freilinger et al. 1990).

The orbital and palpebral portions of the orbicularis oculi are both innervated by the cranial nerve N. facialis (VII) through its temporal branch (Bron et al. 1997).

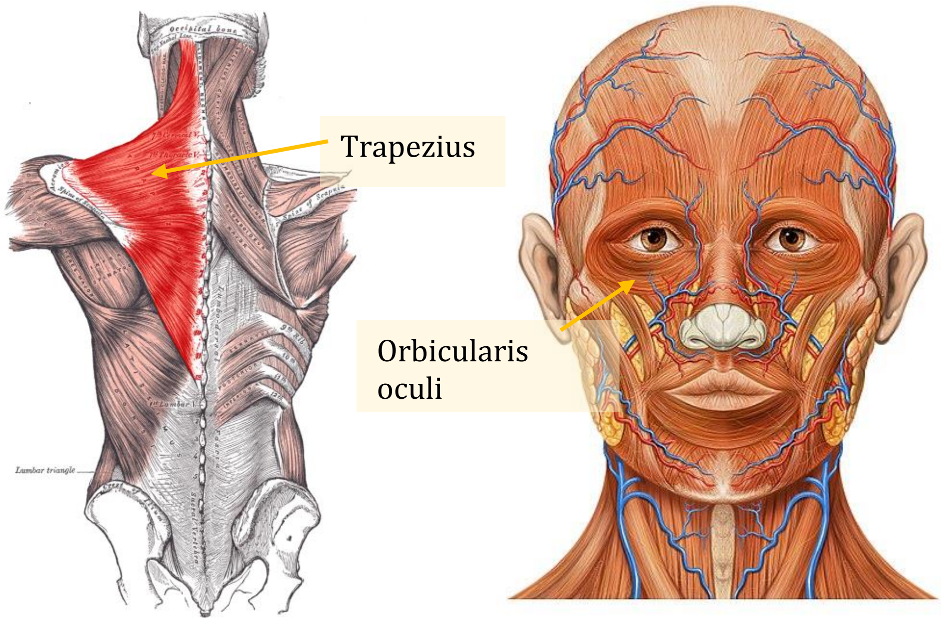


Figure 2.3
Illustration of the superficial muscles of the back of the neck and trunk, with m.trapezius in red (left side) and superficial muscles of the head, frontal view, with m. orbicularis oculi marked (right side). The figures are captured from Wikimedia Commons: https://commons.wikimedia.org/wiki/File:Trapezius_Gray409.PNG (trapezius) and https://commons.wikimedia.org/wiki/File:Head_ap_anatomy.jpg (orbicularis oculi)

M. trapezius

The trapezius muscle is the large, superficial muscle covering the posterior neck and uppermost portion of the trunk (Nordin and Frankel 2001). See Figure 2.3. It has a broad origin along the spine from the occipitalis and upper cervical vertebrae down to the lower thoracic vertebrae and inserts into the clavicula, acromion, and spina scapulae (Putz and Pabst 2001). It consists of three different anatomical and functional subdivisions: the upper descending, the middle transverse, and the lower ascending portions. The trapezius muscle acts on the scapula, the shoulder girdle, and the head and neck and may have both stabilizing and movement functions (Johnson et al. 1994; Keshner et al. 1989; Nordin and Frankel 2001). The cranial nerve N. accessory (XI) innervates the trapezius muscle.

The descending part of the trapezius is often used to investigate muscle activity in relation to computer work, both because it is easy to reach with non-invasive measurements and because it is a prevalent site of pain (Sommerich et al. 2000).

2.5 Associations between the visual system and the neck area

The scientific literature has suggested the existence of close interactions between the visual system and the musculoskeletal system, with co-occurring symptom development and interdependent activation of eye and neck muscles (Gerr et al. 2002; Helland et al. 2008; Ranasinghe et al. 2016; Richter et al. 2011b; Wiholm et al. 2007). Such interactions have been reported to be present both during visually demanding conditions and in natural visual scanning and fixation actions.

In this regard, the scientific literature points out that high visual demands, like accommodation or vergence stress or non-optimal vision during near work, can initiate changes and trigger discomfort in the neck and shoulder muscles (Domkin et al. 2016; Lie and Watten 1987; Lie et al. 2000; Richter et al. 2011a; Richter et al. 2011b; Sánchez-González et al. 2018; Zetterberg et al. 2013; Zetterberg et al. 2015). Possible mechanisms for the observed associations between the eyes and the neck during visually demanding work may include alternation of posture to ensure optimal vision, increased demands for stabilization of the gaze, and / or a central mediated response.

According to the involvement of posture on the association between the visual system and the neck area, poor visual conditions are reported to induce in non-ergonomic work positions or posture during computer work (Ko et al. 2014). The saying that 'the eyes lead the body' means that the body prioritizes good vision over good posture when facing visually demanding conditions (Boyce 2014). During computer work, altered posture may occur in order to avoid glare exposure or to make the letters visible, with the subject leaning forward due to non-optimal corrected vision. In the case of glare, for instance while working in an inappropriately adjusted workstation with the computer screen placed in front of a window, the worker will be exposed to excessive light entering the eyes. As a result, ergonomic adaptions may be performed and result in awkward postures and increased postural load in order to reduce the glare exposure (Anshel 2005). On the other hand, poorly adjusted ergonomic conditions, such as overly high positioning of the computer screen, may negatively affect the visual system (Blehm et al. 2005).

Regarding the involvement of gaze stabilization to be a possible cause of eye-neck interactions, Richter (2014) suggested that sustained periods of oculomotor load influence the posture and muscle activity in the neck muscles, with higher oculomotor load resulting in higher musculoskeletal activity. A close relationship between eye-lens accommodation (contraction of the ciliary muscle) and trapezius muscle activity has been reported in several studies (Domkin et al. 2016; Richter et al. 2011a; Zetterberg et al. 2013). Furthermore, accommodative dysfunctions have been reported to be related to decreases in the range of motion of the cervical spine and a greater risk of neck pain (Sánchez-González et al. 2018), also pointing out a close functional relationship between the visual system and the head-stabilizing neck muscles.

To cope with the demands of daily activities, motion, and work tasks, including near work, human depend on finely tuned cooperation between the muscles that control the eyes, the head, and the body. The direction of gaze depends on the position of the body in space, the head's position on the torso, and the eyes' position in the head. The fine control of gaze thus requires very close coordination of eye and neck muscles (Donaldson 2000). In line with this, proprioceptive information from ocular muscles and neck muscles are shown to be activated synchronously (Biguer et al. 1982; Bizzi et al. 1971; Bruenech et al. 2012; Han and Lennerstrand 1995; Han and Lennerstrand 1998), indicating that the proprioceptive messages are centrally processed together and are mutually influential. When looking at a visual target, the eyes and head movements have been reported to be activated synchronously with respect to the onset of eye movement (Biguer et al. 1982), and vibrations of different neck muscles (proprioceptive signals) have been demonstrated to induce eye movements (Han and Lennerstrand 1995). The presence of eye movement reflexes (including the vestibulo-ocular and opto-kinetic reflexes) indicate further that the oculomotor system receives detailed information from the vestibular apparatus and proprioceptors in the somatic muscles in the neck and torso (Paduca and Bruenech 2018). The close connection between the visual system and the neck is also demonstrated by findings that both subjects with neck pain (often exhibiting decreased active range of motion in the cervical spine) and healthy individuals with experimentally immobilized cervical spine have increased eye stabilization reflexes (de Vries et al. 2016; Ischebeck et al. 2018; Stenneberg et al. 2017).

Many head movements can be observed during natural and unrestrained viewing conditions, even when attempts are made to keep the head as still as possible (Steinman, 2003). Head movements will accordingly require compensating eye movements to ensure a clear visual picture. In line with this, working at close distances, small movements of the head or eyes lead to a greater displacement of the visual image on the retina than the same movement would cause when looking at distance. Hence, prolonged near work places a high demand on eye-neck image stabilization. Moreover, a functional centrally controlled eye–head–neck–shoulder motor programme that connects the visual system and neck muscles has been suggested (Biguer et al. 1982; Richter 2014), with the intention of stabilizing gaze in order to maintain a clear, single picture on the retina during dynamic and static visual functioning.

Moreover, another possible interaction between the visual system and the musculo-skeletal system during visual stress exposure may be triggering of an alertness response due to central activation. Visual stress exposure induced by watching 3D video has been reported to activate the sympathetic nervous system and interrupt autonomic balance; the cause has been suggested to be visual fatigue and cognitive load that induces arousal and disturbs the autonomous stability (Park et al. 2014). Moreover, glare and excessive light exposure have, as noted previously, also been reported to affect the activity of the autonomic nervous system in both humans and animals (Abrahams et al. 1964; Belkić 1986; Belkić et al. 1992; Niijima et al. 1992; Noseda et al. 2017; Saito et al. 1996).

2.6 Visual ergonomics

Ergonomics is a broad discipline with many sub-specialties, one of which is visual ergonomics; it has been considered a specialised area by the International Ergonomics Association (IEA) since 2009 (Long 2014). Visual ergonomics is defined as:

‘*The multidisciplinary science concerned with understanding human visual processes and the interaction between humans and other elements of a system. Visual ergonomics applies theories, knowledge and methods to the design and assessment of systems, optimizing human well-being and overall system performance. Relevant topics include, among others: the visual environment, such as lighting; visually demanding work and other tasks; visual function and performance; visual comfort and safety; optical corrections and other assistive tools*.’ (IEA 2012).

Visual ergonomists aim to create work, home, and leisure environments that fit the human being and its visual capabilities by examining the relationship between the individual, the work task, and the environment. Lighting and glare conditions are included in the evaluation of the physical environment. Because visual ergonomics is an interdisciplinary field that aims to evaluate the work environment from a broad perspective, multifaceted problems may occur. It may require multidisciplinary work involving different professions (Long and Helland 2012). Hence, optometrists, ergonomists, and lighting designers working in the field should be aware that effective workplace optimization can only be achieved if vision, lighting, and ergonomics are all considered together.

2.6.1 Evolutionary stress model in visual ergonomics

To describe the link(s) between vision, oculomotor factors, and the musculoskeletal system during computer work, Fostervold, Watten and Volden (2014) put forward an evolutionary stress model to be used in visual ergonomics. The model was an effort to apply theoretical considerations about and knowledge of human evolutionary adaptations to explain why changes in some environmental conditions lead to negative consequences for human beings while other environmental changes do not. The notion of evolutionarily novel environments is a key element in this regard. An environment is regarded to be evolutionarily novel if important conditions in the environment departs from conditions for which the human species has developed specific phenotypic adaptations. In such environments, adaptations that are functional under other conditions closer to the environment in which the species has evolved may give rise to new problems. Near work, as computer work, is not evolutionarily novel as such, because the visual system has long had the ability to focus at near. The challenge regarding computer work is rather the *intensity* and *duration* of the near work that is demanded of the visual system. According to this model, subjective complaints associated with computer work can be understood as a mismatch between evolutionary adaptations to vision at close distance particular to a species and the demands posed by the environment (in this case, computer work).

3. Research gap and aim of research

As has become evident, certain knowledge gaps exist related to the effect of glare exposure on human during computer work and development of neck pain among computer workers. Some of these gaps are addressed in this thesis.

Computer work and other near work tasks on digital devices are highly demanding for the human visual system and we rely on good and precise visual information. Optimal visual conditions depends upon, among other factors, appropriate visual correction and optimal visual surroundings, including the lighting conditions (Osterhaus et al. 2015; Rosenfield 2016). Eye and neck muscles have an important and interdependent role in gaze stabilization and are found to be highly coordinated (Donaldson 2000). Furthermore, development of both eyestrain and neck pain is widespread among computer workers, and a growing amount of research points towards a connection between the eyes and the visual system and the neck and the musculoskeletal system, suggesting the possible involvement of visual conditions in musculoskeletal disorders.

As to lighting conditions, computer workers are prone to be exposed to glare if the work environment is not optimally adjusted. The high gaze angle required during computer work results in more potential glare sources within the peripheral visual field of the worker that may be disturbing or annoying and hence lead to discomfort (Boyce 2014). Additionally, the possibilities of adjusting position to avoid these glare sources and still maintain an appropriate work posture are limited, and persistent glare conditions may exist.

From a public health perspective, it is therefore important to understand all possible factors involved in the development of visual discomfort and neck pain among computer workers. In this regard, visual ergonomics, which facilitates optimal visual conditions, can be a valuable asset. Many studies have looked into associations between the eyes and the neck area by means of excessive visual load put on the accommodation–convergence system or induced refractive errors, and the effect on trapezius muscle activity and/or neck discomfort (Lie and Watten 1994; Lie et al. 2000; Richter et al. 2011a; Richter et al. 2010; Richter et al. 2011b; Sánchez-González et al. 2018; Zetterberg et al. 2013). However, visual stress, induced as glare exposure, during computer work and its effect on neck muscles in human have previously been limited investigated, and whether functional interactions between the visual system and neck muscles is present during glare conditions remains unclear.

Knowledge of how inappropriate visual conditions, like glare exposure, during computer work affects human beings would be useful for professions treating subjects with both visual and musculoskeletal disorders: physiotherapists, ergonomists, optometrists, and the like. Further, this understanding may have broader public health implications, as it could contribute to improved management of work-related disorders, appropriate preventive actions in the workplace, and a possible reduction in sick leave among computer workers.

3.1 Aims and objectives

The main aims of this thesis were to explore the responses to direct glare exposure (visual stress) and to investigate possible functional interactions between the visual and the musculoskeletal systems during computer work with glare in young, healthy subjects with normal vision.

The main aims were addressed by means of three objectives:

I. To investigate the effect of glare exposure during computer work, by measuring subjective symptoms, state moods, perceived lighting and stress, as well as skeletal muscle responses in orbicularis oculi and trapezius, with and without glare and psychological stress exposure (all three papers).

II. To investigate possible functional interactions between the visual and the musculoskeletal system, by measuring subjective and objective responses in the eye and in the neck area during computer work with and without glare exposure (all three papers).

III. To investigate if muscle blood flow and muscle activity in the trapezius muscle is related to neck pain development during computer work with glare exposure (paper I and III).

4. Material and methods

In order to achieve the aims of the thesis, two different projects were carried out. Both projects were conducted as within-subject laboratory experiments with a counterbalanced, repeated-measures design. The experiments were accomplished at the visual ergonomics laboratory at the University of South-Eastern Norway (USN) in Kongsberg, Norway.

The data collection for project 1 was the origin of paper I in this thesis, and was achieved during winter (November–March) 2013. Papers II and III are both based on the data collected in project 2, and the collection of data was divided into two periods, one in 2015 and one in 2016, both in the winter (December–February). The PhD candidate was the test leader during all testing and performed all the measurements in both experiments. Please refer to the enclosed papers for more details about the methodology for each experiment.

Pilot studies were carried out before both project 1 (n = 5) and project 2 (n = 2). This step ensured that the parameters and planned conditions were sensible, as a part of the quality assurance of the design and procedures, and as an exercise for the test leader to carry out all measurements.

4.1 Participants

All participants in both projects were undergraduate students, recruited from the University of South-Eastern Norway (USN) at Kongsberg. The recruitment procedure was as follows: optometry classes at USN were presented with an overview of the project, and any student interested in participating signed up using a form. The participants were only included in one of the projects, no one participated in both projects.

In project 1, 20 healthy, young undergraduate optometry students with normal binocular vision were included in the experiment. However, five were removed from the analysis because of either exclusion criteria, incomplete data sets, or both. A final group of 15 participants was therefore included in the analysis: 12 women and 3 men, aged 21 ± 2 years (mean ± SD), range 19–25 years.

In project 2, 40 of the participants were optometry students. However, because of a lack of interest and a shortage of suitable participants for the study, the last four participants were recruited from another educational track. During the data collection, 24 and 20 participants were tested in 2015 and 2016, respectively. One participant was removed after testing because of the exclusion criteria. The sample included in papers II and III therefore consisted of 43 healthy students with normal binocular vision, aged 21.4 ± 2.4 years (mean ± SD), range 17–27. All participants included in project 2 were female. This decision was made to obtain a largely homogenous study group. Females and males are known to respond differently to psychological stressors (Collins and Frankenhaeuser 1978; Luine et al. 2017) and a higher prevalence of both musculoskeletal pain and visual symptoms has been shown in females during computer work (Courtin et al. 2016; Larsson et al. 2007; Paksaichol et al. 2012; Ranasinghe et al. 2016).

4.1.1 Optometric examination

All participants underwent an eye examination prior to participating in the experiments to ensure that they had normal or corrected to normal binocular vision and therefore fulfilled the inclusion criteria for vision. The optometric examinations were performed at the USN, National Centre for Optics, Vision and Eye Care, in Kongsberg, Norway.

In project 1, third-year optometry students, with supervision and guidance from an experienced optometrist, performed the eye examinations. In project 2, optometry students with supervision and guidance did the eye examinations for the 24 participants tested in 2015, whereas one experienced optician examined all 20 subjects participating in 2016. The test leader performed some additional binocular tests, including accommodation amplitude and convergence near-point with an RAF ruler and stereo acuity with the TNO test at the test day for participants examined by optometry students.

All participants in both projects had normal binocular vision and vision functions, as well as good eye health. Normal visual function was defined as < 0.0 logMAR visual acuity, > 1.85 log contrast sensitivity, ≤ 60” stereo acuity, no uncompensated FDs, no double vision, accommodation and convergence amplitudes within age normal limits, and no amblyopia or other ocular or systemic diseases. Please see the enclosed papers for more details about the participants’ visual status.

4.1.2 Exclusion criteria

The exclusion criteria for projects 1 and 2 were abnormal binocular vision, chronic pain in the neck and shoulder area over the preceding six months, history of eye trauma or surgery, dyslexia, or systemic disease or regular use of medications affecting circulation, pain sensation, vision, and visual comfort. In project 2, mental illness was also included as an exclusion criterion since psychological stress was included as an exposure in that project.

All participants filled out a form either on the testing day when they arrived at the laboratory (project 1) or in a pre-meeting some days before the testing day (project 2), in which they were asked questions related to the exclusion criteria for the studies.

Since 5 of 20 tested participants were excluded after project 1 and some of them because of the exclusion criteria, in project 2, the use of a pre-meeting offered greater assurance that the participants were actually appropriate for that role. Nevertheless, one participant had to be excluded afterwards.

4.2 Design and procedure

All participants visited the laboratory for one occasion in conjunction with the experiments, arriving between 8:00 a.m. and 12:00 p.m. All experiments were performed early in the day to minimize confounding effects of the time of day, to ensure that participants were as refreshed as possible and to reduce the possibility of fatigue responses due to demanding work or studies undertaken before arriving at the lab. Symptoms associated with binocular stress are shown to be more likely reported after a day of work than early after a night's rest (Yekta et al. 1987). The whole test procedure lasted for 3–3.5 hours for each participant. The first 90 minutes at the lab were used for preparation activities before the experiment. In this phase, the participants were given information about the experiment and completed the various forms included in each project. Besides personal details, data such as number of hours of sleep the previous night and information about exercise, demanding near work, coffee consumption, and tobacco use in the 12 hours before attending the lab was obtained. In project 2, information about personality traits was also collected. In addition, connection and calibration of the measurement equipment was carried out during this initial preparation period. The experiments itself lasted for about two hours.

4.2.1 Computer tasks

The computer tasks in both projects were performed on an external computer screen connected to a laptop. The display had a 24'' anti-reflection LCD-screen at a resolution of 1920 x 1200 pixels and a mean refresh rate of 69.5 Hz (HP LA2405x, USA). The brightness of the external computer screen was set to 60% of maximal light, giving a luminance of 155 cd/m^2 from the computer screen.

In both projects 1 and 2, the text to be read or worked with was in the students' native language (Norwegian) and chosen from the basic curriculum of optometry students. This decision was taken in order to make the text as interesting as possible and promote achievement of the task during the experiments. However, for the four non-optometrist students in project 2, this text was without their study field.

Computer task in project 1 (paper I)

In project 1, the task performed was to read a text on a computer screen under two different lighting conditions; one session in an optimal workplace environment (the *optimal condition*) and one with exposure to direct glare (the *glare condition*). Each reading condition lasted for 30 minutes and was performed at the same workstation. In addition to the computer task, each condition included a rest recording before the start of the reading task (rest before, RB), a break after the conditions, and a rest recording after the break to measure recovery (recovery rest, RR). Figure 4.1 shows the different parts of the conditions in project 1.

