A proper lookout

Studies of contrast sensitivity

Vilhelm F Koefoed

Thesis for the Degree of Philosophiae Doctor (PhD)
University of Bergen, Norway
2018

UNIVERSITY OF BERGEN

A proper lookout

Studies of contrast sensitivity

Vilhelm F Koefoed

Thesis for the Degree of Philosophiae Doctor (PhD)
at the University of Bergen

2018

Date of defence: September 14th

Year: 2018

Title: A proper lookout

Name: Vilhelm F Koefoed

Print: Skipnes Kommunikasjon / University of Bergen

Scientific environment

This project was carried out at the Department of Clinical Medicine, Faculty of Medicine at the University of Bergen in collaboration with the Section for Occupational Medicine, Department of Public Health and Primary Health Care, Royal Norwegian Naval Academy, Norwegian Armed Medical Forces and Institut de médecine aérospatiale du service de santé des armées, French Armed Forces.

The Norwegian Centre for Maritime Medicine financed the research.

Scientific contributions to this project were made by:

Vilhelm F Koefoed, Gunnar Høvding, Department of Clinical Medicine, University of Bergen

Eilif Dahl, Norwegian Centre for Maritime Medicine

Bente E. Moen, Kristian S Gould, Valborg Baste Research Group for Occupational and Environmental Medicine, University of Bergen

Jörg Assmus, Uni Health

Corinne Roumes, Institut de médecine aérospatiale du service de santé des armées. French Armed Forces

Acknowledgements

I would like to express my gratitude to the following people:

✓ Professor Gunnar Høvding, for being my supervisor. Your lectures given in medical school in 1986 gave me the first ideas of the topic of this thesis. I really appreciate your efforts in guiding me.

✓ Professor Eilif Dahl, for valuable support and careful proofreading as my second supervisor.

✓ Professor Bente E. Moen, for your patience, ever-optimistic comments and for giving me an office.

✓ Surgeon Rear Admiral Jan Sommerfelt-Pettersen, for your leadership giving individual freedom and a prosperous working environment.

✓ Director Alf Magne Horneland, for your willingness and efforts to support my work.

✓ Dr. Kristian Gould, for giving my studies a kick-start and for your never-ending encouragement.

✓ Irene Berg, for collecting contrast sensitivity data and quite talks.

✓ Commander ® Hjalmar Johansen, for your effort as my scientific assistant and help in the collection of colour vision data.

✓ Dr. Jörg Assmus, for statistical guidance.

✓ Dr. Valborg Baste, for statistical advice.

✓ Bente Haughom, for bringing up new ideas and good conversations.

✓ Dr. Corinne Roumes and Justin Plantier for valuable assistance both scientifically and in France.

- ✓ Dr. Inger Rudvin, for setting up the Vigra C and collecting data.
- ✓ Dr. Nicolas Øyane, for collecting contrast sensitivity data.
- ✓ Commander Petter Lunde and Commander Frode Voll Mjelde, for help with setting up and running the simulator experiments at the Naval Academy.
- ✓ Everyone at the Section for Occupational Medicine, for fruitful discussions and advice. A special thanks to Magne Bråtveit, Kaja Irgens-Hansen, Ole Jacob Møllerløkken, Nils Magerøy, Inger Haukenes, Kristin Bondevik, Camilla Hauge, Erlend Sunde, Hilde Gundersen and Gunhild Koldal.
- ✓ Royal Norwegian Navy for giving me access to the cadets at the Naval Academy and generous support.
- ✓ Institute of Aviation Medicine for hosting me a year and giving me the opportunity to have insight in aviation medicine and experimental research in hypoxic environments.
- ✓ Ecole de l'Air, Salon de Provence, France for excellent facilites and help.
- ✓ Gunhild for letting me feel the contrast.
- ✓ To my children, Ingrid, Jacob, Ine, Olav and Aksel, whom all have patiently waited for my attendance at times.

Abbreviations

cd	Candela (luminous intensity)
cpd	Cycles Per Degree of visual field
CS	Contrast Sensitivity
CSV-1000E	Instrument for testing CS by Vector Vision
CV	Colour vision
CVD	Colour vision deficiecy
ETDRS	Early Treatment of Diabetic Retinopathy Study
ICS	Index of Contrast Sensitivity
LogMAR	Logarithm of the Minimum Angle of Resolution
MAR	Magnification Requirement
Optec 6500	Instrument for testing visual acuity and contrast sensitivity by Stereo Optical
PIP	Pseudoisochromatic plate
RNoN	Royal Norwegian Navy
RNoNA	Royal Norwegian Naval Academy
VA	Visual Acuity
VIGRA-C	Instrument for testing contrast sensitivity

Abstract

Naval navigation and watch keeping in littoral waters is highly dependent on visual function, and all navigators are required to have normal visual acuity (VA) measured by Snellen's table or equivalent. Although visual functions obviously are important for navigators and watch keepers, there are few studies on visual problems as a cause of marine accidents or navigation performance.

Visual function may be evaluated by several means, but it has been a long tradition to use Snellen's table to describe VA as the main descriptor. Snellen designed his table in 1862 and the method has later been modified into a diversity of test, like the ETDRS table. The improvements enable more accurate testing of VA, but the test still lacks the possibility to test contrast sensitivity (CS).

Contrast sensitivity is believed to be a better predictor of visual performance and can be tested on different sizes of objects and for achromatic light or coloured lights in dynamic or static modes.

Contrast sensitivity is dependent on the clarity of the optical light way in addition to retinal and neurological function. The CS can be disturbed by corneal changes, as might be seen after corneal surgery or by lens degeneration. Corneal surgery and implantation of intraocular lenses are frequently performed on personnel trying to qualify for work demanding good VA. Few studies have evaluated the work performance and its correlation to VA or CS, and the studies are often non-conclusive.

Sailors often stay on long watches and become sleep deprived. Very few studies have studied the visual function after prolonged sleep deprivation and none has looked at the effect of sleep deprivation on CS.

The primary research goal of the present study was to obtain more information about the usefulness of various vision tests available for selection of personnel who perform work highly dependent on good visual function.