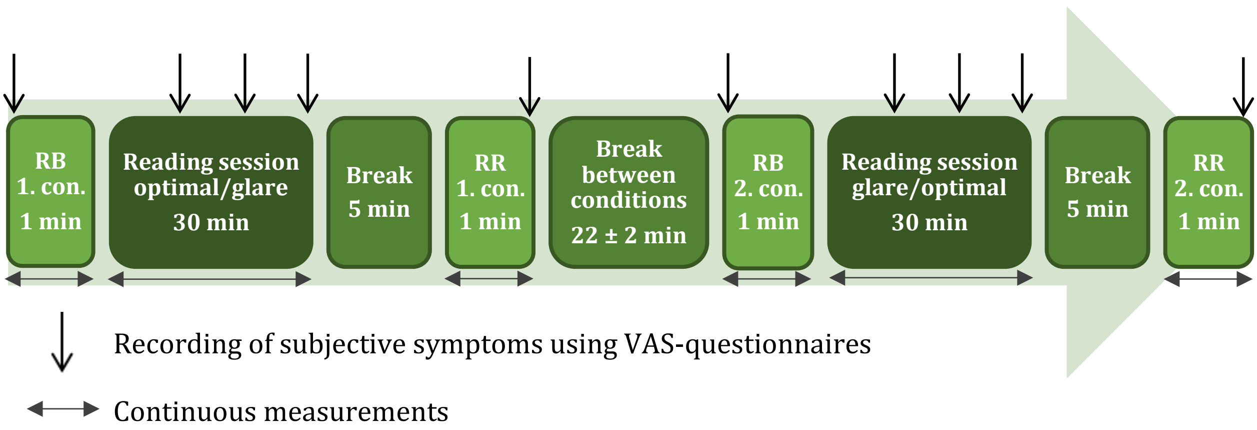


Figure 4.1
Flowchart showing the different parts of the experiment in project 1. Both the optimal and glare conditions (con.) consisted of the same parts and the order was counterbalanced. RB = rest before the computer work sessions, RR = recovery rest after computer work. The continuous measurements were conducted throughout the rest and reading sessions (not in the breaks), and the participants filled into the questionnaire in conjunction with the rest sessions before and after the work sessions.

In project 1, an important issue was to examine the effect of direct glare on the neck muscle trapezius as isolated as feasible and thus to make the study as 'clean' as possible. Therefore, the test leader aimed to reduce factors that affected the trapezius throughout the reading sessions. The trapezius muscle activation was reduced to a minimum as the muscle was kept relaxed with appropriate forearm support and by performing a reading task instead of active computer work. The only activity participants had to carry out was scrolling down the text on the screen using the index finger on a wheel on a standard wireless laser mouse. All measurements on the trapezius were also performed on the non-dominant side, on the neck/shoulder of the arm that was not used for scrolling.

To encourage participants to concentrate and work properly during the reading conditions, they were told that they would have to answer questions from the text read after each condition.

Computer task in project 2 (papers II and III)

In project 2, four 10-min computer work conditions were performed in random order. Each condition contained the same computer task but had different lighting and stress requirements, as follows: low stress (LS), glare (visual stress, VS), psychological stress (PS), and glare and psychological stress (VPS). LS was similar to the optimal condition in project 1, whereas VS was equal to the glare condition.

Psychological stress was included as an additional exposure when designing project 2. This was because the glare-induced TBF response in the first project was proposed to be influenced by a centrally mediated alertness effect and in project 2 the underlying mechanisms involved should be further investigated. In the conditions with psychological stress, a combination of three stress-inducing procedures was used in order to induce the psychological stress: (1) the participants were told to work as fast and accurately as possible and that their performance would have a major influence on the test outcome (time and precision pressure). (2) The participants were told that, after the condition, they would have to answer questions from the text they had read (social-evaluative threat). (3) A visible video camera was turned on to monitor the participants throughout the computer-work session (social-evaluative threat). Additional to the psychological stress, the PS condition consisted of computer work with simultaneously appropriate lighting (glare source turned off) and the VPS condition consisted of computer work with simultaneously glare exposure. The responses provoked by the glare exposure were compared to those elicited by psychological stress exposure, in order to investigate the glare effects further.

In all four conditions, the participants accomplished the same proof-reading task: they read a text on the computer screen, identified spelling errors in the text, and marked these errors in bold using a standard wireless laser mouse as a pointing device. The spelling errors were incorrect consonant doublings, and there was an average of one spelling error for every three lines, though the errors were unevenly distributed throughout the text.

All four computer work conditions consisted of (1) a one-minute rest recording before computer work (rest before, RB), (2) ten minutes of computer work under one of the four conditions (LS, VS, PS or VPS), (3) a break (13.9 ± 2.1 min (mean ± SD, n = 43)), and (4) a one-minute rest recording after the break to measure recovery (*Recovery rest, RR*). The recovery periods at the end of the first three conditions were concurrent with the rest sessions before the succeeding conditions (Figure 4.2). The rest session before the first condition for each participant was used as the baseline value for the muscle blood flow and fixation disparity results.

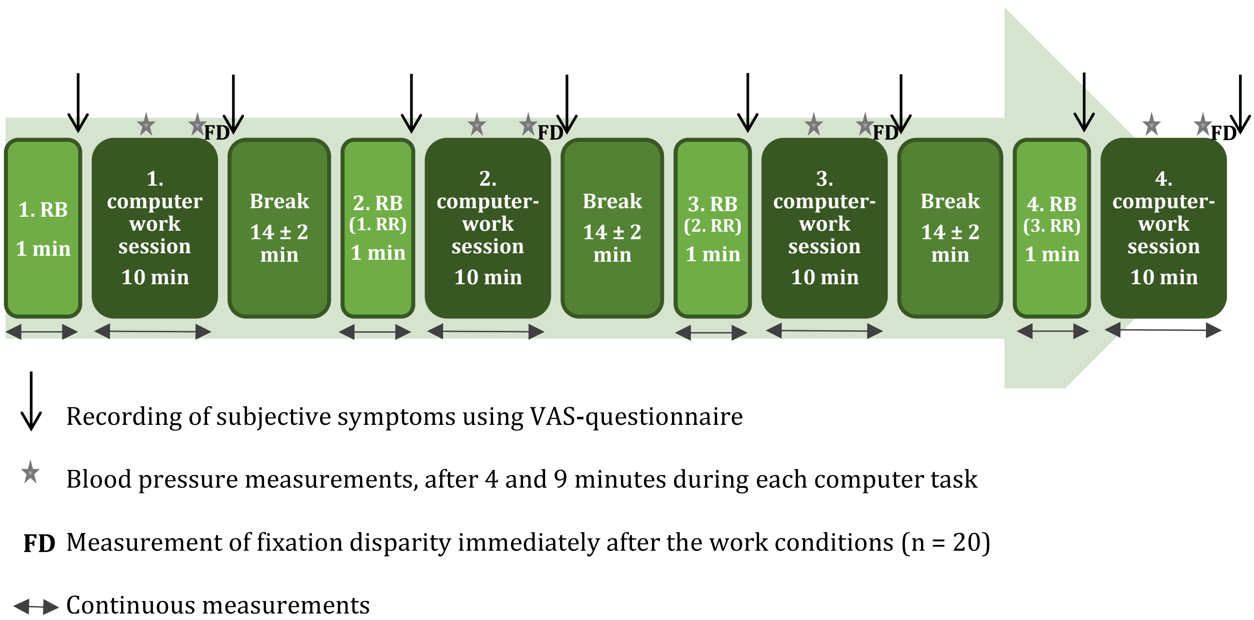


Figure 4.2
Flowchart of the computer work conditions in project 2; all four conditions consisted of the same key parts. RB = rest before the computer work sessions, RR = recovery rest after computer work. The measurements throughout the experiment are also marked in the flowchart. The order of the computer work conditions was counterbalanced.

4.2.2 Workstation

In both projects, all the computer work tasks were performed at the same workstation and the participants sat in a stable stationary office chair placed with their body close to the table top at a corner table. The sitting position was ergonomically optimized for each individual by the test leader according to Norwegian and international recommendations and standards (Arbeidsplassforskriften 2011; ISO-9241-5 1998; Woo et al. 2016) in order to reduce any influence of ergonomic factors during the experiments. First, the height of the chair was adjusted according to their leg length, after which the electrically height-adjustable table top was adjusted based on the participants' elbow height in sitting position. Forearm support during computer work has previously been shown to be beneficial for reducing trapezius load and musculoskeletal disorders (Aaras et al. 1997; Hoe et al. 2018). The participants were involved in the adjustments of the chair and table top to ensure the most comfortable sitting position as possible for each individual.

Then, the initial viewing distance to the computer screen was adjusted according to each participant's subjective preference within recommended values (Woo et al. 2016). It has previously been reported that subjects forced to work at a shorter distance than their preferred viewing distance report more eyestrain and that individual adjustments may contribute to avoiding such discomfort (Jaschinski 1998). The viewing distance and viewing angle (from the horizontal plane to the middle of the reading field on the screen) were measured while sitting in the initial optimally adjusted position. The test chair had five rubber platforms instead of wheels to prevent participants from moving the chair around during the computer tasks; this ensured that the measured postural angles would reflect, to the greatest extent possible, only the movement of the relevant body parts and thus also alternations in viewing distance.

The viewing distances before the optimal and glare conditions in project 1 were 62 ± 3.6 cm and 63 ± 3.1 cm (mean ± SD, n = 15), respectively. The viewing angle, measured as the angle between an imaginary horizontal line at eye level and the midpoint of the readable window on the screen, was 20 ± 2° before both conditions (mean ± SD, n = 15). In project 2, the distance to the screen before start of the experiment was 65 ± 6 cm (mean ± SD, n = 42), while the viewing angle was 21 ± 2° (mean ± SD, n = 42) downward.

The ambient air temperature (°C) and air humidity (%) in the laboratory was measured at each testing day by a thermometer and a hygrometer to register the indoor environment quality during the data collection.

4.2.3 Lighting at the workstation

Optimal lighting condition

The conditions with optimal lighting in the experiments included the optimal condition in project 1 and LS and PS in project 2. At the workstation, two luminaires containing three light tubes each (OSRAM T5 HE 28W/830), with one tube illuminating downward and two tubes upward, were hanging from the ceiling at each side of the participants (Figure 4.3). The colour rendering index of the tubes was ≥ 80, and the correlated colour temperature was 3000 K. The luminance distribution in the conditions with optimal lighting was within the recommended luminance ratio of 5:3:1 for a workstation (Anshel 2007), with the working area (computer screen) as the brightest area within the visual field. The illumination level on the desktop with the glare source turned off was also within recommended values (> 500 lux).

Further in this thesis, both the phrase 'optimal lighting' and 'non-glare' conditions are used when the optimized work lighting conditions are discussed.

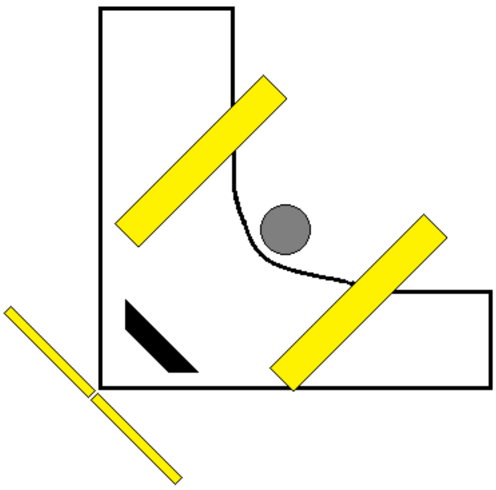
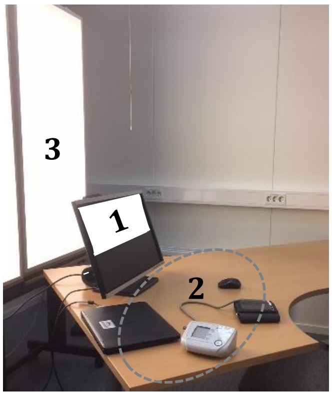


Figure 4.3
Overview of the workstation in both projects, showing the luminaires hanging down from the ceiling at each side of the participants, and the glare source placed behind the computer screen.

Glare condition

In the glare conditions (project 1: glare condition, project 2: VS and VPS), two large luminaries centred behind the computer screen were turned on (Figure 4.3). The glare source was designed to simulate an unfavourably positioned office window behind the computer screen that exposed participants to direct glare (visual stress). The size of each glare luminaire was 1.25 m x 0.57 m; each consisted of six T5-fluorescent tubes (Starcoat T5 F28W/830 HE). The colour-rendering index of these tubes was 85, and the correlated colour temperature was 3000 K. When turned on, the luminaires had an average luminous intensity of 4268 cd/m^2 in project 1 and 4634 cd/m^2 in project 2 (mean value of many measure points measured across the two screens). Such values are similar to the luminance from a window on a dry but overcast day. The lux value from the glare source at the workstation measured vertically at eye height towards the glare source was measured in project 2; it was 13,031 lux, as measured by a GL optic spectrometer (GL SPECTIS 1.0 Touch).

In the glare conditions, the luminance ratio was far beyond the recommended luminance ratio, with excessive light in the background area of the working field (glare source). The



AREAS IN LUMINANCE RATIO	OPTIMAL LIGHTING (project 1 / project 2)	GLARE (project 1 / project 2)
1. Working field (computer screen)	155 /155 cd/m^2	155 / 155 cd/m^2
2. Immediate surrounding area	75 / 90 cd/m^2	590 / 520 cd/m^2
3. Background area	46 / 61 cd/m^2	4268 / 4634 cd/m^2

Figure 4.4
A photograph showing how the areas used in measurements of the luminance ratios (distribution of the light) at the workstation were defined in the current thesis: (1) the working field, (2) the immediate surrounding area, and (3) the background area. The photograph is taken during a glare condition, but does not perfectly reflect the light conditions during the experiments.
The table in the figure shows the average luminance levels (cd/m^2) within the three different areas during both the optimal lighting conditions and the glare conditions in project 1 / project 2.

luminance distribution in project 1 was 1:4:28, and it was 1:3:30 in project 2. The working field was the least bright area in the field of view in the glare conditions. The picture in Figure 4.4 shows the areas defined as the working field (1), the immediate surrounding area (2), and the background area (3) in the current thesis, and therefore where the values in the luminance ratios (light distributions) were measured. The table in Figure 4.4 shows the luminance in the three different areas from both projects, for both the glare and non-glare conditions. These values are given as the average luminance and were measured from several measure points within each area from the participants' eye level. The light measurements were carried out by a Hagner Universal Photometer (Model S4; Sweden) and a Hagner Lux Meter (Model EC1; Sweden).

4.3 Measurements performed in both projects

In the following, all measurements included in both projects 1 and 2 are described. See Table 4.1 for details about what measurements were performed in each project. The data analysis for each measurement is described in the relevant sections below. Finally, general aspects of the data analysis are reported in a separate section.

4.3.1 Muscle blood flow in trapezius and orbicularis oculi

Muscle blood flow in trapezius and orbicularis oculi were measured in both projects 1 and 2 using photoplethysmography (PPG). PPG is a non-invasive optical technique that can be used to detect blood volume changes in the microvascular bed of tissue in both peripheral blood circulation like skin perfusion and from deeper vascular compartments like skeletal muscles (Allen 2007; Sandberg et al. 2005b). For measurement, the PPG probes should be tailored to each specific muscle by using an appropriate combination of optical wavelengths and distances between the light source and photodetector (Hagblad et al. 2010; Lindberg and Oberg 1991; Sandberg et al. 2005b). In this thesis, special custom-designed optical probes (Department of Biomedical Engineering, Linköping University, Sweden) were developed and optimized to measure muscle blood flow in the respective muscles, trapezius and orbicularis oculi (Figure 4.5). Similar applications of PPG have previously been validated and used to measure muscle blood flow in these muscles (Sandberg et al. 2005a; Sandberg et al. 2007; Thorud et al. 2012; Thorud et al. 2014). The probes, integrated into a black-coloured silicone plate, were placed over the relevant muscles. The probes were attached to the skin with medical adhesive tape and covered

Table 4.1
Overview of all measurements achieved in the current thesis and in which project they were performed.

MEASUREMENT	Project 1	Project 2
Muscle blood flow		
• Trapezius	x	x
• Orbicularis oculi	x	x
Muscle activity		
• Trapezius	x	x
• Orbicularis oculi	x	
Postural angles		
• Head	x	x
• Back	x	x
• Upper arm	x	
Cardiovascular responses		
• Heart rate	x	x
• Blood pressure		x
Questionnaire		
• Subjective symptoms	x	x
• State moods, positive and negative		x
• Perceived workstation lighting and task difficulty		x
Other measurements		
• Work performance	x	x
• Personality traits		x
• Blink rate*		x
• Fixation disparity (FD)*		x

* Only measured part two of project 2 in 2016 (n = 20)

with black-coloured adhesive tape to avoid noise from the glare source and the surrounding light. Near-infrared light (810 nm) from light-emitting diodes (LEDs) in the PPG probes were directed toward the skin over the respective muscle. The reflected light from the muscle tissue was received by a photodetector placed adjacent to the LEDs. Setting the LEDs at 810 nm ensured that the blood flow signal would be insensitive to variations in oxygen saturation. Thus, variations in the measured PPG signal are related to changes in blood flow and blood volume in the tissue.

The signals from the photodetectors were processed in an amplifier and sent via Bluetooth to a computer. The PPG signal appeared on the screen as shown in figure 4.5

and correlated to muscle blood flow and was synchronous with the heart rate, reflecting the arterial blood flow in the vascular bed (Lindberg and Oberg 1991).

Muscle blood flow measurements in trapezius

The measurements of muscle blood flow in m. trapezius were performed at the upper descending part of the muscle, on the non-dominant side in project 1 and at the dominant m. trapezius in project 2. The size of the trapezius probe was 48 x 40 mm; it consisted of two LEDs and two photodetectors. The centre-to-centre distance between the LED and the photodetector was 25 mm for the trapezius probe (see also Figure 3 in paper I). The location of the PPG probe on the trapezius was medial to the EMG electrodes, on the upper belly of the muscle (Figure 4.6b).

Muscle blood flow measurements in orbicularis oculi

The measurements of muscle blood flow in m. orbicularis oculi were achieved from the orbital part of the muscle. In project 1 the probe was attached to the skin over the right eyes muscle, whereas in project 2 the measurements were done at the muscle of the near-dominant eye. The orbicularis oculi probe was 30 x 15 mm and consisted of one near-infrared LED and one photodetector. The centre-to-centre distance between the LED and the photodetector was 11 mm. The PPG probe was placed 15 mm beneath the lower lid, on a vertical line intersecting the pupil when looking straight ahead (Figure 4.6a).

Analysis of muscle blood flow measurements

The muscle blood flow was recorded at a sampling frequency of 240 Hz using software developed in the Department of Biomedical Engineering at Linköping University in Sweden. The muscle blood flow was then analysed in MatLab R2009b (The MathWorks, Inc., USA) using software developed in the Department of Biomedical Engineering, Linköping University, Sweden, by means of the pulse-by-pulse amplitude of the AC component of the PPG signal. Because of excessive noise in the PPG signal, especially for the orbicularis oculi signals, some participants ended up with incomplete muscle blood flow measurements. Because of this, some individuals had to be excluded from the analysis including these missed results.

The muscle blood flow results were given as values relative to a rest value. In paper I the muscle blood flow during computer work was related to the lowest rest value registered, based on the premise that this value was the rest value for each muscle. In paper II, the

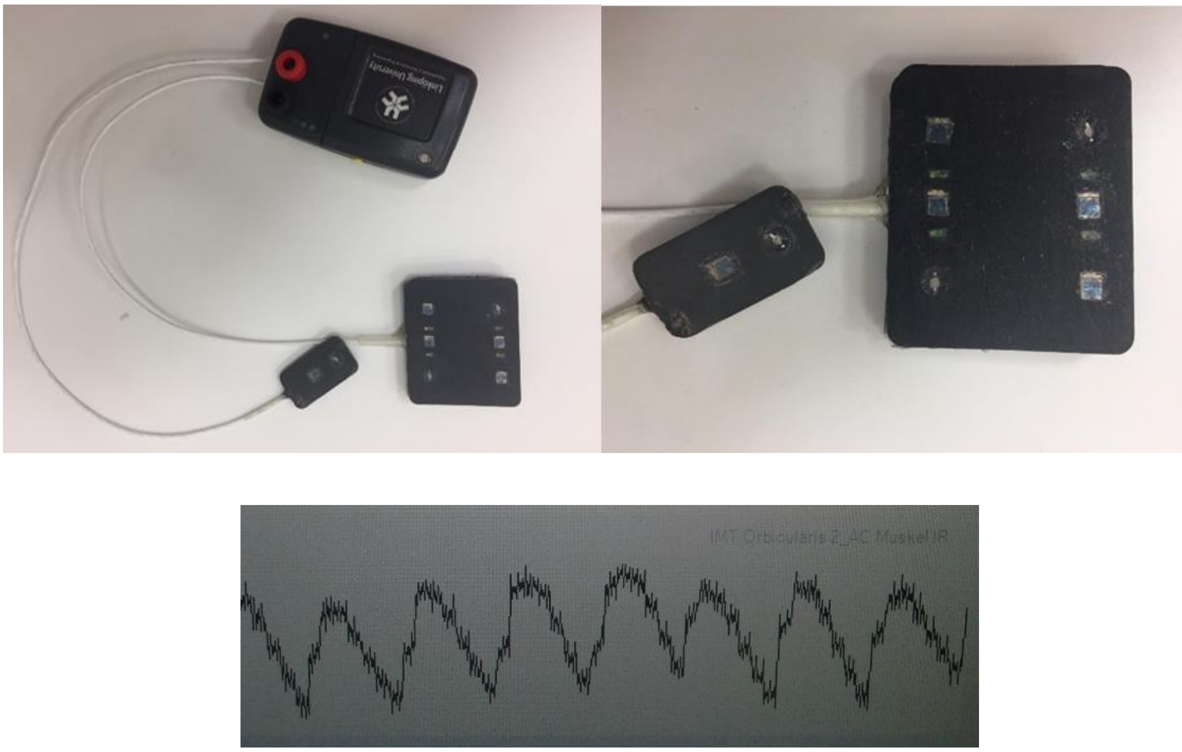


Figure 4.5
The upper photograph shows the PPG probes used in this thesis to measure muscle blood flow in m. orbicularis oculi (the small one) and in m. trapezius. The Bluetooth device sending the signals to the computer is also shown in the photograph on the left side. The lower photograph shows how the signals appeared on the computer screen, showing the PPG-signal that was further analysed by the software.