The first study aimed to compare two different CS test methods and to establish reference values for CS in young adults with normal VA under photopic and mesopic light conditions. A total of 180 recruits, age 18-25 years was examined for CS and VA, and the test results were described and compared. In addition, a collated Index of contrast sensitivity (ICS) was computed and described.

The agreement between the photopic tests indicated that they might be used interchangeably. There was little agreement between the mesopic and photopic tests. The mesopic test seemed best suited to differentiate between candidates and might therefore possibly be useful for medical selection purposes.

In the second paper, sixty cadets at the Royal Norwegian Naval Academy (RNoNA) performed a visual observation task in a ship simulator. Their task performance was recorded according to VA, CS, gender and environmental light. Performance was highly correlated to increased environmental light and to gender. Men seemed to perform better than females, probably due to different approaches to decision making. No significant correlation between performance and CS or VA was found. This apparent absence of proven predictive value of visual parameters for observation tasks in a maritime environment may presumably be ascribed to the normal and uniform visual capacity in all our study participants.

The third paper describes the possible influence of prolonged sleep deprivation on CS. During 60-hr sleep deprivation, CS was measured in 11 naval officers every sixth hour. Prolonged sleep deprivation does apparently not cause clinically or occupationally significant changes of CS in otherwise healthy subjects with normal VA.

List of publications

Koefoed, V.F., Baste, V., Roumes, C., Høvding, G. **Contrast sensitivity measured by two different test methods in healthy, young adults with normal visual acuity.** Acta Ophthalmol, 2015. 93(2): p. 154-161.

Koefoed, V. F., Assmus, J., Høvding, G. **Correlation between observation task performance and visual acuity, contrast sensitivity and environmental light in a simulated maritime study**, Acta Ophthalmol, 2018. 96: p. 390-396.

Koefoed, V.F., Assmus, J., Gould, K.S., Høvding, G., Moen, B.E. **Contrast sensitivity and the effect of 60-hour sleep deprivation.** Acta Ophthalmol, 2015. 93(3): p. 284-288.

Contents

1. INTRODUCTION

1.1 The sea and requirements to the seafarer

Navigation at sea is a demanding task often exercised in harsh conditions and unfriendly environment. Linda Greenlaw[8] describes the sea in her book “The Hungry Ocean”:

> *“The complex and all-consuming Ocean feeds man, but also feeds upon men. The flat calm that gently digests my troubles is capable of violent turbulence of enough gluttony to chew up and spit out vessels of the strongest steel. Often swallowing men and ships whole…”*

Accidents at sea might be associated to navigation when it is not optimally performed. According to a study by Marine Accident Investigation Branch[9], a majority of collisions took place during nighttime (65 %) and was due to late or none awareness of other objects (43 %). Possible causal factors were incompetence of lookout (80 %) or fatigue (25 %).

In addition to the difficulties intrinsic to seafaring, military operations pose an additional challenge to mariners by introducing tasks with narrower safety margins than in civilian life. Tactical exercises at sea may involve sailing in shallow waters at high speeds, often with sustained duty periods over several days, uncomfortable resting facilities and a concept of “lean manning”[a] with increased risk of general fatigue.

Navigation and watch keeping in littoral waters is highly dependent on visual function, and International Maritime Organisation[10] (IMO) emphasizes this:

> *“Every ship shall at all times maintain a proper look-out by sight and hearing as well by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision, stranding and other hazard to navigation. Additionally, the duties of*

---

[a] The ship’s crew number is reduced to minimum of safe staffing for ship handling and operation.

> *the look-out shall include detection of ships and aircrafts in distress, shipwrecked persons, wrecks and debris."*

An important asset to a proper lookout is appropriate vision, and all mariners are required by law or regulations to have normal visual acuity by Snellen's chart or equivalent[11]. The interpretation of the phrase "normal" is not evident. The regulations use normality as conforming to the standard set by Herman Snellen in 1862, who on the other hand chose to define a standard vision which was well below the population mean described by his college de Haan[12]. In addition, the level of satisfactory vision for a proper lookout has hardly ever been clarified, neither in relationship to Snellen's normal vision or to other standards.

1.2 Medical selection

Selection medicine is defined as medical assessment of personnel who are planned to fulfil certain occupational health requirements. According to Rayson[13], the purpose of medical selection of fitness for work is to make sure that individuals are fit to perform the task effectively and without risk to their own or others' health and safety. The standard or criteria of which the selection is to follow is in principle evidence based, but often tainted by the aim of the stakeholder or the authority issuing the requirement. The prime intention of medical assessment of seafarers in Norwegian legal regulations[11] has been to ensure that the candidate is fit to do the task without jeopardizing ship, passengers, fellow sailors or external environment. A secondary intention, which is evident in International Labour Organization (ILO) regulations[14], is to assure that the seafarer do not suffer from a disease or condition that may be made worse by the job. A third intention is to assess the occurrence of diseases that may cause incidents of repatriation[b] and thereby reduce cost for insurance[15].

---

[b] To restore or return to the country of origin, allegiance, or citizenship.

There are two main principles when assessing a person's fitness for work. The most commonly used is to regard everyone as "fit, until proven unfit". Only candidates with a medical condition believed to have implications for the job performance are excluded. The second principle is to regard the candidate at "unfit, until proven fit". Based on a task or job analysis that have established minimum criteria for safe and effective performance of the work, the candidate may be proven fit for work. Both principles are found in most regulations. Sensory capacities, like vision, colour vision and hearing, are examples of such minimum criteria for fitness. Ideally, the minimum criterion should be agreed upon by solid evidence after a task analysis. Evidence quality has been discussed, and systems for evaluation of recommendations have been developed[16]. The Grading of Recommendations Assessment, Development and Evaluation (GRADE) working group rates the quality of evidence by four categories, from "*High Quality Evidence*" to "*Very Low Quality Evidence*". A second method to establish fitness criterions is by the Delphi technique[17]. This is a method for formulating group judgment[18] by seeking consensus among experts within a topic, and is based on the principle that forecasts from a structured group of experts are more accurate than those from unstructured groups or individuals[19]. A third method to make regulations is by expert opinion, from either single experts or groups of experts without having additional processes of quality assurance. This method is often regarded equivalent to "very low quality evidence" by the GRADE system. A fourth system for development of fitness standards is by revision of existing standards based on dispensations or complaints. Standards are often influenced by political guidance and negotiations between the parts involved, as Longmore[20] already pointed out in 1885. Beard et al.[21], discuss the occupational vision standards in detail and mention that the visual requirements are influenced by several of these mechanisms.