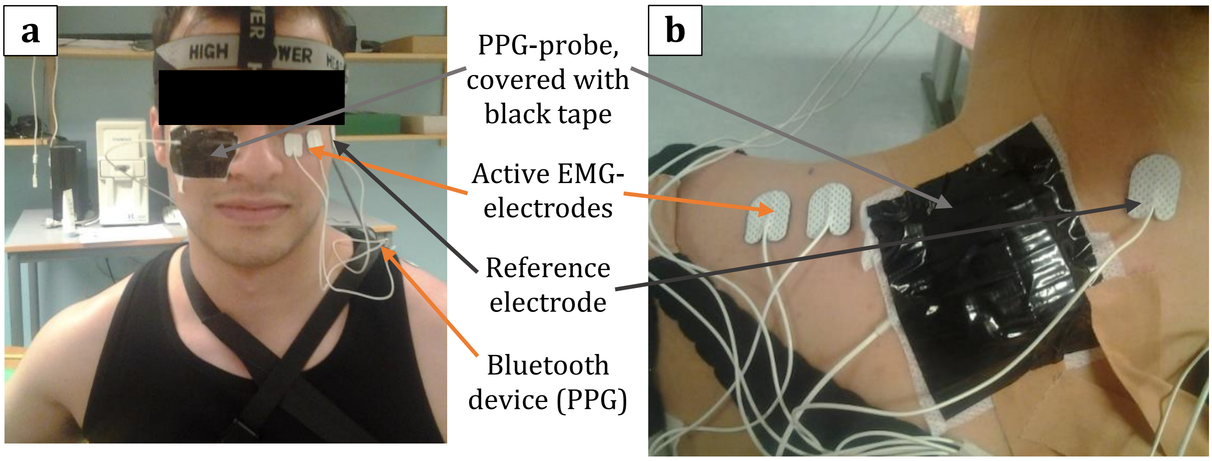


Figure 4.6
Placement of the PPG probes and the electromyography (EMG) electrodes (active and reference) on a) the orbicularis oculi muscle and b) the trapezius muscle.

muscle blood flow during work conditions was related to the mean muscle blood flow during baseline (the one-minute rest recording carried out before the first condition for each participant).

In paper III the participants were divided in two subgroups regarding average trapezius muscle blood flow (TBF) during the four computer work conditions in order to investigate the associations between TBF and neck pain. The subgroups were *High TBF*: participants with TBF equal to or higher than the median value (n = 17), and *Low TBF*: participants with lower TBF measurements than the median value (n = 15).

4.3.2 Muscle activity in trapezius and orbicularis oculi

Muscle activity was continuously measured during each rest recording and all work sessions using electromyography (EMG) on the orbicularis oculi and on the trapezius in project 1 and on trapezius only in project 2 (see below and Table 4.1). Two active surface electrodes and one reference electrode (Ambu, 70010-K/12; Neuroline 700, Denmark) were attached to the skin over each muscle to be recorded. The size of the electrodes was 15 x 20 mm. The skin at the attachment sites was first cleaned with alcohol and lightly abraded with P600 sandpaper (which was pre-soaked in alcohol for a minimum of 10 seconds) to reduce resistance and optimize the electrical signals.

The recordings of muscle activity by EMG and the postural angles (see separate section about postural angle measurements) were carried out by using a physiometer (Premed A/S, Norway) connected to a computer. The method for EMG measurement was based on the relationship between electrical activity in the muscle (measures in microvolt, μV) and generated muscle force (measured in newton, N). The EMG signals for both trapezius and orbicularis oculi muscles were normalized by performing a calibration procedure with a calibration platform attached to a force transducer (Aaras et al. 1996a). First, maximum force and maximum electrical activity (EMG) were obtained as the participants performed a maximal voluntary contraction (MVC) of the relevant muscle. MVC was calculated by the computer from the displayed maximum EMG root mean square (EMGrms) (μV) and force (N). Then, the EMG and force were recorded while the participants gradually contracted and increased the force of the relevant muscles linearly, from zero up to 30% MVC, with visual guiding of the contraction on a computer screen (see figure 4.7). The result was considered satisfactory when the EMG_{rms} showed a continuous increase. From this, an EMG_{rms}/N relationship for the actual range of the workload below 30% MVC was established by the computer and calculated by linear regression, and the muscle activity data were presented in % MVC (Aaras and Ro 1997; Aaras et al. 1996b).

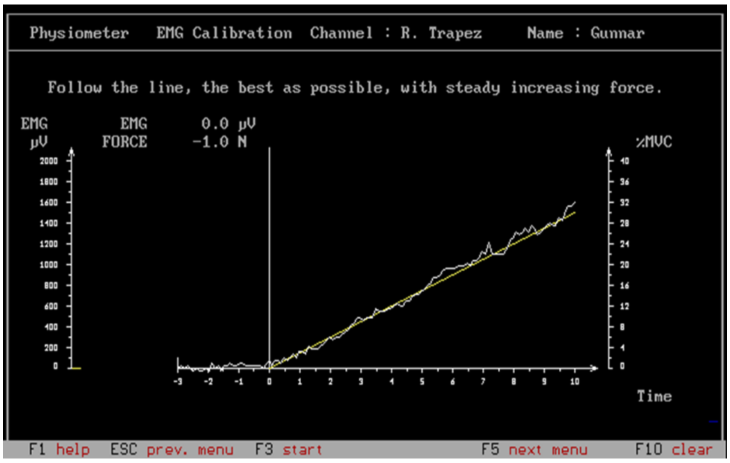


Figure 4.7
Example of how the screen looked like during the EMG calibration procedure step of visual guided muscle contraction. The yellow line represents an imaginary perfectly gradual increase in force generated by the muscle from 0 to 30% of the MVC, and the white line shows the actual contraction of the muscle performed by a specific participant.

Muscle activity measurements and calibration procedure of trapezius

Muscle activity in m. trapezius was recorded in both projects 1 and 2 unilaterally on the upper descending part of the muscle. The measurement was performed on the non-dominant arm in project 1 and on the dominant arm in project 2. The centre-to-centre distance between the two active electrodes was about 2 cm. The location of the electrodes was 2 cm lateral to the midpoint on the line between the C7 (cervical spine) and the acromion (the outer lateral bone process of scapula) (Jensen et al. 1996); see Figure 4.6b. The reference electrode was located near the spine at the height of C7.

The trapezius was calibrated in a standing position with the arms hanging down (Figure 4.8a). On the calibration platform, two padded horizontal bars, each attached to a force transducer, were firmly placed on the subjects' shoulders in order to ensure no slip between the bars and the shoulder. The bars were placed lateral to the EMG electrodes to avoid disturbance of the electrode signals during the calibration procedure. Initially, the subjects performed a MVC of the trapezius muscle by execution of a maximal isometric elevation of the shoulders towards the bars. The bars were not moveable, but the force transducer registered the force achieved against the bars. To isolate the use of the trapezius in the contraction, the main direction of the contraction was instructed to be upward (or upward and slightly backwards), and all participants were instructed to only use their shoulders (not their legs) to press, to use both shoulders equally, and not to draw the shoulders forward in the elevation.

Muscle activity measurements and calibration procedure of orbicularis oculi

Muscle activity in the orbicularis oculi was recorded unilaterally on the left side in project 1. In project 2, the orbicularis oculi muscle activity was not included. The two active electrodes were placed on the orbital part of the orbicularis oculi muscle approximately 15 mm below the lower lid on a vertical line intersecting the pupil when looking straight ahead. The distance between the two electrodes was approximately 0.5 cm. The reference electrode was located on the temporal process of the zygomatic bone (Figure 4.6a).

Calibration of the EMG signal for the orbicularis oculi muscle was performed while supporting the chin and forehead on a specialized calibration platform (Figure 4.8b). A soft rubber end rested firmly on the skin located directly over and superficial to the right orbicularis oculi (15 mm below the lower lid margin), and the lever arm was connected to the force transducer. The maximal contraction was then executed by a contraction of the orbicularis oculi of both eyes, which involved performing a maximal eyelid squint while keeping the mouth closed and relaxed. The participants were informed of the importance of using equal force on both sides (since the calibration signal was obtained from the contralateral side from the electrodes) and to use the orbicularis oculi muscle in isolation. A training session was carried out before the calibration procedure was performed.

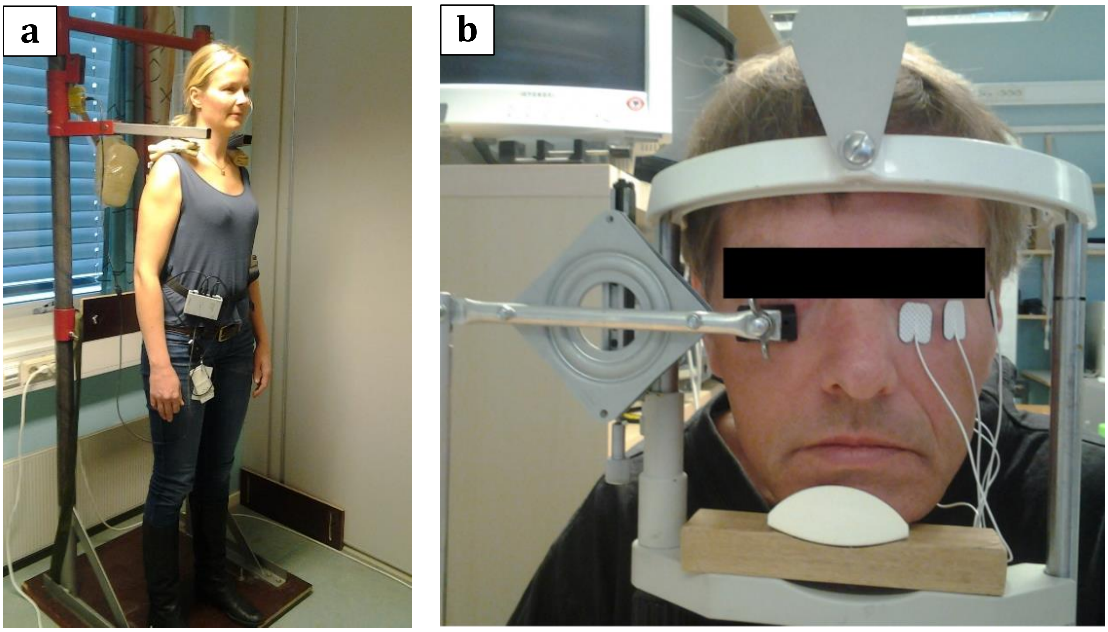


Figure 4.8
The calibration platform for the EMG measurements of a) the trapezius muscle, and b) the orbicularis oculi muscle. The subjects in the photographs did not participate in the experiments; they are only demonstrating the equipment used.

Analysis of muscle activity measurements

Analysis of the muscle activity measurement (together with the postural angles) was obtained by ranking the interval estimates (0.1 s duration) to produce an amplitude probability distribution function (Aaras and Ro 1997; Jonsson 1982). Static, median and peak levels were defined as amplitude probability distribution function levels of 0.1, 0.5 and 0.9, respectively. The static force level was defined as the level of muscular contraction corresponding to a probability level of 0.1, meaning that the muscle load was higher than this level for 90% of the working period. Peak load was similarly defined as the load corresponding to a probability level of 0.9, meaning that the muscle had a higher force level for only 10% of the recording period. A probability level of 0.5 defined the median level of contraction. The static and median levels for the muscle activity results are reported in the papers.

4.3.3 Postural angles

To make the experimental conditions as close to actual work situations as possible, participants were allowed to move freely within normal postural ranges during the computer work conditions. The sitting position and viewing distance were therefore not fixed, but were controlled for by continuously measuring postural angles. For instance, if the participants changed their viewing distance during computer work, this would be reflected in the measured angles. Postural angles were measured in both projects 1 and 2, in the rest sessions and in the computer work conditions using dual axis inclinometers attached with straps to the respective body parts (Figure 4.9) (Aaras and Stranden 1988). As with the EMG measurements, the inclinometers were connected to a physiometer (Premed A/S, Norway).

The inclinometers were attached to the upper back and the back of the head in both projects, and to the non-dominant upper arm in project 1. Flexion/extension and lateral flexion of the head and back, and flexion/extension and abduction of the arm was measured. The angles were measured in terms of deviation from a reference body position, which was defined when the subjects were (1) seated in a balanced position without back rest and with the arms hanging by the side, and (2) looking at a point at eye height at a distance of approximately six metres (Figure 4.9). When participants were sitting in this reference position, the inclinometers were calibrated to provide a zero value. Flexion and extension of the head, back, and arm were given as positive and negative values, respectively. Lateral flexion was given as a negative value for movements towards the left from the reference position, while a positive value reflected movements to the right. Abductions of the arm were given as positive values.

Before the experiment, the participants were made aware that if they moved into an unfavourable sitting position (e.g., leaning extremely forward or resting the head in one of their hands), they would politely be told to return to a natural working position. This was done to minimize the possibility of posture alternations resulting in unfortunate ergonomic loads (which could mask the effect of the actual experimental exposures) and significant alternations in viewing distance to the computer screen (which was important for the load placed on the visual system). However, few participants actually needed postural correction during the experiments.

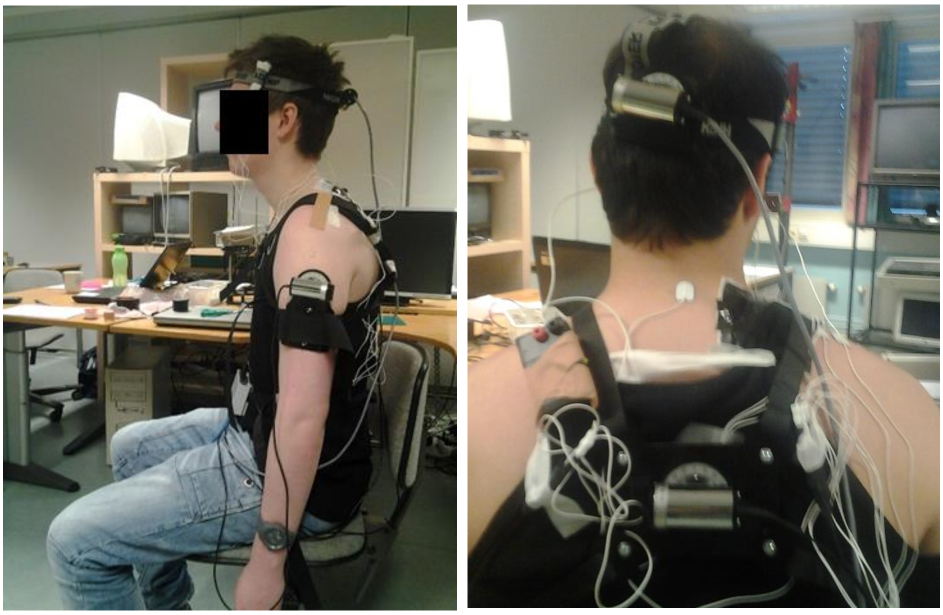


Figure 4.9
Photographs showing placement of the inclinometers used in the experiments reported in this thesis. The left picture shows the participant sitting in the reference body position for the postural angle measurements.

Analysis of postural angles measurements

As with the EMG measurements, an amplitude probability distribution function was produced for the measured postural angles (Aaras and Ro 1997; Jonsson 1982). The static level was reported in the papers.

4.3.4 Heart rate

Heart rate was measured in both projects 1 and 2. The PPG signal was synchronous with the heart rate (Lindberg and Oberg 1991), and the heart rate was thus measured continuously by the PPG method during each rest and computer work session. The heart rate was analysed with the same software used to analyse the muscle blood flow and was estimated by counting the number of peaks per minute in the PPG signals, reflecting the participants' heartbeats (Figure 4.5).

4.3.5 Subjective symptoms

The questionnaires consisted of questions asking the participants to rank, by means of 100 mm visual analogue scales (VAS), the degree to which they perceived different subjective symptoms. The left end-point for all questions was ''nothing'' (0 mm), and the right end-point was ''very much'' (100 mm) (Figure 4.10). All questions about subjective symptoms in the projects, both before and after the computer sessions, asked the participants to base their responses on how they felt the different symptoms exactly at the time when they filled out the questionnaire ("right now").

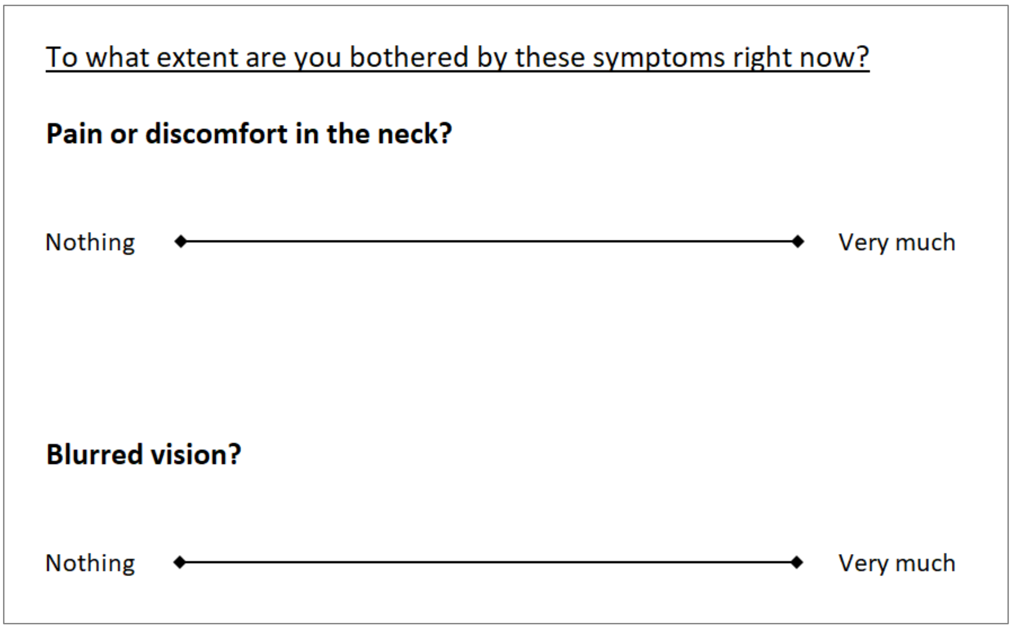


Figure 4.10
An example of a 100 mm Visual Analogue Scale (VAS) used in the questionnaires in both projects in this thesis to measure subjective symptoms. The participants draw a vertical line at the scale to rate the degree to which they felt the relevant symptom both before and after each work condition.

For project 1, subjective symptoms were evaluated with a 10-item questionnaire. Questions 1–10 in the list below were completed in conjunction with the rest sessions before and immediately after 30 minutes of computer work in each condition. Additionally, questions 1–4 were recorded after 10 and 20 minute during the computer work conditions, as well as after the recovery rest session. See Figure 4.1.

In project 2, an 18-item questionnaire was used, where nine of the questions were evaluating subjective symptoms (see section 'Positive and negative state moods' and 'Perceived lighting and task difficulty' for description of the remaining questions). The participants completed the questionnaires in connection with the rest sessions (rest before and recovery rest) and after each computer work session, answering questions 1–8 and 11 from the list below. See Figure 4.2.

1. Tiredness in and around the eyes (called *eye-related tiredness* in papers and thesis)
2. Pain in and around the eyes (called *eye pain*)
3. Pain/discomfort in the neck (called *neck pain*)
4. Pain/discomfort in the shoulders (called *shoulder pain*)
5. Blurred vision
6. Dry eyes
7. Headache
8. Photophobia
9. Tearing eyes (only measures in project 1)
10. Pain/discomfort in the upper back (only in project 1)
11. Head tiredness (only in project 2)

To minimize confounding effects of varying understanding of how to fill into the questionnaires and of localization of the symptoms, an explanation of how the questionnaires were to be completed and a definition of how to localize the eye symptoms and neck and shoulder symptoms was presented to the participants prior to the experiments (see attachment).

4.3.6 Work performance

In project 1, the work performance was evaluated as productivity, defined as the number of words read during 30 minutes of reading (words read/30 min) in both the glare and optimal conditions. In project 2, the work performance was estimated as both productivity and accuracy. The number of words read throughout the ten-minute computer tasks (words read/10 min) was used as a measure of the subjects' productivity per condition. Accuracy was defined as the percentage (%) of correctly marked spelling errors (correctly marked errors divided by the actual number of errors in the text section read).

4.4 Measurements performed only in project 2

4.4.1 Positive and negative state moods

In project 2, the questionnaires described under 'Subjective symptoms' additionally contained questions about various positive and negative state moods. These were also rated by using 100 mm VAS. The state moods satisfied, relaxed, concentrated, strained, stressed, uncomfortable, and bored were registered both before start of each computer work condition and after the work sessions (immediately after the FD-measurements); see Figure 4.2. The registered state moods were categorized into two main groups: negative state moods (stressed, strained, uncomfortable, and bored) and positive state moods (satisfied, relaxed, and concentrated). The indexes were made by using the average scores (mm VAS) of the included state moods.