1.3 Vision

> *Our eyes are marvellous sense organs that allow us to appreciate all the beauty of the world we live in, to read and gain knowledge, and to communicate our thoughts and desires to each other through visual expression and visual arts.*
>
> Helga Kolb

1.3.1 Theory of vision

The visual system may be described as an anatomical part of the nervous system and a system for visual perception. Visual perception is the ability to observe and interpret the surrounding environment by information presented by visible light. In Light Vision Color[22,] Valberg summarize the characteristics of the main physical, neural and mental processes that lead to vision:

1. Imaging. The process that accounts for light distribution on the retina by the optical eye media: The tear film, cornea, pupil, lens and vitreous. Imaging may be explained by physical and physiological optics, while point 2-6 may be explained by biophysics, molecular biology and neuroscience.

2. Detection and discrimination. Transformation of the light energy absorbed by the rods and cones to electric potentials and neural activity.

3. Neural encoding and signal transmission. After reception, four functional cell types in the retina organize the retinal image, decompose it and encode it before the signals are transmitted to higher brain centres.

4. Adaption. The ability to adapt to changing light levels in an intensity range that covers more than 10^{12}.

5. Differentiation and structure. Diverging, converging and parallel pathways in the retina, thalamus and cortex receive input from a common set of receptors. The information is processed in approximately 40 areas in the cortex and in different functional cerebral units and cell types.

6. Identification, recognition and interpretation are processes in visual cortex and higher mental activities like memory, context and experience.

1.3.2 The anatomy of the visual system

The anatomical description of the visual system is complex. A comprehensive description is given in Webvision[4]. The anatomical eye may be divided in two major components; the optical part, or the light way of the eye, and the neurological part, which is a part of the central nervous system.

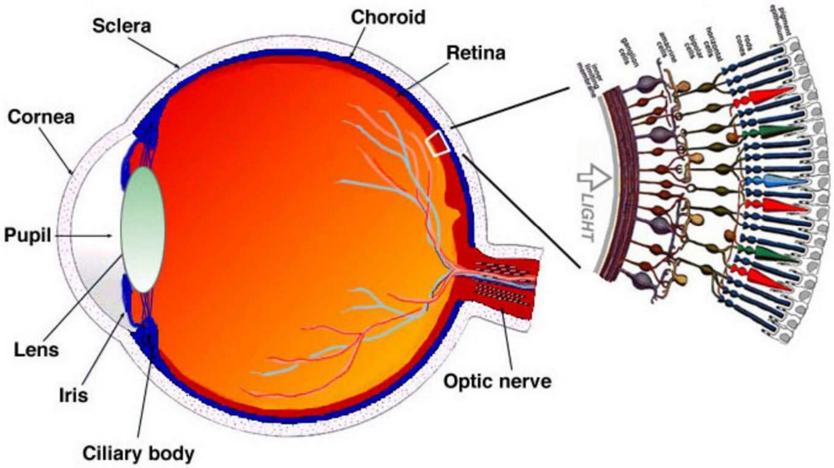


Fig 1. A schematic section through the human eye with a schematic enlargement of the retina.[4]

The eye consists of three layers.

Sclera and the transparent cornea form the external layer. Sclera is the supporting tissue for the eye and is a part of the dura of the central nervous system. Inserted into the sclera are the extraocular muscles providing movement of the eyeballs, pointing the eye at the image.

The intermediate layer, where the iris, ciliary body and lens is the anterior part and the choroid is the posterior part of the eye. The lens is suspended to the ciliary body by zonulae, whose tension is influenced by the ciliary muscles; allowing the lens may

change shape and optical power. The change of refractive power of the lens, called accommodation, allows an object to be in focus as its distance to the eye varies. The pupil, lens and ciliary body divide the eye in three chambers. The anterior chamber and posterior chamber are filled with aqueous liquid, whereas the corpus vitreum in the posterior eye is filled with a more viscous fluid. Cornea, anterior chamber, lens and corpus vitreum are parts of the light way. The choroid is a part of the vascular layer of the eye and provides oxygen and nourishment to parts of the eye structures.
The internal layer (retina) is the sensory part of the eye.

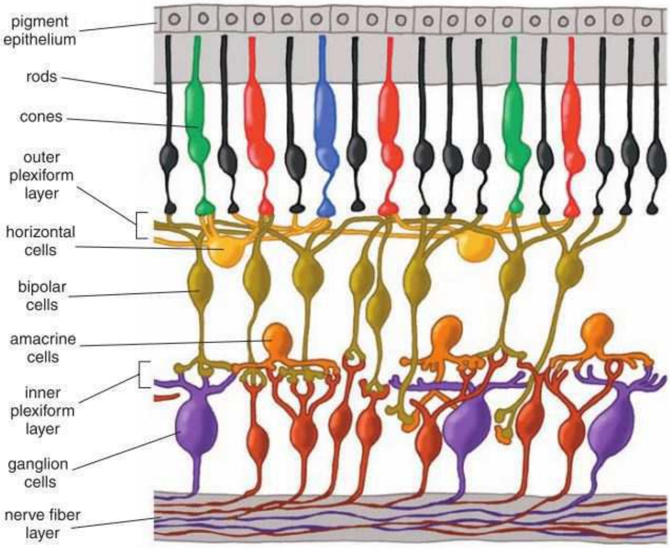


Fig 2. Simple organization of the retina.[4]

Retina consists of several layers and different cell structures. The photoreceptive, light sensitive, cells in the retina are the cones, rods and a few specialised ganglion cells. Rods are highly sensitive to light and may be triggered by a single photon[23]. Rods are used for scotopic vision[c] in contrast to the cones, which are used for photopic vision.

---

[c] Scotopic luminance (darkness) levels of 10^{-3} to 10^{-6} cd/m², Mesopic luminance (dusk) level 10^{-3} to $10^{0.5}$ cd/m², Photopic luminance (bright light) level 10 to 10^{8} cd/m²

Cones are concentrated in the central part of retina and have better spatial resolution giving high visual acuity, in approximately 2° of the visual field. The cones have three different types of photosensitive pigment providing the mechanism of trichromatic colour vision, the L, M and S cones[24]. Recently, the photosensitive ganglion cells were discovered. These cells are involved in processes in control of circadian rhythms and suppression of pineal gland melatonin release. In addition, retina consist of several other cell types, all forming a complex network that perform the first stages of processing of sensory input before the electric response is transported to the brain by the optic nerve for further processing and visual perception.

The rods and cones have a photosensitive part made up by a stack of membranous disks made of invaginations of the cell membrane, the ribbons[d]. Photoreceptors undergo daily renewal and shedding of their outer segments[25].

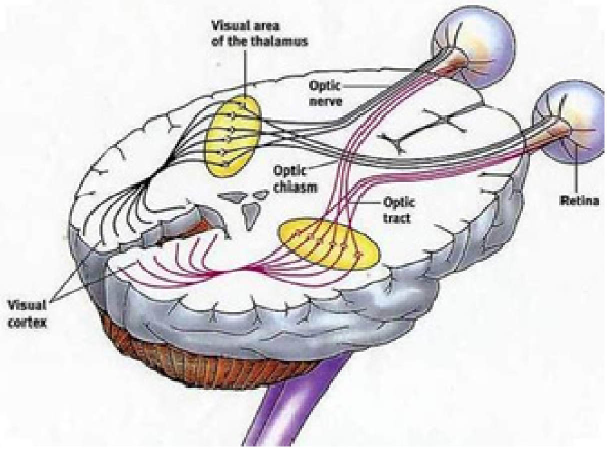


Fig 3. Visual pathways in the brain from retina to visual cortex.[4]

Final visual processing happens in the visual cortex in the posterior part of the occipital lobe. The visual cortex consists of several different neurons with unique capacities working in a system only partly understood. Before reaching the occipital lobe, visual

---

[d] Ribbons are one of two types of vesicular neuronal synapses.

information passes the lateral geniculate nucleus (LGN) of thalamus where it is processed. Additional processing in LGN is done by retrograde cortico-thalamic pathways[26].

1.3.3 Visual channels

To be able to see objects, the eye must be able to resolve edges, contours, structural details and ambient light of different luminance and colour. This requires a detailed processing of the image posed on retina and may be explained by the theory of visual channels. In principal, four such channels are described. There are two achromatic luminance contrast channels. One consists of the rods, working in scotopic light, the other one within the photopic luminance. The photopic channel relies on the sum of L and M cones (L+M) and does not carry colour information. The two colour channels are dived in the red-green (RG) and the yellow-blue (YB) channel. Red-green discrimination is based on the difference (L-M) in the light absorption of L and M cones, while YB also take in account the signal generated by the S cone (L+M+S)[24].

Another approach to the theory of visual channels is based on the assumption that an object or image may be described by the light distribution of each of the Fourier components, given in several sine wave formulas[27].

Fourier analysis is the study of the way general functions are represented or approximated by sums of simpler trigonometric functions, i.e. sine wave. The decomposition process is called a Fourier transformation. The visual system acts on several independent detector mechanisms, each tuned into a relatively narrow band of frequencies and each detector constitute a separate channel. Campbell and Robson[27] examined the CS for several sine wave gratings and concluded that the "*envelope of the contrast sensitivity function for all of the channels would be the contrast sensitivity function of the overall visual system*". This has been well demonstrated by Ginsburg, who performed Fourier transformation on images and illustrated how the sum of channels made the total perceived image[28].

1.3.4 Vision and effects of circadian rhythms

$Yij\ (t) = \beta i,1\ \cos(\omega t + \varphi i) + m\beta i,2\ (t) + \beta i,0 + \varepsilon ij\ (t)$[e]

Jörg Assmus

Several known retinal mechanisms; like gene expression visual sensitivity, synaptic communication and metabolism, are regulated by the circadian clock and the system allows to predict the normal cycle of photopic and scotopic visual conditions that alternate with the cycling of day and night[1,29].

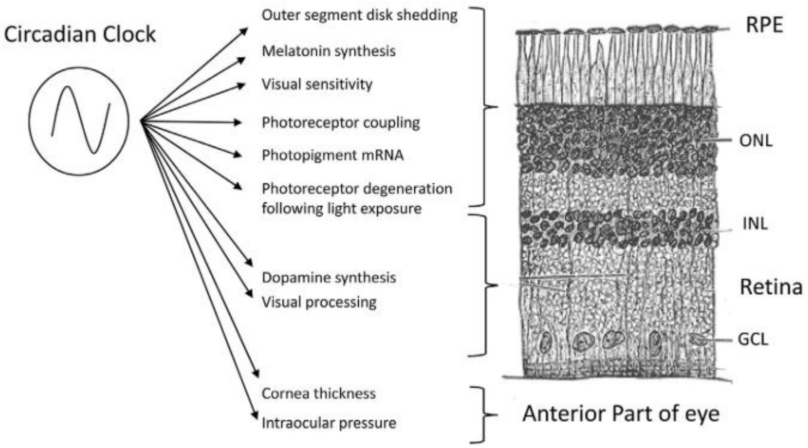
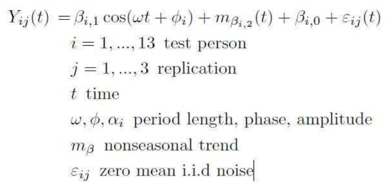


Fig 4. Retinal structures and processes influenced by the retinal circadian clock. RPE: retinal pigment epithelium, ONL: outer nuclear layer, INL: inner nuclear layer, GCL: ganglion cell layer [1]

---

[e] From statistical considerations prior to paper III



$Y_{ij}(t) = \beta_{i,1}\cos(\omega t + \phi_i) + m_{\beta_{i,2}}(t) + \beta_{i,0} + \varepsilon_{ij}(t)$

$i = 1, ..., 13$ test person

$j = 1, ..., 3$ replication

t time

ω, ϕ, α_i period length, phase, amplitude

m_β nonseasonal trend

ε_{ij} zero mean i.i.d noise

In studies, diurnal visual changes have been shown to occur with maximal visual resolution and detection before midday and a minimum after midnight[30,31]. Maximal sensitivity was found two hour after light onset and a minimal sensitivity four hour later, also corresponding to the length of the ribbons of the photoreceptors in studies on mice[32]. In a recent study, the retinal shedding process has been described in more detail and disk shedding, reduction of ribbon length, has been demonstrated throughout the day, with highest intensity in the morning[25]. Hwang et al. have demonstrated changes in CS, but not in VA in mice, indicating a reduction in all low and middle frequencies during nighttime[33]. The explanation for this is most likely diurnal and light induced variation in dopamine and regulation of the signal pathway in retinal ganglion cells[33].