While registering state moods before start of the computer work sessions, the participants were asked to rate the degree to which they were affected by the different moods at the precise moment they completed the questionnaire. When measured after the computer work sessions, the participants were asked to rate the degree to which they were affected by the moods throughout the computer work sessions. See Figure 4.11.

4.4.2 Perceived lighting and task difficulty

In project 2, the questionnaire also consisted of questions regarding how pleasant/unpleasant the participants perceived the ambient lighting at the workstation, and how easy/difficult they perceived the task they performed during the work sessions. These questions were also rated with VAS. Perceived lighting were asked for both before and after each working condition (Figure 4.11), whereas task difficulty was only rated after performance of the work tasks.

4.4.3 Personality, trait affect

In project 2, the participants' positive and negative personality traits were registered. This was done because subjects dominated by a negative personality have been shown to be more easily autonomously activated compared than those who are dominated by a positive personality (Kreibig 2010). The 10-item mood scale Positive and Negative Affect Schedule (PANAS) (Watson et al. 1988) was used to register the 10 personality traits. The index scores for the negative (indignant, shameful, nervous, unfriendly, scared) and positive (active, watchful, inspired, determined, attentive) personality traits were used in the study as covariates to control for the influence of personality on the other measurements.

QUESTIONNAIRE, BEFORE TEST

Base your answers on how you feel RIGHT NOW

1. How stressed do you feel right now?

Nothing — Very stressed

….

8. How do you perceive the lighting where you sit (at the workplace) right now?

Very comfortable lighting — Very uncomfortable lighting

QUESTIONNAIRE, AFTER TEST

Base your answers on the way you felt DURING the work session

1. How stressed did you feel while working?

Nothing — Very stressed

…

8. How did you perceive the lighting at the workplace while you were working?

Very comfortable lighting — Very uncomfortable lighting

Figure 4.11
Example of questions from the VAS-questionnaire used in project 2 to show how the questions were asked related to perceived state moods (here: stressed), and how the participants experienced the lighting used in the experiment before (upper half) and during (lower half) the work tasks.

4.4.4 Blood pressure

In project 2, systolic and diastolic blood pressure measurements were captured both in the rest sessions and two times during the computer work sessions; after four and nine minutes of computer work. The measurements were made from the non-dominant upper arm using an automatic oscillometric blood flow monitor (A & D Medical, Model UA-767Plus 30). The artery position mark was placed 1–2 cm above the elbow, in a medial position on the upper arm (in line with the ring finger on a supinated forearm). Before the start of the experiment, the participants were encouraged to stay focused on the computer task throughout the blood pressure measurements and try not to be disturbed and interrupted during the conditions. To familiarize participants with the equipment, one measurement was performed during the preparation phase.

Unfortunately, differences in arm position between the measurements in the rest sessions (arms resting in the participants lap) and during the computer work sessions (arms resting on the tabletop) prevented the data's comparison. Pickering et al. (2005) have pointed out that position of the arm has a major influence on blood pressure measurement, with readings being too high if the upper arm is below the level of the right atrium of the heart or too low if the arm is above heart level. Therefore, the data from the rest situation were not comparable to those during work, and measurements of differences in blood pressure from rest to work situations could not be included. Accordingly, only the measurements captured during the work periods could be included in the analysis in this thesis.

4.4.5 Blink rate

In project 2, one of the stress-inducing procedures in psychologically stressful conditions (PS and VPS) was to monitor the participants during computer work using a video camera. These videos were additionally used to calculate the participants' blink rate (blinks per minute) during these conditions, by using a manual counter. Unfortunately, only the videos from the second test period (in 2016) were appropriate for use in the analysis of blink rate, giving blink rate data for 20 participants. The blink rate was counted in the rest sessions, during the first minute (0–1 min) of each condition, and the average blink rates in the following ranges: between 2–4 min, 5–7 min, and 7–9 min.

The overall analysis of blink rate during computer work included the average blink rate of all measuring points, or as the blink rate in the first minute of the computer work period

(0–1 min) compared to the rest of the work session (average of blinks/min during 2–4, 5–7, and 7–9 min).

Ideally, the blink rate should have been measured in all conditions. However, it is known that awareness of being filmed can induce psychological stress. The video camera was therefore not used in the LS and VS conditions to avoid adding psychological stress in those conditions. Hence, blink rate data were only available from the PS and VPS conditions.

4.4.6 Fixation disparity

Measurements of horizontal FD were added to the experiment in the second test period (in 2016) of project 2, thus providing FD data for 20 participants. The FD test was accomplished in the preparation phase before the experiment (baseline) and immediately after completing the four different 10-minute computer work conditions. The participants turned the chair around, put on a pair of polarized glasses, and placed their head in a chin-and-head support facing a Sheedy Fixation Disparometer (Dwyer 1982); see Figure 4.12. The test distance was 60 cm, about the same as during the computer work periods.

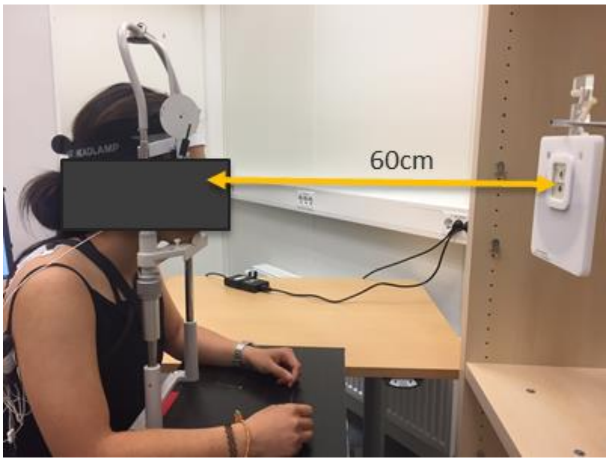


Figure 4.12
Set-up for the fixation disparity (FD) measurements in project 2.

The disparometer consists of successive pairs of Vernier lines within a structure-less field, with each line being viewed by only one eye through the polarizing glasses. First, the participants were asked to read the text on the disparometer in order to focus the eyes on the correct distance before measuring FD. The disparometer was adjusted to zero disparity at start and was then adjusted to increasing angular separation of the lines until the participants reported that the lines appeared to be aligned.

In this thesis, only one FD measurement at each measuring point was carried out, resulting in 5 measurements for each participant (baseline, and after LS, VS, PS and VPS). The change in FD-value from baseline to the measured level after each computer work condition was used as a variation measure and was called FD_{change}. This value reflected the change in FD for each participant from the participants' own FD-baseline (0), a change in either an eso direction (+) or exo direction (−). Therefore, the statistical analyses of the FD measurements were conducted with both the actual measured FD value after the work conditions, and FD_{change} for each condition. Both measurements were given in arcmin.

In addition, to analyse the variation in FD and any effect on visual discomfort, the participants were divided into two subgroups according to their observed FD_{change}. The subgroups were as follows: (1) *No change in FD*: participants with little or no FD change relative to baseline (± 2 or less arcmin, range = 2 exo – 2 eso, n = 12) in all computer work conditions, and (2) *Changed FD*: participants with ≥ ± 4 arcmin disparity change (range = 10 exo – 12 eso, n = 8) in at least one of the conditions.

4.5 Data analysis - general aspects

Specific aspects of data analysis regarding each measurement are presented in the respective sections above. In this section, some general aspects of the data analysis are presented.

Regarding the continuous measurements in this thesis (EMG, PPG, postural angles, and heart rate), some of the data captured throughout the computer task conditions had to be excluded from the analysis to avoid the risk of these results to be disturbed by other measurements that was collected along the way. In project 1, this was the case for data captured during and after completing the questionnaires every ten minutes during the work sessions. The subjects filled into the VAS questionnaires every 10 minutes during the computer task. The fill-in took on average 33 ± 8 seconds (mean ± SD, n = 15). To minimize the possibility of this task influencing the results, the two minutes after start of completion of the questionnaire were not analysed. The continuous variables in project 1 were thus analysed as the mean of the last 3 minutes for every 5 minutes during the 30-minute conditions. Accordingly, time point '5 min' was the average value for data captured in 2-5 min, time point ‘10 min’ was the average value for data captured in 7-10 min, time point ‘15 min’ was the average value for data captured in 12-15 min, etc.

In project 2, the blood flow measurements performed after four and nine minutes during the work sessions made it necessary to exclude the data captured for the continuous data during and after the blood pressure measurements (between the fourth and fifth minute and between the ninth and tenth minute) from the analysis. The continuous data were therefore analysed as the mean of 0-4 and 5-9 minutes and presented in the results as time point ‘5 min’ and ’10 min’.

During the rest sessions, the mean value of the continuous data captured throughout the one minute measurement was analysed in both projects.

4.6 Statistics

The power analysis before project 1 was conducted based on the results from the study of (Thorud et al. 2012), using the same PPG probes and electrodes to measure muscle blood flow and muscle activity, as well as the same glare source. Sample size was calculated with a test power of 80 %, a significance level of 5 % (two-tailed) and the standard errors from Thorud et al. (2012) (Owen 1962). The calculations showed the need of 20 participants to the experiment to detect a difference between optimal and visual demanding conditions.

Power analysis before project 2 was conducted based on the trapezius muscle blood flow measurements from project 1, as this was a key variable in the study as to be able to investigate the mechanism behind the finding of increased TBF due to glare exposure in project 1. Sample size was calculated with a test power of 80 %, a significance level of 5 % (two-tailed) and standard errors based on the previous photopletysmography measurements in project 1 (Owen 1962). The calculations showed that we needed 36 participants to find a 15% difference in trapezius blood flow between the LS and VS conditions. It should also be mentioned that to find a corresponding difference between LS and VS for the orbicularis oculi muscle blood flow the power analysis showed that the experiment had to include 100 participants.

In project 1, non-parametric analyses were used, whereas the analyses in project 2 were performed using parametric statistics. The non-parametric statistics were chosen in project 1 because the assumptions for parametric statistics were not fulfilled; for example, there was a low number of participants.

Several statistical analysis methods were applied in the enclosed papers and they will be outlined in the following. All statistical analyses were performed using IBM SPSS Statistics; Version 17.0 in project 1 and Version 24.0 in project 2 (SPSS Inc., USA). In all analyses, a statistical difference was considered significant at $p < 0.05$ (two-tailed). Statistical analysis revealing differences at $p \leq 0.06$ was presented in the results as borderline but not significant.

In project 1 (paper I), overall differences between the conditions were tested by comparing means of area under a curve with Wilcoxon signed-rank tests (for related variables) and Mann-Whitney U tests (for independent variables). Overall time effects were tested with the Friedman test and if significance was indicated, differences at each time point compared to the rest level (RB) were tested by Wilcoxon signed-rank tests or Mann-Whitney U tests. Spearman's rank correlation coefficients were used to examine correlations between variables.

In project 2 (papers II and III), the overall statistical analysis was performed with ANOVA Repeated Measures (factorial repeated $2 \times 2 \times 4$ design). Planned contrasts were used to compare conditions if the overall analysis indicated either main effects (effect of glare, psychological stress, or time) or interaction effects (e.g. glare * time). Inspection of the variables revealed that several variables departed from the normal distribution, and base-10 logarithm transformation was executed on these variables. For the variables that were normally distributed, untransformed data were used in the analysis. For many of the ANOVA analyses, Mauchly's test indicated a violation of the assumption of sphericity, and the Greenhouse–Geisser correction was therefore used in these cases. Untransformed data were presented in the figures, except for the blood flow data, which was shown as percentage muscle blood flow increase relative to the baseline level. Correlation analysis (Pearson) was performed on transformed data. When only self-reported symptoms/ moods were included in the correlation analyses, the differential scores (mm VAS score after computer work – score before start) was used instead of the actual reported VAS scores. This was to avoid bias due to the disadvantage of self-reporting in research; subjects may overall report high or low values, making such correlations between two self-reported symptoms/moods significant in a too large extension.

An overall ANOVA was performed to investigate potential overall time effects (test order effects) throughout the experiment, independent of condition. Independent-samples t-test were conducted to compare subgroups of the participants in paper III. Personality data was used as a covariate in the analysis to ensure that it did not affect the participants intra-subjectively differently during exposure to psychological and visual stresses.

4.7 Ethical considerations

In the current thesis, no large and pronounced ethical issues were clearly related to the projects. All participants performed the same experiments (if in different order), all received the same standardized information, and all measurements performed were non-invasive. In both projects, all participants received verbal and written information about the study before giving their informed consent.

The study protocol was approved by the Regional Committee for Medical and Health Research Ethics, Norway (2013/610), and followed the tenets of the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The funding from the Norwegian Extra Foundation for Health and Rehabilitation and the Spine Association, Norway, had no impact on the study in terms of design, data collection, analysis, or presentation of the results. None of the authors in the enclosed papers of the thesis had any conflict of interest in the research.

5. Summary of papers and main results

Results from the experiments performed in project 1 formed the basis for paper I included in the current thesis, whereas paper II and III report data collected in project 2. Short summaries of each paper and the main results are presented below. Please refer to the enclosed papers for more details. Some results not included in the papers are presented separately in the 'Additional results' section.

5.1 Paper I

'Effect of Direct Glare on Orbicularis Oculi and Trapezius during Computer Reading'

The aim of this study was to investigate how exposure to direct glare during reading on a computer screen affects the muscles m. trapezius of the neck and m. orbicularis oculi around the eyes, as well as the development of eye, visual and neck symptoms.

Fifteen healthy young students with normal binocular vision read a text on a computer screen in two different conditions: 30 minutes reading with glare exposure (*glare condition*) and 30 minutes reading with appropriate lighting (*optimal condition*). The development of eye symptoms and musculoskeletal pain in the neck area were recorded at every tenth minute during the tasks (after 10, 20 and 30 minutes), as well as in a rest session both before and after the reading tasks, using 100 mm VAS. EMG and PPG continuously measured muscle activity and muscle blood flow in the trapezius (in-active side) and in the orbicularis oculi. Heart rate was also registered during the work tasks and rest sessions. Postural angles were registered continuously using inclinometers at the head, upper back and upper arm, to control for the participants' sitting position throughout the conditions.

Exposure to glare during computer reading resulted in a 30–40% increase in trapezius muscle blood flow (TBF), a significantly greater increase compared to appropriate lighting conditions (Figure 5.1). Additionally, glare exposure induced increased orbicularis oculi muscle activity (eyelid squinting) (Figure 5.2a) and more pronounced development of eye and visual symptoms (significantly increased eye pain, dry eyes, blurred vision, photophobia, and headache). Furthermore, there was a borderline significant higher muscle blood flow in orbicularis oculi during the glare condition (Figure 5.2b) compared to working with optimal lighting.

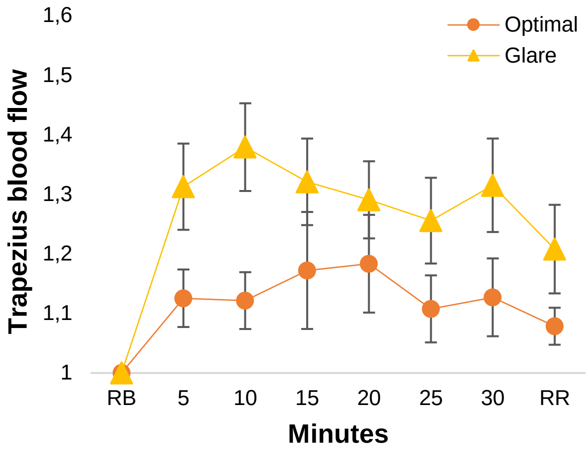


Figure 5.1
Trapezius muscle blood flow (relative values) every five minutes during the optimal (orange circles) and glare (yellow triangles) conditions. Results are given as mean ± SEM, n = 14. RB = rest before reading task, RR = recovery rest five minutes after end of reading task.

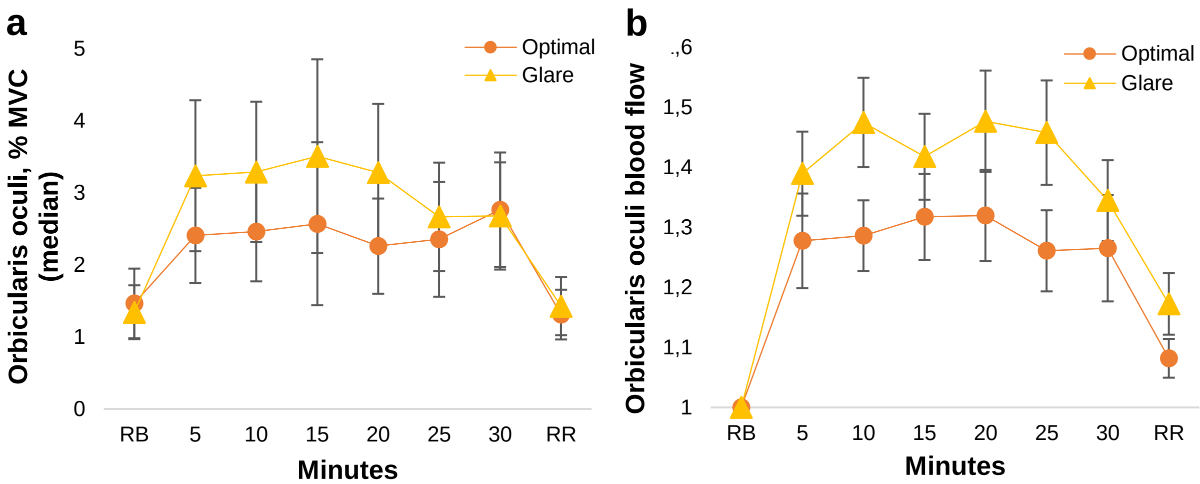


Figure 5.2
Orbicularis oculi a) muscle activity, and b) muscle blood flow (relative values) every five minutes during the optimal (orange circles) and glare (yellow triangles) conditions. Results are given as mean ± SEM, n = 14. RB = rest before, RR = recovery rest.

Table 5.1
Significant correlations between eyelid squinting (orbicularis oculi muscle activity) and trapezius muscle blood flow (TBF) and neck pain at different time points (min after start; *10, 20, 30*, or in rest session before start; *RB*) throughout the 30 min computer session with glare (n = 14).

		Eyelid squinting					
		5	**10**	**15**	**20**	**25**	**30**
TBF	**10**	.578*				.660*	.583*
	20	.814**	.748**	.619*	**.707****	.784**	.801**
	30	.600*				.597*	**.602***
Neck pain	**RB**	.686**	.759**	.658*	.683**	.692**	.743**
	10	.595*	**.693****	.558*	.590*		.563*
	20	.558*	.632*		**.558***		
	30	.691**	.793**	.719**	.687**	.676**	**.714****

The correlations are given as Spearman's rank correlation coefficients, ρ.
*/** Statistically significant correlation at p < 0.05 and 0.01, respectively.

Significant associations were observed between eyelid squinting, and both TBF and neck pain during both conditions. In the glare condition, more eyelid squinting was related to higher TBF and more reported neck pain. However, the associations between eyelid squinting and TBF were in opposite directions with glare and optimal lighting. See Table 5.1 for the correlations during glare exposure.

There were no significant differences in trapezius muscle activity, posture, or heart rate between the glare and optimal conditions.

Paper I provided evidence that direct glare exposure during computer reading affects the trapezius muscle by inducing increased TBF, seemingly not attributable to posture. This, in addition to the observed associations between eyelid squinting, TBF, and neck pain, indicated an interaction between the human visual system and head-stabilizing muscles in the neck during glare, possibly due to a centrally mediated alertness and/or a gaze stabilization response. The findings further supported the notion that glare leads to more eyelid squinting and eyestrain during computer work, possibly due to stress added to the visual system by the excessive light exposure.

The results also indicated that the orbicularis oculi muscle is activated during both glare exposure and during computer work *per se*. This may be due to a squinting response to avoid light from entering the retina in the case of glare, and due to the inherent visual and attentional demands of computer work as such.

5.2 Paper II

'Visual and psychological stress during computer work in healthy, young females – physiological responses'

The aim of this study was to further explore the finding in paper I showing that direct glare exposure during computer work resulted in increased TBF. This suggested the presence of a link between the visual and musculoskeletal systems and it was proposed that exposure to glare may involve a centrally mediated stress response, as previously reported due to psychological stress exposure. In line with this, both excessive light and psychological stress exposure are previously reported to activate various physiological responses. This study therefore explored how the occupational simulated stressors direct glare (visual stress) and psychological stress affect various physiological responses during computer work in young females with normal vision.

Forty-three healthy females performed four ten-minute computer work sessions with different stress requirements: 1. no additional stress (low stress, LS); 2. glare (visual stress, VS); 3. psychological stress (PS); and 4. combined visual and psychological stress (VPS). Muscle activity and muscle blood flow in trapezius (active side), muscle blood flow in orbicularis oculi, heart rate, blood pressure, blink rate, work performance and postural angles were continuously recorded. At baseline and immediately after each computer work session, FD in arcmin was measured. A questionnaire regarding perceived workstation lighting and stress was also completed at the end of each work session.

Exposure to direct glare during computer work (VS and VPS) resulted in a TBF increase of approximately 30%, significantly higher than with optimal lighting conditions (LS and PS). See Figure 5.3. Additionally, glare exposure induced an increased blink rate and forward bending of the head. No main effects of glare were observed on orbicularis oculi muscle blood flow or FD during the experiment.

Moreover, the findings showed that exposure to psychological stress induced a more forward-bent sitting position overall (increased back and head flexion), and a small, borderline significant, and transient increase in trapezius muscle activity. However, psychological stress exposure did not affect the TBF.