1.3.5 Vision and sleep deprivation

The function of sleep remains the greatest biologic mystery of all times.
Sudahsu Chokroverty[34]

Sleep may be disrupted due to environmental situations like jet lag, shift work, noise or unfavourable environment temperature, and these are all known to cause changes in the circadian clock system[35]. Circadian rhythm disruption may act on several mechanisms. It has been shown to act on a central level[36] and on a retinal level involving dopamine, retinal cone and rod shedding and gene expression[1].

Few studies on vision and sleep deprivation have shown changes in visual function. In a study of 20 students, a minor loss in VA was reported after 46 hrs[37]. Another study reported loss of CS after 26 hrs sleep deprivation[38]. In our study[39], a small, but significant increase in RG threshold for high and middle CS was detected. Non- retinal effects are most likely to cause changes visual performance. Jackson et al.[40], measured human visually evoked potentials following 27-hr sleep deprivation. Their main findings were no effects on early visual processing, but distinct effects on higher-order cognitive processing. This is in accordance with findings in a paper on navigation[41], which described reduced visual task performance of the participants and suggested that this could be explained by reduced cognitive resources or reduction in visual field. In a paper on visual field performance after sleep deprivation, Rogé and Gabaude found indications of alteration in the participants' decision criteria when responding to a signal detection task, and that this may be the explanation of reduced visual function[42].

1.4 Methodes for assessing visual capability

1.4.1 Visual acuity

The usual method to evaluate vision is to examine the visual acuity (VA), which refers to the ability of the visual system to resolve details. According to the International Council of Ophthalmology (ICO), the visual acuity score of an individual should express the reciprocal of the visual angular size of the critical detail within the smallest optotype that can be correctly recognized by that individual[43].

Fig 5. EDTRS chart for examining visual acuity [2]

1.4.2 The evolution of visual acuity measurement

After early efforts by Heinrich Kuechler (1811-1873) in 1843 and Eduard Jaeger Ritter von Jaxtthal (1818-1884) in 1854, Franciscus Cornelis Donders (1818-1889) took initiative to develop the chart later known as the Snellen's chart[12]. Donders defined a formula and a reference standard for "the sharpness of vision". He instructed his doctoral student Hermann Snellen (1834-1908) to develop a measurement tool, a chart, based on a reference standard, a letter of 5 minutes of an arc. The candidate's view was supposed to be compared with this standard, thus giving the magnification[f] requirement (MAR) needed to bring the candidate vision to the same performance as the standard. Vision half the standard yields a MAR of 2 according to Donder's formula:

$$\frac{Seen\ size\ by\ candidate}{Standard\ seen\ size} = Magnification\ Requirement\ (MAR)$$

Donder defined visual acuity to be the reciprocal of MAR, thus making a MAR of 1 the equivalent of a VA of 1.0:

$$VA = \frac{1}{MAR}$$

Snellen published his chart in 1862, at the same time as V. de Haan published a population study, based on Snellen's chart. V. de Haan clearly showed that normal VA, understood as the population mean, was substantially better than Snellen's standard vision, and this has been verified in later studies[44].

Unlike Keuchler and Jaeger, Snellen designed special characters, or orthotypes, which he arranged in a letter chart both for near and far vision testing based on the standard 5 minutes' arch defined by Donders. Snellen's chart became the dominant tool for measuring VA and soon incorporated into rules and regulations concerning visual requirements.

---

[f] Magnification is the process of enlarging the appearance, not physical size, of something.

There are several pitfalls of Snellen's table[45], and National Eye Institute developed a new chart in 1982 by in accordance to standards later set by ICO[43]. The Early Treatment of Diabetic Retinopathy Study chart (EDTRS) was introduced with proportional spacing, geometric progression and sans serif letters[g], facilitating calculations and statistical processing of data. Anticipating that the VA recording would cover a wide range, it was decided to use graphics with logarithmic scales, thus the introduction of the logarithm of the Minimum Angel of Resolution (logMAR). A logMAR score of 0.0 corresponds to MAR of 1.0, or Snellen 6/6. For better VA (MAR>1.0) logMAR values become negative. On the EDTRS chart, the size progression is exactly 0.10 log units with one letter space between the letters and five letters at each row. Each letter correctly identified, gives a credit of 0.02 logMAR units. The EDTRS is not in common use in ordinary clinical work by most ophthalmologists, mainly due to unfamiliarity to the logarithmic scale (logMAR) of the chart and partly due to the apparent non-logical fact that improved VA yield a reduction in logMAR score.

---

[g] Any typeface in which the letters do not have serifs (small lines) added to them

1.4.3 Contrast sensitivity

Every light is a shade, compared to higher lights, till you come to the sun; every shade is light, compared to the deeper shades, till you come to the night.

John Ruskin (1819 – 1900)

Our ability to perceive details of a visual scene is determined by the relative contrast of an object and the surroundings or background, and the size of the object. The contrast may be due to difference in luminance, colour or both. This was acknowledged by the end of the 18th century, and in 1927 Michelson[46] described contrast as the maximum luminance subtracted by minimum luminance and divided by twice the mean luminance. In 1956 Schade[47] did the first studies of the contrast thresholds, or contrast sensitivity, in humans where he used an extended grating pattern in which luminance was sinusoidally modulated, so called sine-wave gratings.