Bending forward towards the computer screen while working was overall significantly correlated with higher productivity (reading speed) and with increased orbicularis oculi

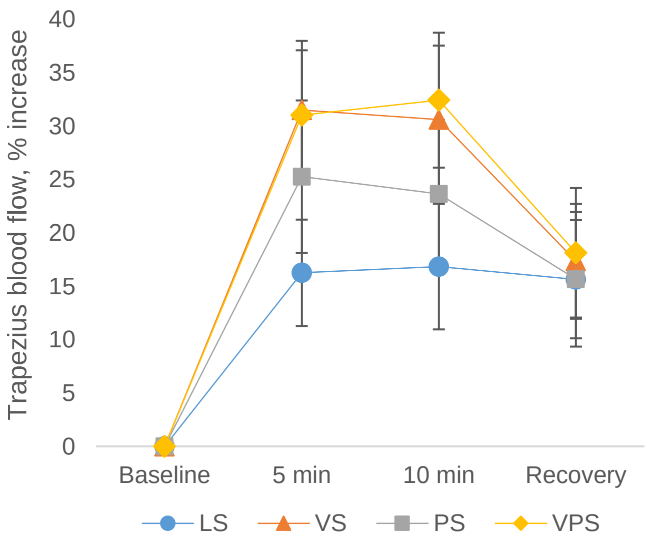


Figure 5.3
Trapezius muscle blood flow (shown as % increase relative to baseline) during the various conditions: LS = Low stress, VS = visual stress, PS = psychological stress, and VPS = visual and psychological stress. Results are given as mean ± SEM, n = 32. *Baseline* = rest before first computer task, *Recovery* = rest recording after a 14-minute break.

Table 5.2
Significant correlations between back angle (leaning forward/backward = positive/negative values) and productivity (reading speed, in words/10 min), and orbicularis oculi muscle blood flow.

Back angle vs.	N	LS	VS	PS	VPS
Productivity	35	.426*	.409*	.346*	.304
Orbicularis oculi blood flow	23	.312	.426*	.323	.410 (*)

LS = low stress, VS = visual stress, PS = psychological stress, VPS = visual and psychological stress.
*/** Statistically significant correlation at $p < 0.05$ and 0.01, respectively. (*) Borderline but not statistically significant correlation ($p \leq .060$). The correlations are given as Pearson's correlation coefficients.

muscle blood flow during glare exposure (Table 5.2). There were no significant differences in heart rate or blood pressure between the different conditions, but heart rate was positively correlated with perceived stress during psychological stress exposure (PS and VPS).

These results support the previous finding that exposure to direct glare during computer work causes a TBF increase in healthy, young women with normal vision, and the increase can apparently not be explained solely by changes in postural load. During psychological stress, a response of increased trapezius activity was indicated, suggesting that a potential centrally mediated mechanism affecting trapezius is dissimilar during visual compared to psychological stresses.

The results further revealed that moving closer to the computer screen while working might be seen as an attention response as leaning forward was correlated to higher productivity overall. The study also indicated that alternations of the distance to the computer screen affected the orbicularis oculi muscle during glare, possibly due to higher retinal illumination with shorter distance to the glare source. Moreover, forward bending of the head during glare exposure may be associated with an avoidance strategy for reducing the amount of light entering the eyes.

Based on the results of the study reported in Paper II, suggestions were made for the importance of both visual and psychological factors to be taken into account when optimizing workstations. This appears essential to reduce the physiological responses, possibly involved in both excessive eyestrain and musculoskeletal demands.

5.3 Paper III

'Discomfort glare and psychological stress during computer work: subjective responses and associations between neck pain and trapezius muscle blood flow'

The aim of this study was to explore how exposure to direct glare and psychological stress affect the development of subjective symptoms and state moods during computer work. In addition, neck pain were investigated in relation to eyestrain and TBF.

Forty-three healthy, young females performed four different counterbalanced computer work sessions, each of which lasted for ten minutes. The low stress (LS) condition had no additional stress added to the computer work task. In the visual stress (VS) and psychological stress (PS) conditions, direct glare and exposure to psychological stressors, respectively, were added. Finally, in the visual and psychological stress (VPS) condition the participants were simultaneously exposed to glare and psychological stressors. Before and after each condition, a 100 mm VAS-questionnaire was completed including eye, visual, and neck symptoms, along with positive and negative state moods. The neck pain data were also analysed in relation to the TBF data from paper II. Personality traits were controlled for in the analysis.

The results reported in Paper III showed that exposure to glare during computer work affected the perceived workstation lighting negatively, and induced significantly more eye-related symptoms (eye-related tiredness, photophobia, and total eye symptoms) and feeling of being uncomfortable than under optimal lighting conditions. Psychological stress exposure, not glare, caused a significant increase in perceived negative state moods and stress. However, the results revealed that the degree to which the participants perceived the lighting as unpleasant was related to how stressed they felt during glare exposure in both VS and VPS (Figure 5.4).

There were significant associations between neck pain and several eye and visually related symptoms present both with and without glare exposure. Additionally, the participants with the highest overall TBF reported more neck pain in all conditions compared to participants with low TBF. See Table 5.3.

The results from this study supported previous research showing that visual stress during computer work induces eyestrain and further revealed that feelings of being uncomfortable may be related to discomfort glare. The study further provides evidence for that direct glare conditions may affect the feeling of stress, or vice versa. Additionally, the findings support the notion of co-occurrence of eye-related symptoms and neck symptoms during computer work, and that TBF might be involved in neck pain development.

These findings call for a recognition that the mechanisms behind neck pain and eyestrain development during computer work are complex and that both workstation lighting, muscle blood flow, and stress might be involved in such work-related discomfort. While further studies are needed to understand the relations fully, the findings highlight the importance of considering a variety of aspects, including visual ergonomics and proper lighting without glare, to promote comfort and well-being among computer users.

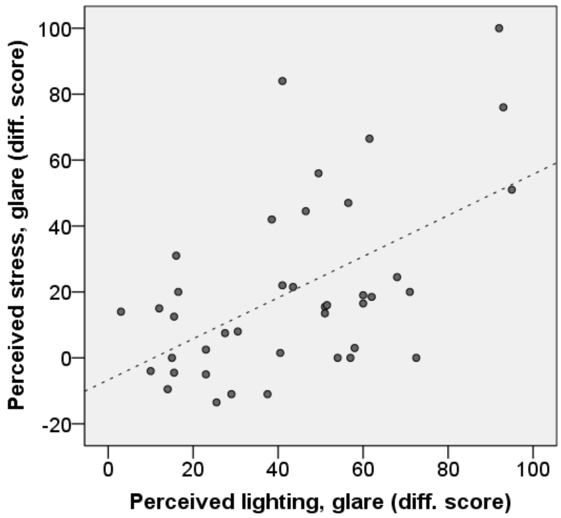


Figure 5.4
Correlation plot showing the association between perceived lighting and stress during the computer work sessions with glare exposure (VS and VPS). The scores are given as differential scores (mm VAS during computer work – mm VAS before start); n = 40 (20 n in each condition). Higher scores reflect worse perceived lighting and more reported stress.

Table 5.3
Average score (mm VAS) for reported neck pain in the participants with Low and High trapezius muscle blood flow (TBF) during the computer work conditions overall.

Symptom	Condition	p-value	t	Low TBF (n = 15)	High TBF (n = 17)
Neck pain	**LS**	.083	-1.79	8.0 ± 2.6	18.6 ± 3.9
	VS	.008	-2.85	7.1 ± 3.7	19.2 ± 4.0*
	PS	.037	-2.18	5.8 ± 2.8	16.3 ± 4.6*
	VPS	.011	-2.70	7.7 ± 3.0	21.3 ± 3.8*

LS = low stress, VS = visual stress, PS = psychological stress, VPS = visual and psychological stress.
Results are given as mean mm VAS ± SEM.
*Statistically significant difference between the groups at $p < 0.05$.
Please see Methods in the current thesis and paper III for more information regarding the TBF grouping criteria.

5.4 Additional results

Some results from the two projects, not included in the papers of this thesis, are presented separately in the section below.

Project 1

Neck pain in relation to visual discomfort and eyestrain

As noted, project 2 (paper III) revealed significant correlations between neck pain and eye and visual symptoms. Table 5.4 shows that there were also associations between eye and visual symptoms and neck pain in project 1 (paper I). Correlations were present in conditions with both optimal lighting and glare. However, there was a tendency for more numerous and stronger correlations during the glare conditions.

Table 5.4
Summary of correlations between neck pain and eye-related symptoms in the optimal and glare conditions, after 30 min of computer work (30) and in the recovery rest session after computer work (RR).

	Neck pain, optimal		Neck pain, glare	
	30	RR	30	RR
Eye-related tiredness	.026	.322	.195	.548*
Eye-related pain	.301	.504(*)	.372	.509(*)
Dry eyes	.382	.408	.302	.638*
Blurry vision	.562*	.521*	.811**	.722**
Photophobia	.221	.213	.319	.530*
Headache	.359	.248	.663**	.603*

Results are presented as Spearman's rank correlation coefficients, ρ. (n = 15). */** Statistically significant correlation at $p < 0.05$ and 0.01, respectively. (*) Borderline but not statistically significant correlation ($p \leq .060$). The symptoms dry eyes, blurry vision, photophobia and headache were not measured in RR, and therefore the measure point '30' was used in both analysis.

Project 2

Perceived lighting

Figure 5.5 shows that there were between-individual differences in how participants perceived the lighting in project 2 (papers II and III) while working, both with and without glare exposure. Overall, however, they experienced the lighting as significantly more unpleasant in VS and VPS with the glare source turned on, as presented in the papers. This supports previous literature that points towards the existence of subjective differences regarding the experience of lighting and glare (Bargary et al. 2015; Berman et al. 1994; Karlsen et al. 2015; Stone and Harker 1973).

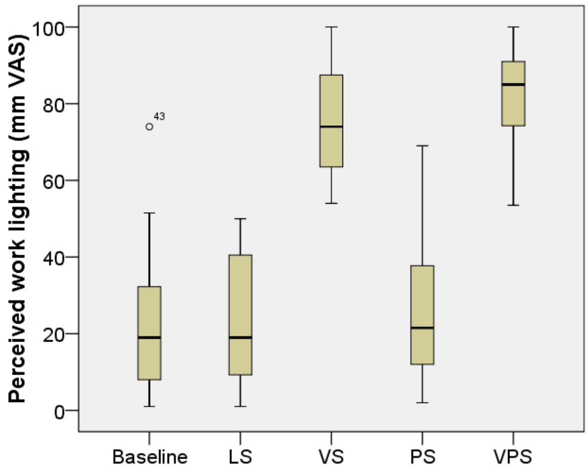


Figure 5.5
Boxplot showing the spread of how participants perceived the workstation lighting during baseline (before start of the experiment) and during all computer work sessions. LS = low stress, VS = visual stress, PS = psychological stress, VPS = visual and psychological stress. The scores are given as mm VAS, n = 43. Score of 0 means that the participants perceived the workstation lighting as very comfortable, whereas 100 represent very unpleasant.

Fixation disparity change and discomfort glare

There were no associations between average measured FD and symptoms in paper III. However, to elucidate further how variation in FD (please refer to FD_{change} in paper II and the Methods section in the current thesis) affected subjective measurements in paper III, the participants were divided into two subgroups regarding change in FD_{change} observed in the four conditions.

Table 5.5 shows the subgroup scores for perceived ambient lighting and reported photophobia. The participants with greatest FD_{change} reported more photosensitivity and perceived the lighting as more unpleasant in the glare conditions, indicating that they were more affected by glare compared to those with less FD_{change}. These results should be interpreted with caution given the small size of the subgroups applied in this particular analysis (see also 'Methodological issues').

Table 5.5
Mean scores (mm VAS) for perceived lighting and photophobia for participants with no or little change in fixation disparity (FD_{change}) relative to baseline (*No FD change*, n = 12), and for participants with the greatest FD_{change} (*Changed FD*, n = 8).

Mood/experience	Condition	p-value	t	No FD change	Changed FD
Perceived lighting	**LS**	.540	-0.62	20.8 ± 5.2	27.2 ± 9.1
	VS	.004	-3.26	53.6 ± 5.4	78.1 ± 5.6*
	PS	.719	-0.37	29.4 ± 8.5	21.4 ± 4.8
	VPS	.171	-1.53	53.3 ± 6.5	69.6 ± 7.4
Photophobia	**LS**	.128	-1.56	3.5 ± 2.8	6.3 ± 2.4
	VS	.000	-5.30	8.0 ± 4.4	34.7 ± 5.1*
	PS	.164	-1.16	3.7 ± 2.9	6.9 ± 3.0
	VPS	.025	-2.66	9.5 ± 4.7	23.0 ± 6.6*

LS = low stress, VS = visual stress, PS = psychological stress, VPS = visual and psychological stress. Results are given as mean mm VAS ± SEM. * Statistically significant difference between the groups at $p < 0.05$.

6. General discussion

The current thesis explored how young, healthy subjects with normal binocular vision were affected by direct glare during computer work, and investigated possible functional interactions between the visual system (eyes) and the musculoskeletal system (neck) during such visual demanding conditions. This is one of the first studies, as known by the author, conducted to explore how glare exposure during computer work affects skeletal muscles and symptom development in the neck area.

The results revealed that glare during computer work gave rise to increased trapezius muscle blood flow (TBF) and eyelid squinting (enhanced contraction of the orbicularis oculi muscle), as well as increased eyestrain, blink rate, and head flexion compared to computer work with optimal lighting conditions. Additionally, glare exposure made the participants feel more uncomfortable and perceive the workstation lighting more unpleasant compared to working with appropriate lighting. During glare, correlations between poorer perceived workstation lighting and higher levels of perceived stress were also observed.

The research identified a potential functional interaction between the visual and the musculoskeletal systems during glare, as glare exposure affected the neck muscle trapezius and resulted in increased TBF. The TBF response could not be explained solely by changes in posture and was seemingly induced by different mechanisms than those active during exposure to psychological stress. The increase in TBF may have been influenced by an increased demand for gaze stabilization and/or a centrally mediated alertness response due to the excessive light exposure onto the retina, resulting in a vasodilation response in trapezius.

The suggested eye-neck interaction during glare may further be reflected in the observed positive associations between eyelid squinting, TBF, and neck pain. Increased eyelid squinting was proposed to reflect increased discomfort glare and annoyance among the participants, and the correlations suggested intersubjective differences in glare sensitivity and discomfort. Accordingly, glare exposure caused a more pronounced eyelid squinting response and apparently affected TBF and neck pain more in the most glare-sensitive participants.

Additionally to the responses observed during glare, the orbicularis oculi muscle appeared to be activated during computer work as such. This eyelid squinting response, along with alternation in posture by leaning forward towards the computer screen, seemed to be characteristics involved in an attention response during computer work.

In the following sections, the findings from the current thesis are discussed in order to connect results from the three separate papers into a larger context. The discussion will be organized in three subchapters, based on the three objectives in the thesis: 'Responses due to direct glare during computer work' (6.1), 'Interactions between the visual system and the musculoskeletal system' (6.2), and 'The trapezius muscle and neck pain' (6.3). The discussion focus on the observed glare effects and possible eye-neck interactions during glare from project 1 and 2, whereas responses observed due to psychological stress exposure are included in the discussion whenever appropriate in order to provide a better understanding of the glare responses. Methodological issues of the implemented experiments are outlined in a separate section (6.4). Please see the enclosed papers for in-depth discussions regarding each paper.

6.1 Responses due to direct glare during computer work

The results from this thesis revealed that glare exposure during computer work, compared to working with optimal lighting conditions, caused significant main effects on these variables: increased eyelid squinting, increased eyestrain, increased blink rate, increased trapezius muscle blood flow, increased head flexion, more unpleasant perceived workstation lighting, and feeling more uncomfortable. Additionally, the results revealed significant positive associations between perceived workstation lighting and stress while working with glare.

The finding of increased TBF due to glare will be discussed both as a main effect of glare in the following and as a potential eye-neck interaction (6.2). Additionally, some of the findings (head flexion, perceived workstation lighting, feeling uncomfortable, and the associations between perceived lighting and stress) are not discussed separately in this section, but will rather be discussed in the context of other main results and/or in subchapter 6.2.

Glare in an evolutionary perspective

Humans have at all times been exposed to glare conditions, as by direct glare from the sun or by reflections from the water or other glossy surfaces. Therefore, glare as such cannot be considered evolutionarily novel from an evolutionary perspective (Fostervold et al. 2014). The visual system has evolved several adaptations intended to reduce the negative impacts of glare. These adaptations aim to reduce retinal illumination and include the anatomical shape of the human face with the eyes placed within the orbital cavity, reduction in pupil size (Ellis 1981; Hopkinson 1956; Lin et al. 2015), increased eyelid squinting and blink rate (Gowrisankaran et al. 2007; Nahar et al. 2007; Sheedy et al. 2003b), as well as behavioural countermeasures like changing posture, looking away, or shielding the eyes from the bright light source (Boyce 2014). In ordinary environmental settings, these adaptations and countermeasures often eliminate, or at least substantially reduce, the effect of glare. In line with this, some of the observed responses during glare exposure in this thesis, for instance increased eyelid squinting, flexion of the head, and increased blink rate, might be considered as adaptations performed by the participants, trying to cope with the visual demanding computer work environment they were exposed to during the glare conditions.

However, the common glare adaptations and countermeasures may not suffice in such modern computer environments in the same way as in other settings. Postures with high gaze angles (i.e., small angles relative to the horizontal plane) during computer work increase the risk of potential glare sources within the peripheral visual field. This in combination with reduced opportunities of changing posture during the static and intensive near work, make computer workers highly susceptible to glare exposure. Thus, glare during computer work may indeed be considered evolutionarily novel, as human adaptions to cope with this relatively new environment are not satisfactory. According to the evolutionary stress model, continuing computer work with simultaneously glare exposure using insufficient adaptations to cope with the environment, may thus initiate increased load, and lead to complaints and negative consequences for computer workers (Fostervold et al. 2014).

6.1.1 Increased eyelid squinting

The results revealed significant increased eyelid squinting during glare exposure compared to optimal lighting, supporting previous studies reporting enhanced eyelid squinting due to glare conditions (Gowrisankaran et al. 2007; Nahar et al. 2007; Sheedy et al. 2003b). Increased eyelid squinting is seen as a functional adaptation to glare, by resulting in decreased amount of light from the superior visual field entering the eyes (Sheedy et al. 2003b), and the eyelid squinting response was probably an attempt among the participants trying to reduce the retinal illumination while working with glare.

Moreover, eyelid squinting has also been reported to be strongly related to how uncomfortable subjects feel during glare and has previously been proposed as an objective measure for discomfort glare (Berman et al. 1994; Murray et al. 2002). Glare is known to be distracting and to induce annoyance and discomfort among computer workers (Boyce 2014), and Berman et al. (1994) suggested that the sensation of discomfort glare may give rise to an aversion response in humans that appears as an involuntary contraction of the muscles around the eyes. In line with this, the increased eyelid squinting among the participants in the current thesis may thus, in addition to a response to decrease incoming light rays into the eyes, reflect an increased feeling of discomfort glare. The eyelid squinting during glare was also accompanied by significantly more reporting of being uncomfortable and the workstation lighting to be significantly more unpleasant compared to working under optimal lighting, supporting this view.

It should be noted that less severe glare conditions than those used in this thesis have previously been reported to affect perceived discomfort and unpleasant lighting (Karlsen et al. 2015; Lin et al. 2015; Osterhaus and Bailey 1992). In the current thesis, the luminance of the visual object (computer screen) was 155 cd/m^2, whereas the luminance of the glare source placed behind the computer screen was above 4500 cd/m^2. Studies have reported that subjects prefer surrounding luminance to be slightly below the luminance of the visual object (Sheedy et al. 2005), and ambient luminance above 600 cd/m^2 has previously been rated as disturbing (Berman et al. 1994). This support the premise that the glare source in the present thesis provoked discomfort glare among the participants, and possibly that the eyelid squinting response objectively reflect this induced discomfort. Accordingly, the self-reported state mood uncomfortable may seem to be related to the sensation of discomfort glare during computer work, reflecting annoyance and distraction caused by the excessive light exposure while working.

6.1.2 Increased eyestrain

Computer work with exposure to glare resulted in increased eyestrain compared to working without glare in both projects (paper I and III). Inadequate visual conditions like glare are also by others considered to cause visual discomfort and contribute to aggravation of eyestrain symptoms (Blehm et al. 2005; Boyce 2014; Gowrisankaran and Sheedy 2015; Helland et al. 2008). For the glare-induced symptoms eye pain, eye-related tiredness, total eye symptoms, and photophobia, the increase in symptom score from rest before to after computer work was between 10 and 15 mm VAS, which is considered to be a clinically significant difference (Kelly 2001; Ostelo et al. 2008). The other symptoms significantly affected by glare increased with less than 10 mm VAS and may thus not be clinically significant. However, compared to actual computer workers, the participants worked for short periods, and eyestrain development would likely be more pronounced with the inclusion of computer work with longer duration, as previously shown (Strøm et al. 2009a; Thorud et al. 2012).

The underlying cause for increased eyestrain due to glare exposure, however, is not clear from the results in the current thesis. High visual demands and increased load on intra- and extraocular muscles, are assumed to be involved in the development of eye symptoms (Bruenech and Kjellevold Haugen 2007; Sheedy et al. 2003a; Zetterberg et al. 2017). Furthermore, glare conditions have been reported to put extra load on the visual system and thus affect accommodation (Shahnavaz and Hedman 1984; Wolska and Switula 1999), binocular coordination (Glimne et al. 2013; Glimne and Österman 2019), eye movements (Glimne et al. 2015; Lin et al. 2015), and the iris muscle's regulation of pupil size (Ellis 1981; Hopkinson 1956; Lin et al. 2015). Among others, some possible involved factors in the glare-induced eyestrain and discomfort under glare conditions may be: involvement of the orbicularis oculi muscle, automatic pupil size regulation, or involvement of the extraocular muscles, as outlined below.

Involvement of the orbicularis oculi muscle

In this thesis, the participants exhibited significantly higher muscle activity in the orbicularis oculi muscle (eyelid squinting) during glare exposure. Additionally, a borderline significant increased orbicularis oculi muscle blood flow was observed in paper I, also indicating a possible glare response in the orbicularis muscle simultaneously with eyelid squinting. The involvement of orbicularis oculi in eye symptom development has been suggested previously by others (Berman et al. 1994; Gowrisankaran et al. 2007; Murray et al. 2002; Thorud et al. 2012; Yamin Garretón et al. 2015). Thorud et al. (2012) measured orbicularis oculi muscle blood flow and muscle activity during two visual demanding computer work sessions (one-hour) with exposure to glare and small font letters. Significant positive correlations were observed between orbicularis oculi muscle activity and the symptom eye-related tiredness, and between orbicularis oculi muscle blood flow and eye-related pain, indicating that eyestrain during visually demanding computer work might be related to the orbicularis oculi muscle. Furthermore, Yamin Garretón et al. (2015) reported that reduced degree of eye opening, due to eyelid squinting, was a good predictor of visual discomfort under glare conditions.

Continuous glare conditions during computer work will possibly result in prolonged muscle contraction of the orbicularis muscle due to eyelid squinting intended to reduce incoming light from the glare source and/or reflecting an annoyance response. In line with this, the orbital part of the orbicularis oculi muscle responsible for performing the eyelid squinting consists of a low composition of slow-twitch muscle fibres (Cattaneo and Pavesi 2014; Freilinger et al. 1990), the most appropriate muscle fibres for static and prolonged muscle work. With this in mind, it may be supposed that sustained and static eyelid squinting may be involved in muscle fatigue and possible increased eye symptom development in this thesis and other studies. However, no significant associations were found between the orbicularis oculi muscle and eyestrain development in the current research.

Based on the borderline significant increased orbicularis oculi muscle blood flow in paper I, as well as studies reporting stress-induced muscle blood flow responses in other facial muscles (Hidaka et al. 2004; Nilsen et al. 2007; Tsai et al. 2002), a hypothesis that glare affect orbicularis oculi muscle blood flow was formulated ahead of project 2. However, no effect of glare on orbicularis oculi muscle blood flow was revealed in that project. The small number of participants with complete orbicularis oculi blood flow data and the short exposure duration of ten minutes may have had an influence, and further studies are needed to clarify whether or not orbicularis blood flow is affected by glare exposure and consequently involved in eyestrain development.

However, the results in paper II revealed that while working with glare, the participant's chosen posture/viewing distance affected the orbicularis oculi muscle blood flow;

bending forward towards the screen, and hence the glare source, was associated with increased muscle blood flow. This may indicate that a shorter distance to the glare source resulted in a stronger eyelid squinting response and thus increased muscle blood flow in the orbicularis oculi, due to higher retinal illumination and/or as an escalated annoyance response to glare.

Regarding viewing distance, the finding that the participants were significantly more productive when leaning forward, may further reflect that leaning forward towards the screen may be part of an attention or concentration response. A plausible explanation for this is that mental work/demanding concentration tasks induce a more forward bent position to increase proximity to the visual object of interest. However, this finding was observed independent of glare exposure, during computer work as such.

Pupil size

In this thesis, the computer work in both projects involved a reading task, and reading is shown to be both visually and cognitively demanding (Orchard and Stern 1991). In project 2, psychological stress exposure was also included. Regarding these exposures, mental workload and stress is known to increase pupil size by sympathetic activation of the autonomic nervous system through non-photic pupil effects (Laeng et al. 2012; van der Wel and van Steenbergen 2018), whereas glare exposure results in decreased pupil size by the means of parasympathetic stimulation through the pupillary light reflex (Loewenfeld 1993). Dual exposure, as simultaneously reading/psychological stress and glare in this thesis, may thus be assumed to influence the iris muscle and pupil size regulation with opposite actions (dilation and constriction). In line with this, it is reported that the pupillary light reflex is responsive to varying cognitive loads, and that descending cortical stimuli may inhibit the activity of the motor centre for the pupillary sphincter muscles in the Edinger-Westphal complex of the midbrain during cognitive demands (Steinhauer et al. 2000).

The iris muscle, responsible for regulating the pupil diameter, is known to contain many free sensory nerve endings thought to be involved in iridomotor-induced visual discomfort. Previous studies have suggested that muscles regulating pupil size, may contribute to the development of eyestrain and discomfort during glare exposure (Fry and King 1975; Hamedani et al. 2019; Hopkinson 1956; Lin et al. 2015; Nakamura 1997; Stringham et al. 2011; Yamin Garretón et al. 2015). In the review of Hamedani et al. (2019)

looking into physiological responses connected to visual discomfort during glare exposure, relative pupil size was concluded as a very promising involved factor related to glare-induced visual discomfort, whereas the absolute pupil diameter are considered an insignificant factor in this regard. Further, the involvement of pupillary unrest was defined as uncertain.

A possible involvement of muscles responsible for pupil size regulation in eyestrain development due to glare and/or dual exposure in this thesis are not possibly to state, as neither pupil diameter nor pupillary unrest was measured in this thesis. Future studies are needed to determine whether, and optionally how, the iridomotor system as such and possible contrary effects on the pupil size regulation with dual demands, is involved in glare-induced eyestrain development during computer work.

Extraocular muscles

Increased load on the extraocular muscles during sustained near computer work and glare might also be an involved factor in the observed eyestrain development in the present thesis. During sustained convergence actions in near work, the rectus medius muscles work at their outer limit in order to direct both eyes towards the visual object at close distance. Moreover, glare are reported to affect eye movements even in young subjects with normal vision (Glimne et al. 2015; Lin et al. 2015), and it is likely that altered eye movement patterns will increase the demands put on the visual system and the extraocular muscles to stabilize the retinal image while working. As Bruenech and Kjellevold Haugen (2007) found nociceptors in the rectus muscles, the involvement of extraocular muscle contractions in creating eyestrain during glare cannot be excluded.

In line with this, only 20% of the muscle fibres in the extraocular muscles are of the type multiply innervated small muscle fibres (MIFs) (Bruenech et al. 2012). These muscle fibres are primarily responsible for a person's ability to maintain stable fixation and to perform smooth pursuit eye movements, and thus used for prolonged convergence such as during computer work. In an evolutionary perspective, this, together with the distribution of muscle fibres in the orbicularis oculi muscle as discussed previously, reveals that there exists a deviation between species-specific evolutionary adaptations in muscle fibres distribution for muscles used at close distance and during glare, and the demands put on the worker in the modern office environment (Fostervold et al. 2014). It may be reasonable to assume that amplified requirement for eye stabilization during glare conditions may be a factor involved in the observed development of eyestrain in the current thesis. However, this possible involvement needs further investigation.

In view of the significantly elevated eyestrain among participants during computer work with glare exposure in the current research, this points to the importance of ensuring optimal lighting during computer work in order to minimize visual stress and discomfort among computer workers.

6.1.3 Increased blink rate

In paper II, a significantly increased blink rate was observed during computer work with glare exposure. Glare are also previously reported to cause elevated blink rates (Gowrisankaran et al. 2007; Nahar et al. 2007) and is understood as an indication of ocular fatigue or discomfort (Kaneko and Sakamoto 2001; Rodriguez et al. 2018; Stern et al. 1994). This suggests that the increased blink rate observed in this thesis may reflect an increased reflex blinking due to the external demands and additional stress put on the visual system by glare and hence visual fatigue/discomfort.

By contrast to elevated blink rate due to glare, decreased blink frequency have been related to tasks involving concentrated attention and stress, such as computer use, reading, and cognitive load (Chu et al. 2014; Gowrisankaran et al. 2012; Helland et al. 2008; Nielsen et al. 2008; Rodriguez et al. 2018; Wolkoff 2008). In the two conditions were blink rate was counted in project 2 in this thesis, videotaping was one of the induced psychological stressors, and the blink rate was analysed from these videos. Therefore, both the 'control condition' without glare (PS) and the 'glare condition' (VPS) included psychological stress exposure. The blink rate during glare averaged 13 blinks per minute. Comparably, the mean blink rate during 'easy conversation' has by others been reported to be 21-22 blinks per minute, whereas it is reported to be 7–10 blinks per minute during computer work (Helland et al. 2008; Tsubota and Nakamori 1993). Additionally, during computer reading with comparable glare exposure (5500 cd/m^2) as used in this thesis, blink rate was reported at 16–17 blinks per minute (Nahar et al. 2007). In the current thesis, the psychological stress may have resulted in less frequent blinks than reported in other glare studies, whereas the glare may have triggered more frequent blinks than reported in other studies investigating computer work and psychological stress. Rodriguez et al. (2018) point out that blinking is a complex phenomenon that is affected by several endogenous and exogenous factors. Blink rate provides information of the ocular surface health, the cognitive state and alertness, and the fatigue level of the subjects. Nevertheless, despite the small blink rate differences between the two experimental conditions in this thesis, the result was significant, and support the notion that glare induce an increased blink rate, even with simultaneous exposure to psychological demands.

The increased blink rate due to glare compared to non-glare may reflect an adaptation response in an evolutionary perspective. As noted, the blink rates were overall lower than previously reported during relaxed conditions (Helland et al. 2008). Reduced blink rate during computer work may seem appropriate from an evolutionary viewpoint (Fostervold et al. 2014), as suppression of blink rate may be an adaptive mechanism to optimize processing of visual input (Rodriguez et al. 2018). Thus, during near attention and concentration tasks like computer work, a reduced number of blinks may be seen as an adaptation to maintain focus for shorter periods. However, during prolonged and intensive near work with decreased blink frequency, the environment exceeds the parameters for which the human visual system is adapted. Sustained efforts to cope with conditions like computer work by employing a decreased blink rate may lead to alterations in the precorneal tear film and hence dry eyes (Nielsen et al. 2008; Rodriguez et al. 2018; Wolkoff 2008; Wolkoff et al. 2005), and this may contribute to eyestrain and other symptoms experienced during computer work (Rosenfield 2011; Wolkoff et al. 2005). Furthermore, dry eye development and an unstable tear film may increase scattering light into the eyes, contribute to reduced retinal contrast, and may increase the risk of disability glare (Huang et al. 2002; Puell et al. 2006). The increased blink rate during glare exposure in this thesis may therefore reflect an adaptive response in the visual system intended to regenerate the tear film and prevent dry eye conditions as human vision is dependent on maintaining sharp, single images on the retina. In line with this, dry eye development due to glare was observed in project 1 in the current thesis, but in project 2, where blink rates were measured, no dry eye symptoms were indicated during the glare conditions.

6.1.4 Increased trapezius muscle blood flow

One of the main findings in this thesis was that glare exposure was shown to affect the muscle blood flow in the neck muscle trapezius in two separate experiments. In both paper I and II, a TBF increase was observed when the participants were exposed to glare during computer work, compared to during computer work with appropriate lighting.

In paper I, the TBF measurements were performed on the in-active trapezius muscle, and the task was a passive reading task instead of a more active computer task. This approach in project 1 was chosen in order to investigate the effect of glare exposure on the trapezius muscle as separate as possible. As skeletal muscle tension and circulation are related (Sarelius and Pohl 2010), minimizing the active use of the measured trapezius muscle throughout the experiment would reduce affection of the muscle blood flow data due to muscle contraction. In paper II, the increased TBF due to glare was replicated, in a more active and occupational-like computer task, measuring TBF on the active trapezius muscle. Both projects included in this thesis also made special efforts to maintain strict control as to visual anomalies and posture, parameters that may have implications for symptom development and increased muscle activity (Aaras et al. 1997; Aaras et al. 1988; Rosenfield 2011). Accordingly, several potential sources of error were excluded, and the results implies the presence of a specific visual stress response due to glare, were glare exposure can be stated as a likely factor involved in the observed TBF rise during computer work in the current thesis.

Previous studies have investigated TBF responses in different experimental and occupational settings, as outlined in the background (Elvin et al. 2006; Gold et al. 2017; Hallman et al. 2011; Larsson et al. 1993; Larsson et al. 1995; Rosendal et al. 2004; Røe and Knardahl 2002; Sandberg et al. 2005a; Sjogaard et al. 1986; Sjogaard et al. 2010; Strøm et al. 2009a; Strøm et al. 2009b). However, this is the first time, to the author's knowledge, that TBF has been studied during computer work with glare exposure. In paper I, the TBF increased significantly with 30%–40% relative to baseline in the 30 minute reading condition with glare, whereas in paper II the TBF steadily increased to about 30% above baseline throughout the 10 minute proofreading tasks with exposure to glare. This shows a relatively stable blood flow increase, and that the responses on the active and passive sides were similar. The muscle blood flow response also seemed to be insignificantly affected by the psychological stress as the TBF response was similar in the condition with only glare (VS) and in that with dual stress (VPS). Furthermore, there were no similarities in other responses during glare and psychological stress exposure. This suggests that these two occupational stressors, glare and physiological stress, may have different underlying mechanisms and provoke dissimilar stress responses during computer work.

Compared to other studies performed on healthy subjects during computer work only, it is plausible to assume that TBF would be higher in this study, since glare exposure was added to the computer task. However, Strøm et al. (2009a) investigated TBF in healthy, pain-free subjects, during a 90-minute computer task without glare but with psychological stressors, like precision demands and time pressure. Significant increases in TBF relative to baseline on both the active and passive trapezius were reported, with a considerably higher blood flow increase in the active shoulder (70%–120% above baseline during the initial 30 minutes) compared to in this thesis. The dissimilarities in TBF between this thesis and the study of Strøm and co-workers may be related to that the study design, measures, and induced exposures differed. Furthermore, Strøm et al. (2009a) did not control the participants' working posture or visual status, both of which may influence neck load (Aaras et al. 1988; Lie et al. 2000; Mork and Westgaard 2007; Rosenfield 2011; Sánchez-González et al. 2018) and possibly TBF.

The finding of increased TBF caused by glare exposure, as outlined above, may indicate a potential interaction between the visual system and the musculoskeletal system during exposure to such visual stress. Further discussion of possible underlying mechanisms will be presented in the following subchapter.

6.2 Interactions between the visual system and the musculoskeletal system

From the results in the current thesis, a possible interaction between the eyes and the neck area was suggested. This interaction was observed as the significant rise in trapezius muscle blood flow during computer work with glare exposure (paper I and II), and further reflected in the positive correlations between eyelid squinting, TBF, and neck pain in paper I. The glare-induced increase in TBF suggested an effect of glare on the neck area during visual stressing conditions, whereas the observed correlations may reflect the involvement of intersubjective differences in glare discomfort, where the most glare-sensitive subjects exhibited a stronger eyelid squinting response, and accordingly more pronounced TBF and neck pain.

In the following section, the two results regarding the possible interaction between the visual and the musculoskeletal systems; 'Glare exposure and increased trapezius muscle blood flow' and 'Eyelid squinting, trapezius muscle blood flow, and neck pain', will be discussed in separate sections. Additionally, relations between eye-related symptoms and neck pain will be discussed.

6.2.1 Glare exposure and increased trapezius muscle blood flow

Glare exposure is potentially detrimental for functional vision and specific responses to glare was therefore expected. As the underlying functional and neurological mechanisms is still unclear, it was difficult to state the exact cause for the observed blood flow response in trapezius, and also whether or not it represented a direct interaction between the visual system and the musculoskeletal system. However, some underlying mechanisms could be involved in the TBF increase and thus the possible eye-neck interaction due to glare, and some possible explanations are outlined below.

Postural changes

One possible explanation for the increased TBF was that glare induced alterations in the participants' posture in order to avoid or at least reduce the excessive light exposure (Boyce 2014; Ko et al. 2014). In this thesis, the subjects' sitting position was continuously registered through all work sessions, and the results showed no significant differences in postural angles between the glare and non-glare conditions in paper I. In paper II, however, glare did induce a significantly forward-bent posture of the head, likely reflecting an attempt to avoid excessive light entering the retina. The glare source used was large (resembling a window) and placed directly in front of the participants, exposing them to light both from above, directly ahead, and below. Eyelid squinting has been shown to be beneficial under glare conditions in reducing the amount of environmental light entering the eyes, primarily from overhead light sources (Sheedy et al. 2003b). With exposure to glare covering a large part of the visual field, as was the case in this thesis, the eyelid squint response did probably not suffice to heavily reduce excessive light from entering the retina. Head flexion may therefore be seen as a compensatory mechanism or adaptation performed during glare conditions as an attempt to further reduce retinal illumination while working.

However, the notion of posture as the *main* reason for the observed blood flow increase in trapezius is questionable. As mentioned, the same significant head flexion response as detected during glare exposure in paper II, was not shown in paper I. Furthermore, in paper II, it was also observed increased head flexion during exposure to psychological stress, but this head flexion response was not accompanied by a simultaneously increased

TBF like during glare exposure, indicating that head flexion as such may not fully explain the observed muscle blood flow increase during computer work with glare. Additionally, the registered back angles in paper II tended to be in the opposite direction in the two conditions with exposure to glare: the participants were leaning backwards during the condition with glare only (VS), whereas they were leaning forwards during the condition with simultaneous exposure to glare and psychological stress (VPS). This further supports the notion that posture adaptations cannot be the main reason for the observed TBF increase. Moreover, the differences in postural angles between the different conditions were small (< 5 degrees), and there were no significant associations between TBF and any of the measured postural angles in any of the projects.

Furthermore, if postural load were involved in the increased TBF during glare, a change in trapezius muscle activity would also be expected (Aaras et al. 1988; Ng et al. 2014). However, no glare-induced increase in muscle activity was observed. Additionally, trapezius muscle activity was low throughout the experiments, and no significant correlations between muscle activity and muscle blood flow data were found. It is therefore unlikely that either posture or a locally mediated vasodilation effect due to muscle contraction fully account for the increase in TBF during glare exposure observed in this thesis.

Increased gaze stabilization

The observed link between glare and increased TBF may also have occurred due to that the glare exposure induced an excessive need for gaze stabilization among the participants during the computer tasks. The eyes and the neck area are, as previously outlined, shown to be closely connected, and this indicates an important role of neck muscles in normal visual performance.

Earlier studies have reported interactions between myogenic activity in the smooth ciliary muscle of the eye (accommodation), the oculomotor muscles, and cross-striated neck muscles, like the trapezius (Richter et al. 2010; Richter and Forsman 2011; Zetterberg et al. 2013). From this, extra need for gaze stabilization has been suggested as a possible cause for why the neck muscles are affected during visually demanding conditions. This notion involves neural commands between sustained accommodation when fixating on a near target and postural muscles in the neck area, which is activated in order to stabilize the gaze, and thus the picture on the retina. In line with this, Richter

(2014) also suggested that the higher visual demands and oculomotor load, the higher activation of the postural neck muscles may be induced.

In line with a proposed gaze stabilization response in this thesis, it is shown that in a standing position, young adults demonstrate significantly lower amplitude of body movement under precise and challenging visual tasks (e.g. difficult searching task) than under easier visual tasks, like free viewing (Bonnet and Baudry 2016; Bonnet et al. 2017). This indicates that the more difficult an active visual task is, the better the postural control in human becomes and indicate a functional synergy between the visual and postural processes. Accordingly, visual demands will increase the need for skeletal muscle activation to stabilize and maintain a posture with less sway. It is plausible to assume that by adding glare to the already visual demanding computer task, like in the current thesis, additional demands is placed on the visual system, and hence possibly an increased need for postural neck muscle activation. In line with this, it is shown that glare and excessive stray light onto the retina may lead to reduced contrast sensitivity, altered visibility, and blurred vision (Fry and Alpern 1953; Mainster and Turner 2012; Maniglia et al. 2018). Both blur and excessive light exposure has also previously been reported to affect eye-lens accommodation (Kruger and Pola 1986; Shahnavaz and Hedman 1984; Wolska and Switula 1999), and glare exposure are shown to affect both eye movements and binocular coordination (Glimne et al. 2015; Glimne et al. 2013; Glimne and Österman 2019; Lin et al. 2015). Accordingly, the results of Bonnet and co-workers indicate that increased visual demands due to glare exposure may result in a greater need for head and neck stabilization, possibly involved in the interaction observed between glare and TBF in the current thesis.