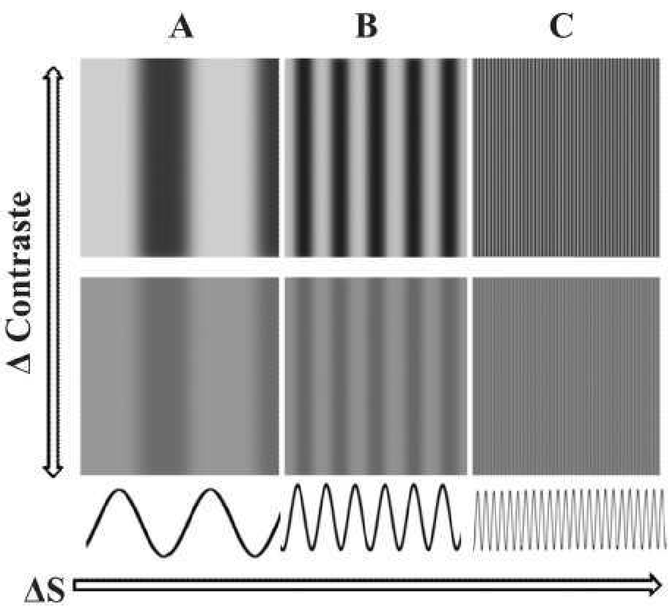


Fig 6. An illustration of sine wave grating. The wavelength decrease on the x-axis, increasing the frequency of cycles per degree of visual field. On the y-axis, the wave height is increased, thus making the gratings more visible. [6]

The reciprocal of the contrast threshold is CS of the visual system and was found to be a function of the frequency of the sine-wave grating. The variation of CS over a range of frequencies described the CS function.

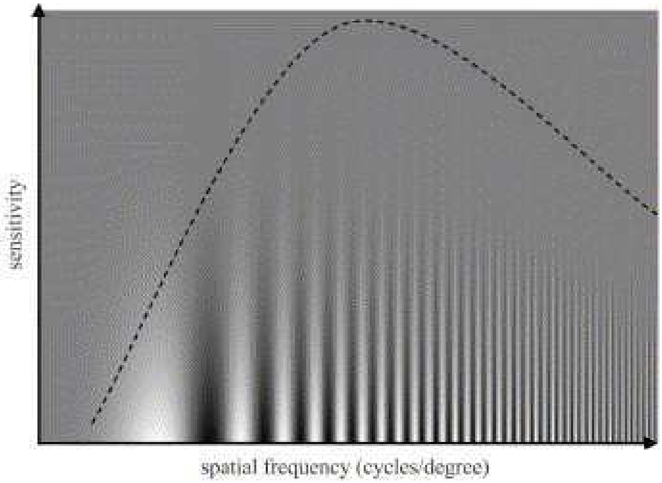
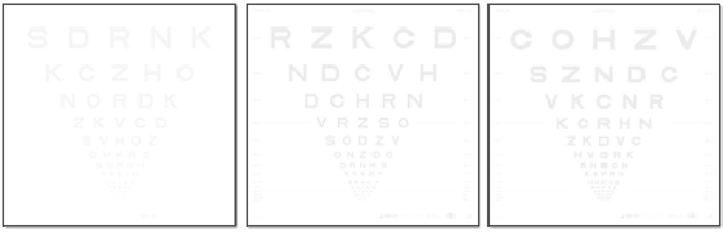


Fig 7. The line represents expected visual threshold or contrast sensitivity (CS) for sine wave gratings. The frequency increase on the x-axis. [7]

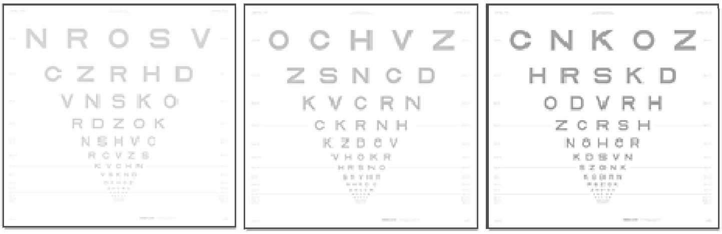
In the 1960s, theories of a multichannel model of the vision developed on basis of Shades research[27,48]. The model states that retina cells have different sizes and orientation and independently process or filter different size information. These functionally independent filters are so-called channels and are the building blocks of visual perception.

Testing contrast sensitivity

During the 1980ies several optional CS tests were developed, commonly using letters[49-51] or symbols, like Landolt C or the E test, printed in diminishing contrast. These tests are easier to perform than the sine wave graded tests and has become the preferred method of CS measurement in clinical settings. Low contrast letter tests are easy and fast to perform, and patients easily understand the reading task. It is questioned if low contrast letter is equivalent to sine-wave graded tests, or if low contrast letter tests is to be understood as low contrast VA tests. It is recommended to use the term *low contrast* *acuity test* for Regan test and *low contrast letter identification test* for Pelli-Robson letter contrast sensitivity chart[52]. The arguments against letter charts were later supported by Rohaly and Owsley[53], who claimed that Pelli-Robson CS and letter acuity cannot be used to predict the peak of contrast sensitivity. In addition, Regan stated that his test charts should be regarded as merely a "shotgun test" of CS and should be used as a low contrast visual acuity test[50]. This was partly opposed by Pelli and Robson, who claimed that attempting to functionally subdivide CS tests seems counterproductive as long as more clinical studies are needed to establish the efficacy of all CS tests[54].



1.25% Contrast 2.5% Contrast 2.5% Contrast version A



5% Contrast 10% Contrast 25% Contrast

Fig 8. Example of letter contrast chart with increasing contrast.[2]

The results of sine wave graded testing may be evaluated in several different ways. Early studies most commonly describe the CS by each single frequency plotted in a figure. The plot will indicate pattern of CS and may show patterns typically associated with clinical diagnoses[52]. The question of which of the different sine wave graded frequencies that correlate best with the visual performance has been discussed among others, according to Ginsburg[55].

A second method to describe sine-wave graded tests is by using a collective descriptor of the different CS frequencies as a generalized parameter for CS assessment. The concept of Index of contrast sensitivity[56] (ICS) is a follow-up on an idea of using and reporting normalized CS values[57] or using area under the curve[58] as a measure of CS. Acknowledging the presumed increased importance of the peak frequency and adjacent frequencies, the ICS gives more power to these frequencies.

1.4.4 Colour vision

Color vision is an illusion created by the interactions of billions of neurons in our brain.

Peter Gouras

Colour vision is the perception of light absorbed by the three types of retinal cones (S, M and L) with different peak spectral sensitivity within the spectre of visible light (400-800 nm). The spectral responsiveness for the different cones defines the visual spectre. S cones have maximal sensitivity in the lower spectre of visible light (420-440 nm), while M (534–545 nm) and L (564–580 nm) cones peak at the longer wavelengths. Colour perception is a response both at retinal and cerebral level, largely influenced by the cone spectral responsiveness. If a type of cone is missing or has a shift in peak sensitivity, chromatic sensitivity change. Such changes may be congenital or acquired.

1.5 Development of visual standard requirements

The need for visual standards has been driven by the technological and industrial development and a growing concern about the consequences of reduced visual function.

1.5.1 Introduction of standards for visual acuity

Surgeon General Thomas Longmore[59] published *The Optical Manual 3rd edition*[20] in 1885, giving us insight in the development of visual requirement in the Royal Armed Forces. Historically, it was the introduction of long-range rifled arms with graduated aims replacing smoothbore muskets, which made it necessary to pay attention to the visual capacity of recruits. From 1863, efforts were made to have recruits with perfect visual acuity, but this made it impossible to obtain a sufficient number of recruits. The limits that became the regulation standard for visual acuity was published as an order from commanding officer:

> "*That man should not be received into the service who do not see well to 600 yards at least, a black centre 3 feet in diameter on white ground.*"
>
> Army Medical Department,
> 3rd December, 1863
> J. B Gibson[h,60]

Test cards with test-dots were developed to test this in a clinical situation. The test-dots were 1/5 of an inch in diameter and scattered on a card presented at ten feet. In this way, the test-dots had the same apparent size as the above-mentioned 3 feet bulls-eye. Test-dots in circular and square variations were developed and used in the following years, until they were subsequently replaced by Snellen's chart. Snellen's chart was introduced to the medical officers as early as 1864, but was considered unfit for use because a

---

[h] James B Gibson was the Director General Army Medical Department from 1860 to his retirement in 1867. The General also saw service in the Crimean War, where he was personal physician to the Duke of Cambridge. The Director did encourage Surgeon General Sir Thomas Longmore to publish Army Medical Officers Ophthalmic Manual in 1863.

substantial number of the recruits were illiterates. According to Longmore[20], an Army report in 1884 suggested that 13.8 % of the recruits were unable to read.

The Royal Navy adopted other standard. As stated by the Queen's Regulation and Admiralty Instructions from 1879, the eyesight should not be defective. The medical officer was instructed to ensure that *"the eyes should be clear, intelligent, expressive of health, and the eyesight be good. Eyesight, or power of vision, should be ascertained by use of test-types. If failure to read the test-types the person is to be tested with objects familiar to him at distances according to the size of the object"*. The reason for retesting was to ensure that the failure of reading test-types was not due to other causes than defective eyesight, e.g. illiteracy.

The German navy had adopted Snellen's chart in 1872 and defined normal visual acuity to Snellen's 1.0. Candidates having visual acuity below 0.5 were considered unfit for duty. The requirement for admission to the navy was visual acuity of Snellen's 0.75 corrected or uncorrected.

Norwegian authorities, after a meeting in 1922 between two ophthalmologists and the head of Norwegian Public Roads Administration, decided requirements for non-professional and professional drivers[i, 61]. The requirements are by all practical means the same today[62].

Standard requirements for VA[21] have developed within several occupations since the introduction of Snellen's table. A common trait is that few of the requirements are based on task-based evidence, and that they have in too little extent been validated.

Snellen's chart as a predictor of visual ability

Thomas Longmore and his colleagues believed that Snellen's chart could be used in the application of any rule of standards concerning visual acuity. He was also aware that

---

[i] Professional drivers: VA of at at least 5/10 for each eye uncorrected or at least 5/6 for best eye uncorrected and 5/15 for worst eye.

other aspects of vision were important and he proceeds later considerations by others[63] on this topic by decades. In his book, he cites “a military friend” who states:

> *“As a rule, from the results of his experience, that a soldier to be effective must be able to distinguish clearly a man from any other object at least at a distance of 500 yards under ordinary illumination, as in a moderately clear daylight, and with no more striking contrast of background than is met in ordinary field or moorland. A sentry*[j] *on advanced post who could not distinguish an enemy at that distance in front of him would endanger the safety of a force. With such a background as the “sky-line”, or any background forming a marked contrast with the object, a man ought to be recognised at 1000 yards. The amount of light reflected from the object looked at relatively to the amount the light reflected from the objects by which it is surrounded, and the character of the background, are always important elements in regard of visual perception, in addition to the size of the visual angel subtended by the object.”*

Longmore further states: “*That the rule of recognition at 500 yards may be applied by means of Snellen’s type. For a man of 6 feet, the visual angle under which he would be seen at a distance of 500 yards is 13’ 44’’, or nearly 2.7 times the visual angel under which Snellen’s type are seen. A man 6 feet in height to be seen would have to stand at a distance of about 1375 yards off. But practically at such a distance, owing to the effect of the intervening atmosphere and other circumstances, the man could not be distinguished, although an object having the same visual angle might be seen plainly in nearer position under adequate illumination.”*

---

[j] Sentry: A guard at a gate or other point of passage.

1.5.2 Colour vision occupational requirements

The request of colour vision test was first addressed by Wilson[64] in 1855, when he pointed out the necessity to use coloured signals secondary to non-coloured signals, but it was not until 1877 the first regulations were adopted. After a railway accident in Sweden in 1877, the Swedish ophthalmologist Holmgren introduced the theory of colour vision deficiency (CVD) as a major cause of the incident[65], although this later has been disputed[66]. The accident was, never the less, one of several contributing factors for the introduction of colour vision (CV) standards. The increased awareness of CVD and the increased use of coloured signals created public demand for better safety in public transportation[67,68].