However, it should be mentioned that the neuromuscular basis for head and eye-movements is yet not fully explored. Pertinent literature advocates that pools of neurons in premotor supra-nuclear structures, such as in the reticular formation, cerebellum, and various cortical regions, is influenced by proprioception from head/neck muscles as well as from extra-retinal information from extraocular muscles and their adnexa (Brodal 1982; Gandhi et al. 2008; Xing and Andersen 2000). It is also shown that proprioceptive information from ocular and craniofacial muscles may influence somatic motor activity, and vice versa (Biguer et al. 1982; Bizzi et al. 1971; Bruenech et al. 2012; Han and Lennerstrand 1995; Han and Lennerstrand 1998; Ischebeck et al. 2016; Ischebeck et al. 2018; King 2013). By suggesting a gaze stabilization response due to glare exposure, the current thesis promotes the view that it cannot be dismissed that increased tonus and muscle activity in one set of muscles, may influence the others.

However, no effect of glare exposure on trapezius muscle activity was observed in this thesis, in contrast to other studies that examined gaze stabilization responses due to other visual stress situations. Those studies have largely examined the associations between accommodation–convergence demands and trapezius muscle activity (Lie and Watten 1987; Richter et al. 2010; Richter and Forsman 2011; Zetterberg et al. 2013). Differences in study design may explain the discrepancies, and the previous studies did not include TBF measurements. Additionally, the trapezius muscle activity data in this thesis might be too low due to the calibration procedure and the possibility for masking potential effects cannot be excluded (see 'Methodological issues'). Consequently, gaze stabilization cannot be completely left out as a possibly involved mechanism for the increased TBF due to glare in the current thesis. However, to verify this, further research is needed to determine if visual stress, induced as glare, boosts the need for stabilization of gaze and affects the trapezius muscle during computer work.

A centrally mediated alertness response

Another possible explanation for increased TBF during glare exposure may be that the glare activated a centrally mediated alertness response through the participants' nervous system. This is previously indicated as an effect due to glare/lighting exposure (Abrahams et al. 1964; Belkić 1986; Belkić et al. 1992; Niijima et al. 1992; Noseda et al. 2017; Saito et al. 1996; Smolders et al. 2015; Smolders et al. 2012). It is known that the optic nerve in humans leads visual input directly into important cortical regions regulating autonomic responses, such as to the hypothalamus (Noseda et al. 2017; Royet et al. 2000). Moreover, vasodilation has been proposed to occur early during the alerting response, and both exposure to flash of light, direct electrical stimulation of the hypothalamus, and activation of the sympathetic nervous system are all reported to affect circulation in skeletal muscles by inducing vasodilation (Abrahams et al. 1964; Shoemaker et al. 2016).

In the current research, the TBF increase was caused by glare exposure to an equivalent of approximately 13,000 lux, horizontal at eye level. This suggests that the visual stress exposure in the present research was even more pronounced than in other studies indicating increased alertness and sympathetic activation due to light exposure (Niijima et al. 1993; Niijima et al. 1992; Saito et al. 1996; Smolders et al. 2015; Smolders et al.

2012). Niijima et al. (1992) reported increased sympathetic activity due to monocular bright light exposure of 2000 lux for 10 minutes, but also that the effect was eliminated after bilateral destruction of the SCN of the hypothalamus. This further implies that the increased TBF observed in the present thesis during the glare conditions may occur due to activation of the participants' autonomic nervous system, possibly involving the hypothalamus and SCN. In view of that, a centrally mediated alertness response seemed reasonable as a possible involved factor for the reported trapezius blood flow response. According to the routes by which lighting can affect human performance described by Boyce (2014), this results suggested a functional interaction between the eyes and the neck that may correspond to a route through the non-image-forming system. The ipRGCs are possibly involved in the process, as they have known functions in the non-image-forming system, with axons converging on hypothalamic neurons (Berson et al. 2002; Chellappa et al. 2017; Noseda et al. 2017; Westland et al. 2017). However, the loss of similarities between the responses observed due to glare and psychological stress, further suggest that the two stressors may have different routes through the nervous system and provoke dissimilar stress responses.

In line with this, in the studies of Bonnet and co-workers (Bonnet and Baudry 2016; Bonnet et al. 2017), postural control was shown to be better while performing visual demanding tasks compared to easy visual tasks and they also reported a significantly higher cognitive workload in the demanding visual tasks. Further, they showed that a greater attentional demand seemed to be involved in observed functional synergies between the visual and postural systems, as significance disappeared when the cognitive workload was controlled for (Bonnet and Baudry 2016; Bonnet et al. 2017). This supports the proposed centrally mediated alertness response in this thesis with involvement of cognitive load in the link between glare and postural neck muscles. Moreover, direct glare during computer work are recently shown to affect cognitive performance in participants with normal binocular vision, where glare of 4000 and 6000 cd/m^2 significantly increased the self-reported mental work load compared to no glare conditions (Glimne and Österman 2019).

Alertness response and cardiovascular responses due to glare

If visual stress, included as glare, activates a central mediated alertness response, a simultaneous cardiovascular response would be reasonable to expect. However, no effect of glare was observed on either heart rate (paper I and II) or blood pressure (paper II) in the current research.

The literature is limited concerning cardiovascular responses due to persistent glare exposure during computer work in healthy humans. However, in the study of Saito et al. (1996), increased muscle sympathetic nerve activity due to excessive light exposure (5000 lux) was accompanied with an increase in heart rate but without any change in blood pressure. In this thesis, the absence of cardiovascular effects indicates that the induced glare exposure during computer work was not sufficient to provoke such responses in young, healthy females, even though the illuminance levels was comparable higher. One possibility for the discrepancy between the two studies could involve the study design and the exposure method. Saito et al. (1996) instructed subjects to gaze directly at a light source for at least five seconds every minute for a total of 20 minutes that led to a high retinal exposure of light during these periods. This may have resulted in a stronger effect on the subjects' autonomic nervous system compared to the experiment in this thesis, where the participants never looked directly at the light source and had another task to focus on throughout the exposure period. In line with this, glare discomfort has previously been shown to be attention and task-dependent (Kent et al. 2019).

In this thesis, exposure to psychological stress did neither cause any cardiovascular responses. The literature is mixed regarding heart rate effects during psychological stress, with some studies showing increased heart rate and others reporting no effect (Hidaka et al. 2004; Iwanaga et al. 2000; Larsson et al. 1995; Nahar et al. 2011; Skoluda et al. 2015). Exposure to a weak and long-lasting mental stressor has previously been reported to induce increased sympathetic nervous activity among females but with no complementary heart rate increase, even though the level was perceived as 'extremely stressful' by the participants (Hidaka et al. 2004). The psychological stress exposure in this thesis resulted in more self-reported stress and negative feelings, and the muscle activity in the trapezius increased initially. Positive correlations between heart rate and perceived stress during psychological stress exposure were also observed, indicating that the participants feeling the most stressed, also had the highest heart rate levels. These findings suggests that the psychological stress exposure in the present thesis did affect the participants, but that it was too weak to provoke significant cardiovascular responses.

Accordingly, the visual stress may also have acted as a weak stressor, not sufficient to provoke cardiovascular responses.

6.2.2 Eyelid squinting, trapezius muscle blood flow, and neck pain

Significant and positive correlations between eyelid squinting and TBF, and between eyelid squinting and neck pain were observed in this thesis during glare exposure. These associations, observed in paper I, pointed to that increased eyelid squinting may result in increased TBF and increased development of neck pain, indicating the presence of an eye-neck interaction.

As eyelid squinting is proposed to be an objective measure of discomfort glare, these correlations may reflect that glare triggered more annoyance and discomfort, and thus led to enhanced eyelid squinting, higher TBF and more neck pain in the most glare-sensitive participants. How employees perceive lighting at work are by others reported to indirectly influence the work engagement through moods (Veitch et al. 2013). Veitch et al. (2008) proposed a linked mechanisms map connecting lighting conditions to appraisal, preference, and mood, which again may affect health, well-being, motivation, and task performance. In line with this, Cohen and Rodriquez (1995) provided a model for how negative affect and moods can influence health outcomes, suggesting a biological pathway with nonspecific responses due to negative emotions and disorders, and this pathway was associated with activation of both the sympathetic nervous system and the HPA axis. Along the same lines, van Eck et al. (1996) reported that even minor events and variations in mood states might be associated with increased cortisol secretion, and suggested that this may reflect a possible mechanism linking subjective experience to health outcomes. Accordingly, the notion that glare may affect discomfort and moods among the participants may therefore be involved in the observed associations between eyelid squinting, TBF and neck pain while working with glare exposure. This further supports the possible view that a central mediated alertness response due to negative affect and moods, such as discomfort and annoyance, may be a possible influencing factor in the observed associations between glare and TBF in this thesis. This may correspond to the mechanism discussed previously (6.2.1) proposing that glare exposure affect TBF by activating alertness and a centrally mediated response through the participants' autonomic nervous system. Accordingly, this may indicate the presence of an interaction between glare (visual stress) and the musculoskeletal system that correspond to the route by which lighting can affect humans and work through emotions and moods, as described by Boyce (2014).

The relation between eyelid squinting, annoyance and discomfort, and neck muscles during computer work with glare have, to the best knowledge of the author, not been previously investigated. Further studies are needed to determine whether stronger contraction of the orbicularis oculi muscle actually is an objective measure for annoyance and discomfort and is involved in the increased TBF and neck pain in glare-sensitive subjects, or whether simply contraction of orbicularis oculi occurs simultaneously with glare exposure, TBF increase and more neck pain during computer work.

Inter-subjective variation in glare discomfort

The negative emotions and moods seemed to affect the participants to various degrees, probably affecting the most glare-sensitive participants differently than the ones more tolerable to glare. That glare exposure affected the participants' negative emotions and moods differently while working was further supported by significant and positive correlations between perceived lighting and stress during glare exposure in paper III, reflecting that the participants experiencing the glare most negatively, also felt most stressed.

In line with this, between-subject variations regarding how unpleasant the participants perceived the workstation lighting was also present in the current thesis (see 'Additional results'), supporting previous studies reporting intersubjective differences in lighting appraisal and glare discomfort (Bargary et al. 2015; Berman et al. 1994; Karlsen et al. 2015; Stone and Harker 1973). Moreover, regarding the presence of intersubjective differences in lighting appraisal, the FD_{change} results also indicated such variation. Participants with the most variable FD (greatest changes in FD during computer work) perceived the workstation lighting poorest and experienced most photophobia while working with glare exposure (see 'Additional results'). A greater FD places a higher demand on the visual system to maintain single vision (Jenkins et al. 1992; Yekta et al. 1987), and the results indicated that the participants who exhibited the greatest change in FD were more sensitive to glare and thus perceived a higher degree of discomfort glare. In line with this, Glimne and co-workers (Glimne et al. 2013; Glimne and Österman 2019) reported that reading with exposure to glare resulted in decreased binocular coordination, observed as increased FD variation. This FD variation induced by glare was further proposed to be an objective measure of visual discomfort and fatigue (Glimne et al. 2013). In this thesis, the change in FD levels from baseline to after computer work was used as a variation measure.

However, it is important to keep in mind that all participants included in the current research had normal binocular vision and that the changes in FD were small and measured in the unit arcmin. Although significant, the small-sized subgroups could lead to statistical bias, and those results should be interpreted with caution (see also «Methodological issues»). Nevertheless, the results pointed towards a possible connection between changed FD and discomfort during glare and cannot be excluded as an aspect affecting vulnerable subjects to experience more discomfort glare and photophobia. Furthermore, since only some of the participants revealed changed FD during the computer work tasks, this might reflect visual factors to be involved in the inter-subjective differences in lighting appraisal during the glare conditions. Further research is needed to determine if and how fine alignments of the binocular vision might be involved in inter-subjective differences in perceiving photophobia and discomfort glare.

Associations without glare exposure

The correlations between eyelid squinting, TBF, and neck pain were present also while working with appropriate work lighting in paper I. In line with this finding, the results also revealed that the orbicularis oculi was activated during computer work as such, both with and without glare exposure.

Eyelid squinting is known, in addition to decrease the amount of light that enters the eyes, to improve visual acuity (Sheedy et al. 2003). In this thesis, all participants had normal vision, and eye squinting during computer work reported may therefore not have been caused by the need for improved visual acuity while working under optimal lighting conditions.

Accordingly, the activation of the orbicularis oculi muscle during the computer work tasks may be explained by increased eyelid squinting reflecting an attention or stress response among the participants, present both with and without glare. Mental stress has previously been reported to activate other facial muscles (Hidaka et al. 2004; Nilsen et al. 2007), and to affect TBF (Larsson et al. 1995), and mental and visual attention is shown to activate the upper trapezius muscle (Hiraoka et al. 2013; Wærsted and Westgaard 1996). If the notion that eyelid squinting may reflect an attention or stress response is correct, the observed correlations between eyelid squinting, TBF, and neck pain in the non-glare conditions may result from increased attention/stress due to the computer tasks and experimental setting as such. In support of this perspective, time effects were observed in the trapezius muscle and heart rate (paper I and II), along with perceived stress and feeling strained (paper III).

However, the associations between eyelid squinting and TBF were in opposite directions during the glare and non-glare conditions. Eyelid squinting was positive correlated to TBF in the glare condition, whereas the correlations were negative in the condition with optimal lighting. These dissimilar associations may be affected by different degrees of gaze stabilization, central mediated alertness and discomfort glare responses due to the presence of visual stress or not.

6.2.3 Eye-related symptoms and neck pain

In connection with the possible interaction between the visual and the musculoskeletal system in this thesis, significant associations were present between eye-related symptoms and neck pain both in project 1 (see 'Additional results') and project 2 (paper III). Such relationship has also been reported previously (Hayes et al. 2007; Helland et al. 2008; Richter et al. 2011b; Treleaven and Takasaki 2014; Wiholm et al. 2007; Zetterberg et al. 2017), indicating co-occurring symptom development in the eyes and the neck region. In this thesis, eye-neck correlations were present both with and without glare, suggesting symptom associations that are present during computer work as such. However, in project 1, the correlations were most pronounced after 30 minutes of computer work with glare, and associations between neck pain and eye-related tiredness, dry eyes, photophobia, and headache were present during glare exposure only, indicating a stronger symptom development during such visual stress.

Furthermore, the associations in project 2 were present in all included conditions, suggesting that the eye-neck symptom associations were independent of exposure during 10-minute computer work. However, ten minutes is a short period of glare exposure compared to prolonged computer work in actual work settings. Studies with more extensive work periods probably would have resulted in more pronounced development of subjective symptoms, and thus possible more evident eye-neck correlations with glare.

6.3 The trapezius muscle and neck pain

Neck pain represents a major occupational health issue. However, the underlying mechanism for the high prevalence of neck pain among computer workers is unclear, as noted in the 'Background'. In the current thesis, TBF increased significantly during computer work with glare compared to with appropriate lighting, suggesting an effect of visual stress on the neck muscle. Yet, it remains unclear from the results whether or not the glare-induced rise in TBF was connected to neck pain development.

No significant main effect of glare on neck pain or significant correlations between trapezius muscle blood flow and neck pain were revealed. However, participants with high TBF overall reported significantly more pain in the neck area compared to participants with low TBF. These results indicated an association between TBF and neck pain, or vice versa, and may point toward that increased circulation in trapezius may be involved in the neck pain development during computer work.

Concerning muscle circulation and neck pain, Gold et al. (2017) found limited evidence of associations between medical biomarkers and musculoskeletal disorders in their review. Yet, trapezius muscle blood flow, relative blood volume, and muscle oxygenation were stated to be worthy of consideration as biomarkers for trapezius myalgia and neck and shoulder pain. The result in the current thesis, indicated that vasodilation may be involved in neck pain, and pointed to a similar mechanism as stated in the blood vessel-nociceptor hypothesis of Knardahl (2002). This hypothesis highlight the interaction between blood vessels and nociceptive fibers in muscle pain, where vasodilation may mechanically stimulate nociceptors in the tissue and chemical factors may contribute to pain sensation.

Muscle circulation is close connected to muscle metabolism, and different metabolites are reported to be involved in both vasodilation and pain sensation (Gerdle et al. 2014; Knardahl 2002; Larsson et al. 2008; Sjøgaard et al. 2000). In line with this, Larsson et al. (2007) pointed to the importance of local muscular processes in muscle pain development with involvement of nociceptors sensitive to chemical substances, supporting the importance of nociceptor activation and muscle blood flow changes (Knardahl 2002; Sandberg et al. 2005a). The diversity and differences in metabolite levels may be involved in the correlations between TBF and symptoms in this thesis and previous studies, but the mechanisms are not yet understood. It should also be mentioned that alternations in intramuscular metabolites were not investigated in the current thesis.

Several of the studies regarding trapezius muscle blood flow and neck pain are performed on subjects with chronic muscle pain that are compared to healthy controls. In this thesis, only young participants without chronic neck pain were included in the experiments and no comparisons to pain afflicted subjects were done. An important question in this regard is whether it is possible to compare the pathophysiological mechanisms and biomarkers for pain development in originally pain-free skeletal muscles and in muscles of subjects diagnosed with chronic myalgia or not.

Further research must be conducted to be able to clarify the question of the connection between glare, TBF and neck pain. Future studies should also clarify whether the relationships observed between increased TBF and neck pain in this thesis holds for each individual or whether it represents a general personality trait, as individuals with higher blood flow tended to report more neck pain.

6.4 Methodological issues

Limitations are a part of science and are present in all studies. The term validity refer to if an inference in research is logical and if it is likely to be correct (Shadish et al. 2002). Validity is a property of the conclusions, not a property of the designs or chosen methods. This is because no method in itself guarantees that the inferences made are valid, even not a randomized experiment, if threats to the validity is present (Shadish et al. 2002). During the whole research process, from recruitment of participants, to data collection and analysis of the collected data, several threats towards the validity of the results could occur. Some of the potential threats to validity can be ruled out by proper study conduction and design controls and minimize the probability and number of threats that remain by the end of a study. However, many threats to validity cannot be ruled out through the study design, and in those cases, the role and influence of the threats to the validity of the study should be identified and explored thoroughly (Shadish et al. 2002).

In this thesis, the experiments was carefully prepared and particular attention was directed towards the minimization of potential threats to the validity of the studies. However, limitations and shortcomings may nevertheless be present; and potential threats that might have affected the results during the projects are discussed in the following. The threats will be related to the following concerns according to Shadish et al. (2002): statistical conclusion validity, internal validity, construct validity, and external validity.

6.4.1 Statistical conclusion validity

Statistical conclusion validity concerns the use of suitable statistics to make a valid conclusion about the relationship between the exposure and the outcome and how strongly they covary (Shadish et al., 2002). According to a presumed covariation between exposure and effect, two types of errors may occur: a Type I error (finding a difference or correlation when none exists) and a Type II error (finding no difference when one actually exists). Statistical conclusion validity concerns the qualities of the study that make these types of errors more likely, and includes ensuring the use of adequate sampling procedures, appropriate statistical tests, and reliable measurement procedures (Shadish et al. 2002).

Statistical tests

Violated assumptions of the statistical methods used may be a risk for the validity of the results (Shadish et al. 2002). For instance, small study sample size may make it difficult to draw definitive conclusions. In project 1, the low sample size and not normal distributed variables resulted in the use of non-parametric statistical analysis. Nonparametric statistics make fewer and less stringent assumptions than parametric tests, and allow hypothesis testing even when certain classical assumptions are not met in the dataset (Pett 2015). The disadvantage, on the other hand, is that non-parametric tests have less power, and a larger sample size can be required to draw conclusions with the same statistical confidence. The results from project 1, revealed significantly increased TBF due to glare exposure. Nevertheless, the possibility of that few participants may have contributed to lack of difference between the glare and non-glare conditions in some of the measurements cannot be ruled out.

The limitation of small sample size in the statistical tests may also be present regarding missing values in project 2, especially obvious for the muscle blood flow measurements of the orbicularis oculi muscle. Missing values and thus incomplete dataset for some participants resulted in exclusion of those regarding certain measurements in the analysis, and small sample size reduce statistical power and may make it difficult to identify significant relationships, with the possibility of resulting in Type II errors (Shadish et al. 2002).

In project 2, parametric statistics were considered as the best method, as the number of participants were higher. However, many of the measured variables appeared to depart from the normal distribution curve, as indicated by the Shapiro-Wilk test of normality. The analyses were conducted with log (log10) transformed values to improve positive skewness and minimize the effect of outliers in the dataset. Transformation of variables is supposed to be appropriate on data with skewed Xs and/or Y or when dealing with variables that are inherently not normally distributed (Cohen et al. 2003). It should be mentioned that all repeated measure analysis in project 2 were conducted with comparing the main effects by using Sidak corrections for confidence interval adjustments, and that transformed and non-transformed data was never entered into the same statistical analysis.

According to the normal distribution of the data in project 2, the Central Limit Theorem states that given an adequately large sample size from a population with a limited level of variance, the mean of the sampling distribution will be approximately equal to the mean of the population (Field 2013). Retrospective calculations performed by statistical personnel at USN, showed that the mean of data from 24 subjects was sufficient to make skewed data become normally distributed. Project 2 included 43 participants, supporting that the Central Limit Theorem was in action with this sample size and that parametric statistics in that project was appropriate.

Fixation disparity measurements

Regarding the FD data captured in project 2, the results should be interpreted with caution. All participants had normal binocular vision and the changes in FD were small and measured in arcmin. The small number of subjects with FD measurements and the small number of subjects per subgroup may limit the analysis and threaten the validity of the results. The design of this thesis could have been improved by including more subjects and by performing several FD measures at each measuring point, instead of only one. However, although we had only a few measurements, it has previously been shown that the test-retest correlation of FD measurements is high ($r = 0.8$) at viewing distances of 40 and 82 cm (Jaschinski-Kruza 1993). Additionally, if the measurements had been performed at 40 cm instead of 60 cm, the FDs might become larger as the demand on the vergence system increases with shorter viewing distance. This could have revealed greater effects or differences in FD in the current thesis and would also make the results more comparable to previous studies. However, the test distance of 60 cm was chosen because it reflected the participants' vergence demand during the computer work conditions in the experiments.

6.4.2 Internal validity

Internal validity concerns causual inferences and whether it can be claimed that covariation between exposure and outcome actual results form a causal relationship (Shadish et al. 2002), or formulated: did in fact the experimental exposure make significant difference in the specific outcome? Internal validity refers to how well an experiment is performed, especially whether it avoids confounding factors (more than one possible independent variable acting at the same time). The less chance for confounders in a study, the higher its internal validity is. Internal validity includes, among other factors, ensuring appropriate measurements of variables, appropriate selections and avoiding systematic differences over conditions, control for attrition, and for testing effects (Shadish et al. 2002).

A within-participants and repeated measures design

The selection of participants to a study and different conditions may represent a threat to the internal validity (Shadish et al. 2002). In this thesis, a within-participants design with completion of all measurements on the same day was chosen for both projects reported. The participants performed all the conditions and thus were their own control in the repeated measures design. Accordingly, the bias of dissimilar selections to be the reason for the observed effects was excluded through the design of the study.

A within-participant design may also positively increase the power in practical experimental designs as it reduces the amount of feasible outside laboratory settings to affect the results, compared to designs that compare results from dissimilar groups of participants (Shadish et al. 2002). However, there are obvious disadvantages of performing all data collection within one laboratory visit; notably increasing fatigue and boredom throughout the experiments. Such effects were indeed indicated in the analysis by significant time effects on several variables, e.g. negative state moods. Such fatigue or contamination effects might represent a risk to the internal validity of the results by affecting the outcome. However, these limitations were considered less serious than those involved by carrying out the measurements over different days. Such a design could imperil equal calibration and placement of the EMG-electrodes and PPG-probes, as well as that the participants' daily moods and current state could affect the results differently on different days. This may have resulted in that the results from the different parts of the data collection could not be compared and analysed with certainty. One visit to the laboratory was therefore chosen in this thesis.

Another aspect with the within-participant design is the potential learning effect when performing the same task several times, and the possibility of the learning effect to mask the exposure effect. However, the learning effects' ability to bias the results was minimized as the conditions in both project 1 and 2 were counterbalanced so as every possible order of the work conditions were conducted in the experiments. There was 2 and 24 possible orders of work conditions in project 1 and in project 2, respectively.

Viewing distance

While working at a computer, the viewing distance to the screen is an important factor regarding the load on the visual system, such as the visual functions of the near response. During the computer work conditions in both projects in this research, the participants were allowed to move freely within normal postural ranges in an effort to make the study setting as realistically occupational as possible. The participants' actual viewing distance were accordingly influenced by changes in posture while working and are not actually known with precision. This factor might have affected the outcome and threaten the internal validity. Other studies within the same research field as this thesis often have placed the participants in strict positions in front of the computer by using chin and forehead support or a bite slice. This gives good control of the participants' viewing distance, but it may also result in other unwanted effects due to a static and unnatural work postures, and could bias e.g. the symptom and skeletal muscle response data.

To minimize the possibility of significantly alternations in viewing distance, as well as ergonomically loads due to awkward postures, the participants' sitting position were initially adjusted as ergonomic as possible and the subjects were also corrected to a proper sitting position if they moved into an obvious non-ergonomic position during the experiments. Furthermore, postural angles were continuously measured both at rest and during all computer work conditions, and if the participants changed their viewing distance significantly during testing, this would have been reflected in the measured postural angels. The head and back angles reflected neck and upper back movements, thus controlling for differences between conditions regarding postural angles of the upper body. Furthermore, the participants were sitting on a chair without wheels, and back flexion and extension did therefore reflect alternations in viewing distance with movements nearer and further away from the computer screen, respectively. Accordingly, a significantly increased viewing distance would have resulted in significantly increased back extension. The postural angle results in the current thesis does not indicate great alternations in viewing distances as the changes in postural angles were overall small and within ±5 degrees in both projects.

6.4.3 Construct validity

Construct validity concerns if the study measure what it is supposed to measure (Shadish et al. 2002). In other words, is the study, tests and measurements constructed in a way that it successfully tests what it claims to test. Construct validity refers to aspects such as reactivity to the experimental situation, experimenter expectancies, and novelty and disruption effects (Shadish et al. 2002).

The authors role and expectations

The author of this thesis was involved in all parts of both projects of the present research. She was involved in the design of the experiments (together with supervisors), she recruited the participants, prepared the test procedure, performed all data collection (except from the eye examination data), analysed the collected data, and wrote the articles/thesis. It is a strength that one person performs all the data collection, as the test context for all participants becomes as similar as possible. However, the fact that the same person both conducts the study design, the data collection, and the analysis may be a risk to the validity of the research. Experimenter expectancies is a known threat where the experimenter can influence participants responses by handing over expectations about desirable responses from the exposures (Shadish et al. 2002). And if participants in a study have anticipations about the objective of the experiment and what the researcher wants to find, such expectations may affect the outcomes. To minimize this risk for such bias, the written and verbal information given by the test leader was standardised so that all participants got the same information and instructions throughout the preparation phase and experiments, and the test leader was aware of being neutral and not give any signals about expected responses. The participants in both projects were thus naive as to the study's specific aim and expected outcomes and were not fully informed about the real purpose of the study prior to participating. They got the needed information about the study initially in order to give informed consent, but they were not explicit told about the specific aim of the study: that the study was exploring glare effects during computer work and that the study investigated if glare affect the trapezius muscle. After the experiment was completed, all participants were debriefed, informed about the study's specific aim and true purpose, and told why they had not received complete information before testing. To ensure that all participants were naive observers, participants who had completed testing were also instructed not to tell other potential participants details about the experiment to after the data collection was completed.

Masking

Furthermore, the conditions throughout the experiment were not possible to mask/blind for the test leader, and the author was aware of the induced exposures when analysing the findings for each test condition. The author was especially aware of this problem throughout the analysing process, and tried to be objective and strict so that data from all the conditions were analysed in a similar way.

According to masking of the conditions, this was not practical feasible neither for the participants, due to the nature of the study design. They did experience the different exposures throughout the experiments. It is important to be aware of that test subjects may alter their behaviour due to research participation rather than because of the manipulation of independent variables in an experiment, and this effect is called the Hawthorne effect (McCambridge et al. 2014). However, as the participants were their own control performing all conditions, this could possible minimize this effect to influence the results in the current research.

Glare source

The glare source in the current thesis was placed behind the computer screen to ensure equal glare exposure to both eyes, but also to simulate glare exposure from of an inadequately placed window in an office environment. Even though the luminance levels, the size, and the uniform appearance of the glare source in the current thesis was comparable to light exposure in an office window on an overcast day, the colour temperature and spectral distribution of the lighting from the glare source were not comparable to light exposure from a daylight source. The glare source was therefore not a perfect representation of a real-world window in a computer work setting. The colour temperature of lighting is reported to affect human beings working in an office, affecting both visual comfort and glare perception, physical heath, mental state, and eye symptoms (Duijnhoven et al. 2017). However, regarding alerting effects of light, the effects of colour temperature and spectral distribution of the lighting seems less clear (Souman et al. 2018). Accordingly, in future studies with a similar design one may consider using light sources with a greater ability to imitate the daylight. However, in this thesis different effects due to glare exposure during computer work are investigated. Glare is, regardless of daylight exposure or not, an important concern regarding artificial lighting in real office environments, and the results provides knowledge about general glare effects. Even so, the results should be generalized with caution in the debate regarding daylight.

Questionnaires

Self-reports, as questionnaire in the current thesis, may be a threat to the construct validity of a study (Shadish et al. 2002). When participants register variables by self-reports, the results may be affected by the participants positive or negative motivation for participating. However, with a within-participants design performed at the same day such threat is reduced, as this motivational factor will probably influence equal in all conditions within each person.

Another limitation regarding the use of questionnaire to measure subjective symptoms and state moods, is limited validity testing of the included questions. The questionnaires used were tested during the pilot studies prior to the experiments, but were not otherwise explicitly tested for reliability or validity. However, questions were made up of 100 mm VAS, which have been considered to be valid in measuring changes in subjective pain, feelings, affect, and well-being (Bijur et al. 2001; Bond and Lader 1974; Monk 1989). The possibility for different understanding of the questions cannot be totally excluded, but the within-participants design contributed to minimize the violated effect of this threat, as the results were analysed as changes in scores within each participant, not between participants that could have interpreted the questions differently. To ensure similar use of the scale for rating the questions among the participants, they were carefully instructed in the use of the questionnaires ahead of the experiments. Furthermore, to ensure similar understanding of questions regarding eye, neck and shoulder symptoms, the participants got drawings for what was defined as neck and shoulder pain, and what was defined as symptoms within and around the eyes (see 9. Attachment).

Skeletal muscle measurements

The objective measurements of muscle activity and blood flow depends on correct placement and calibration of equipment to be valid. Regarding the EMG and PPG measurements of orbicularis oculi, nearby facial muscles may have affected the measurements. For instance, the levator labii superioris muscle has its origin posterior to the orbicularis oculi (Thorud et al. 2012) and may affect the EMG and PPG signals from the orbicularis oculi muscle captured in this thesis. The participants in both projects were instructed not to talk or move unnecessarily during the rest sessions and conditions during measurements, in order to minimize both contribution from the levator labii superioris and noise in the PPG signals, which are sensitive to movement (Hagblad et al. 2010). In addition, due to the possible contribution of the levator labii superioris muscle while performing a MVC during calibration of the orbicularis oculi EMG-probes in project 1, the % MVC recorded during testing may be too low.

Correspondingly, the trapezius muscle activity data showed very low levels of muscular load while working, both in the inactive side in project 1 and on the active side in project 2. Mork and Westgaard (2007) have showed that the muscle activity in trapezius is significantly higher in a standing compared to in a sitting position. In the present study, calibration of trapezius EMG electrodes was performed in standing, whereas the computer tasks were carried out when sitting. This may have influenced the results and too low trapezius muscle activity may have been registered in the experiments.

However, as all participants were their own control and all data collection were performed on the same day with the same placement of probes and electrodes, the relative differences between the conditions should be about the same even though the % MVC was too low in the measured skeletal muscles. Even though, the very low trapezius muscle activity results might have violated the possibility to detect either significant main effects due to induced exposures, or correlations with other variables.

The lack of orbicularis oculi muscle activity in project 2

One limitation observed retrospectively concerning the orbicularis oculi data was that muscle activity was only included in project 1. As orbicularis oculi muscle activity (eyelid squinting) in project 1 was connected to one of the main findings of this thesis - increased TBF during glare - this lack of eyelid squinting measurements hampered the possibility of replicate those results in project 2. During the designing phase of project 2, the decision to exclude orbicularis muscle activity was taken because carrying out EMG measurements on the orbicularis oculi is time-consuming and, given all the other measurements that should be included, it was practically difficult. Additionally, we thought that the muscle blood flow in orbicularis oculi would reflect similar results with inclusion of more participants. In retrospect, this thesis would have been strengthened by including muscle activity measurement of orbicularis oculi in both projects. However, in view of the literature and the fact that the exactly same glare source as in project 1 was used, it is reasonable to assume that the glare exposure caused increased orbicularis oculi muscle activity in project 2 as well.

6.4.4 External validity

External validity refers to the possibility of transferring findings from one experiment considering the samples of persons, settings, and times attained in the study, to and across populations of interest within the field of study (Shadish et al. 2002). Another way of putting it: Is the results valid for and can they be generalized to other individuals, settings and at other times? Threats to the external validity may involve that an effect found in one kind of study sample, experimental setting, or context not holds if another sample, setting or context is used.

Study sample

The study sample in this thesis consisted of young, healthy students with good vision. As the research looks into how inappropriate lighting conditions in a work environment affect humans, one goal was to develop knowledge about glare and preventive advice for lighting for use in the working population as a whole. It is possible to assume that some of the responses to glare exposure might be comparable from the study sample to employees working with computers, at least the younger ones without developed presbyopia. Hence, generalisation of the results to the older subjects is likely uncertain. However, it may be reasonable to assume that when finding responses due to glare exposure in the young, healthy subjects, the observed effects would possible have been even more prominent when including older subjects, with presbyopia or other age-dependent infirmities of the visual system, leading to even more stress on the visual system. If so, some of the effects observed in the current thesis can thus be anticipated to be present in other samples as well. However, investigation of glare responses in older subjects and in the working population as a whole should be accomplished to be able to say something certain of the transfer value of the results in this thesis to other samples, age-groups and professions.

Moreover, the study sample in both projects in this thesis was made up largely of optometry students, who may be over-represented regarding visual anomalies. A large number of volunteers signing up as potential participants had to be excluded due to not fulfilling the visual criteria, which made recruiting participants to the projects more challenging than initially thought. However, the visual examination and exclusion criteria included in the experiments ensured that those included as participants in the projects were suitable and had good vision and health.

Gender

When preparing project 1, the intention was to include 50 % men and 50 % women in the test sample and during the experiment, the sample was randomly separated by gender when deciding which session to start with, the optimal or the glare condition. Retrospectively speaking, this was obviously unnecessary, when considering the low number of men included in the project. In total, five men were tested, but two of them were excluded because of visual anomalies. However, all subjects were their own control in the experiment and we may expect that both genders react in the same way on visual stimuli like glare. Furthermore, the group that started with the Glare and Optimal condition thus became quite similar, as consisting of 2 men and 5 women (7 subjects) and 1 man and 7 women (8 subjects), respectively. To investigate this possible bias further, some additional analyses comparing the included men and women were performed. Only one significant difference between the genders was observed. Trapezius muscle activity (static level) in men was significant higher after 15 minutes in the Optimal session, compared to women. This shows that the difference between the genders probably was insignificant.

Experimental setting

The experimental setting and context might affect the participants in an experiment, and in this case, the data collection was accomplished in a laboratory whereas the results should be used to make suggestions for better visual ergonomics in offices. To minimize this threat, the laboratory was built up to simulate an ordinary computer work office as best as possible. Furthermore, compared to a field study in an real office environment, the laboratory environment controlled for many other confounders present there, such as noise, distracting movements and comments from colleagues, and natural changes in the lighting conditions, among others.

However, the laboratory setting in the present thesis with placement of a lot of equipment, even in the face, and all the measurements and testing procedures, the participants may have exhibited other psychological responses, or more pronounced responses, compared to what they would have in an ordinary computer work setting. This may contribute to make the generalization to an office work setting uncertain. However, the fact that the current research used a within-subjects design performing all conditions in the same laboratory, this threat was minimized. Additionally, the preparation phase gave time for the participants to be familiar with the setting and some of the measurement procedures.

7. Conclusion and implications

7.1 Summary of findings and conclusion

This thesis presents results from two laboratory experiments investigating effects of glare exposure and possible interactions between the visual and the musculoskeletal systems during glare while working on a computer. Healthy, young subjects with normal binocular vision worked on a computer screen with and without the presence of direct glare exposure (visual stress), and both subjective and objective responses were examined throughout the different work situations. The glare exposure was induced by a large uniform glare source situated directly behind the computer screen, simulating a mal-positioned window in an office environment.

In summary, the results revealed that glare exposure during computer work resulted in increased eyelid squinting, more eyestrain, increased head flexion, increased blink rate, increased trapezius muscle blood flow, perceiving the workstation lighting worse, and feeling more uncomfortable, compared to working under optimal lighting conditions. Additionally, associations between perceived workstation lighting and stress were revealed during glare, indicating that poor ambient lighting may negatively influence how stressed some people feel, or vice versa, during computer work.

A possible interaction between the visual system and the musculoskeletal system are also proposed from the results in the current thesis. Glare caused a significant increase in trapezius muscle blood flow, and this suggested a direct effect of glare on the neck area, possibly due to that the visual stress triggered an increased need of gaze stabilization and/or a central mediated alertness response. Moreover, positive correlations between eyelid squinting, trapezius muscle blood flow and neck pain suggested an indirect effect, possible related to intersubjective differences in perceived negative discomfort and emotions related to glare. It could seem as if the more glare-sensitive the participants were, the more eyelid squinting, TBF, and neck pain occurred. This is the first studies, as known by the author, that explore the effect of visual stress, induced as direct glare, on the trapezius muscle and neck symptoms. However, this proposed interaction between the visual system and the musculoskeletal system requires further research as the underlying mechanisms remain uncertain.

Furthermore, orbicularis oculi appeared to be a muscle activated both with and without glare; possible to reduce retinal illumination and as an indicator of discomfort glare during glare exposure, and/or as an attention response during computer work as such.

To conclude, this thesis provides effort to explore the relationship between glare and associated muscular stresses on eye and neck muscles during computer work. The results report that exposure to direct glare during computer work has implications for young, healthy subjects, and may affect both the orbicularis oculi muscle, eye symptoms, the trapezius muscle, and feeling of being uncomfortable and stressed.

However, whether glare exposure is a factor involved in the high prevalence of neck pain among computer workers is uncertain. Indications for TBF to be involved in neck pain development were present, at least for the most glare-sensitive subjects, but the underlying mechanisms is still unclear and further research is required.

7.2 Clinical implications

Globally, several hundred millions of workers use computers on daily basis, and there is a widespread occurrence of complaints among computer workers. The findings in the current thesis highlight the importance of preventing glare exposure during computer work. The results further reveal that ensuring optimal lighting conditions and glare-free work environments are important not only for visual comfort and avoiding eyestrain, but also for reducing the experience of stress, improve well-being, and possibly prevent development of neck pain.

The suggested intersubjective differences among the participants regarding glare sensitivity, further highlight that some workers might be more severely affected by glare during computer work. This further points to the importance of individual adjusted workstations, where lighting and related equipment should be easy adjustable, to avoid additional visual stress, awkward postures, eyestrain, and neck pain.

This thesis points out the significance of interdisciplinary cooperation in preventive work at computer work places, including both traditional ergonomics and visual ergonomics. From a public health perspective, knowledge of how glare conditions during computer work affect human beings is of great importance for preventive efforts in the workplace. Attention towards optimal lighting and prevention of glare may be an important factor involved in reduction of sick leaves among computer workers.

7.3 Implications for future research

As this thesis included subjects with good vision, it is reasonable to assume that by including subjects with presbyopia or inappropriate binocular vision, glare exposure would have led to even more pronounced responses. Regarding including subjects with presbyopia or other age-dependent weaknesses of the visual system, it has been reported that neck pain and less tolerance to glare are more prevalent in older than in young subjects (Bailey and Bullimore 1991). Accordingly, it would be informative to conduct a similar experiment on an older study group that was more representative of the workforce in actual offices. Future studies should also investigate glare effects in subjects with more unstable binocular vision, as it is plausible that glare would have an even greater effect on their binocular vision and discomfort than in those included in this thesis.

This thesis shows that TBF is affected by glare exposure during computer work, and propose that a centrally mediating alertness response activated by visual stress might be involved. However, objective indicators of central activation of the autonomic nervous system due to stress were measured to only a limited extent in this thesis, and this remains a hypothesis. Future studies should include better measurements of sympathetic activation when investigating the effect of glare exposure during computer work.

Possible connections between TBF and neck pain during glare conditions is also a question that needs further investigations. The results in this thesis points to a connection between TBF and neck pain, where those with high TBF had more neck pain compared to those with low TBF. However, if the glare-induced TBF increase is involved in neck pain development during computer work remains uncertain. To look into this questions further, a similar study could have been conducted, but with longer working sessions. Computer work for longer periods would possible induce more pronounced symptoms in the neck area, and could possible contribute to clarify if glare exposure initiates musculoskeletal symptoms or not. Inclusion of a measure, possible both a subjective and an objective one, to decide if the participants are glare-sensitive, would also be helpful regarding the proposed intersubjective-differences in sensitivity to glare.

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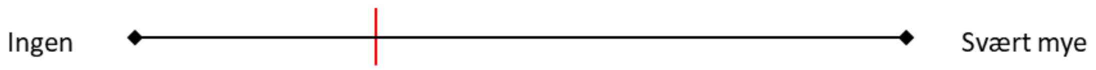
9. Attachments

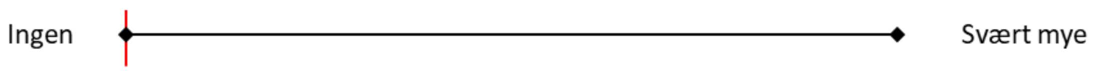
Instructions to the questionnaires

Spørsmålene skal fylles ut slik:

Sett en vertikal strek i det punktet på skalaen du mener representerer riktig grad av det aktuelle symptomet akkurat i dette øyeblikk. Helt til venstre betyr ingen symptom, helt til høyre betyr det verste du kan tenke deg av det aktuelle symptomet. Gradér slik med en **kort, vertikal strek:**



Dersom du for eksempel vil registrere at du ikke har noen problemer med det aktuelle symptomet gjøres det slik:



Lokalisering av symptomer: På figurene under er det indikert hvilke områder vi definerer som nakke og skulder (figur til venstre), og hva vi definerer som *omkring* øyet og *i* øyet (figur til høyre). Bruk disse figurene som en hjelp til å lokalisere eventuelle symptomer du kjenner når du svarer på spørreskjemaet.