Colour vision testing of varying standards and methods were subsequently adopted for railways and maritime activities from 1877 and onward. In 1919, standards were set for the aviation industry and from mid 1930s also for road transportation in Britain[67]. A requirement for normal CV in road transportation was never adopted in Norway[61].

Expect for the British road transportation CV standard, which was brought to an end in 1960, few questions have been made for the validity of CV standards in other occupations. Aviation regulations have adopted the findings of a task performance study[69], allowing a subgroup[k] of deutan[l] and protan CVD to be commercial pilots. In 2001, the International Commission on Illumination (CIE) recommended a new standard[70] for CV testing and classification of the result by classifying the CV in four groups (CIE 1-3 and non-classifiable). This recommendation is now outdated and not according to the findings published by Bailey & Carter[71] and Carter & Barbur[72].

---

[k] Approximately 35 % colour deficient applicants would be classed as safe o fly.

[l] Deuteranomalous observers have two different L-cones and missing the M-cone with reduced function. The same for protanomalous observers who have two different M-cones, missing the L cone.

Testing colour vision

There has been advances in the development of colour vision tests since they were first created in the 1800s, but there is no single colour test that can rapidly and accurately screen, diagnose and classify any colour vision defect[68].

During the second half of the 19th century, several colour tests evolved into an array of methods. Most commonly used are the pseudoisochromatic plates (e.g. Ishihara), but also lantern tests (e.g. Edridge-Green, Holmes-Wright), hue tests (e.g. Farnworth) and computerized tests (e.g. CAD) exist[68].

Pseudoisochromatic plates (PIP) have figures placed in a randomized dot patterns. The plates have three principle functions; *transformation plates* where individuals with CVD should see a different figure than individuals with normal CV, *vanishing plates* where only individuals with normal CV can recognize the figure and *hidden digit plates* in which only individuals with CVD could recognize the figure. Some, but not all, PIP tests give the ability to diagnose and quantify the severity of the CDV[73].

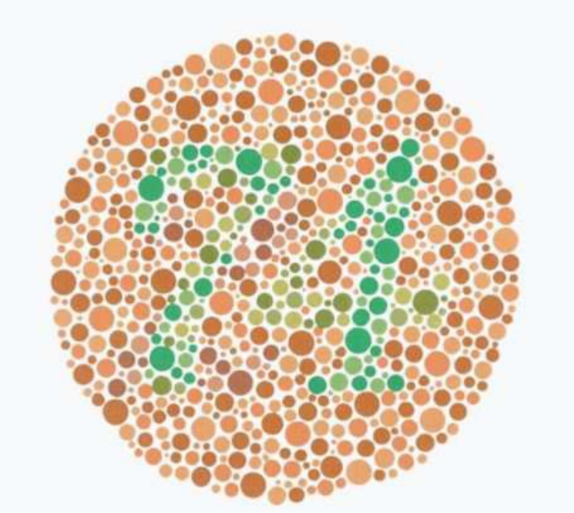


Fig 9. On this Ishihara plate, number 74 should be visible for subjects with normal CV. Viewers with CVD may read it as 21 or may not see any number at all.

A hue test in common use is the Farnsworth-Mansell test. The aim of the subject is to arrange the colours in each row in ascending hue. A hue test may be time-consuming[74], but can diagnose and quantify the severity of CDV in more detail[75].

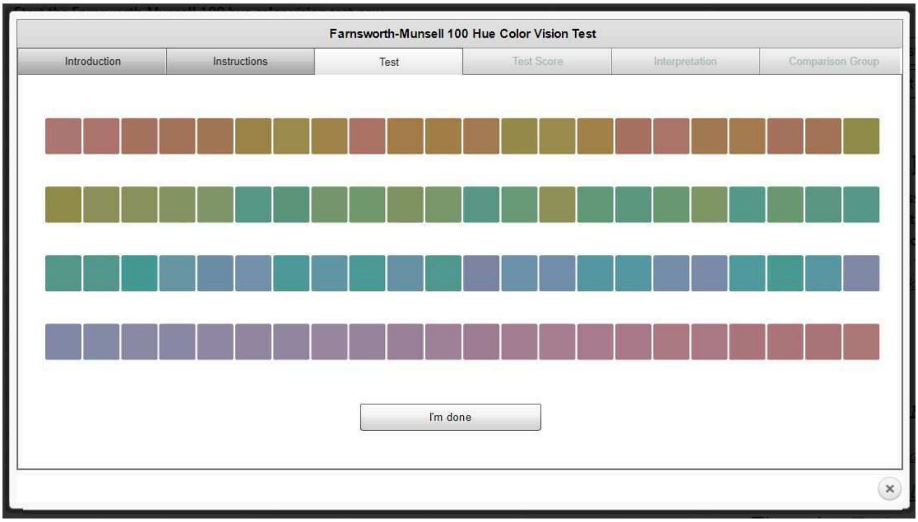


Fig 10. Farnsworth-Mansell hue test. In this example, only the last row is correct.[3]

In a lantern test, the test subject is exposed to light equivalent to signal lights used at sea and is supposed to name the right colours. The lantern test is a practical test and fails the subject in accordance to the task, but it is not suited for diagnosis of the CVD. Lanterns exist in numerous variations, with low inter-correlation and none in compliance with the standard of safe navigation[72,76].

Computerized tests have been developed and are in principle like PIP tests. The advantage of these test are the ability to quantify and qualify the CV[24] also in relevance to the job task[69]. Some limitations in the usefulness of computerized test exist. There is a need for standardization and calibration of the screen, and there are vulnerabilities of the computer and need for software update.

Another method to test colour vision is by chromatic sine wave gratings. Both red-green and yellow-blue chromatic sensitivity testing show a different response than that obtained for achromatic CS. Peak sensitivity for red-green and yellow-blue are at a higher threshold in lower frequencies. Peak CS for red-green is approximately three times the CS for yellow-blue, both on low CS frequencies[22]. This method is rarely in use in clinical settings and no standards to diagnose the CVD have been developed.

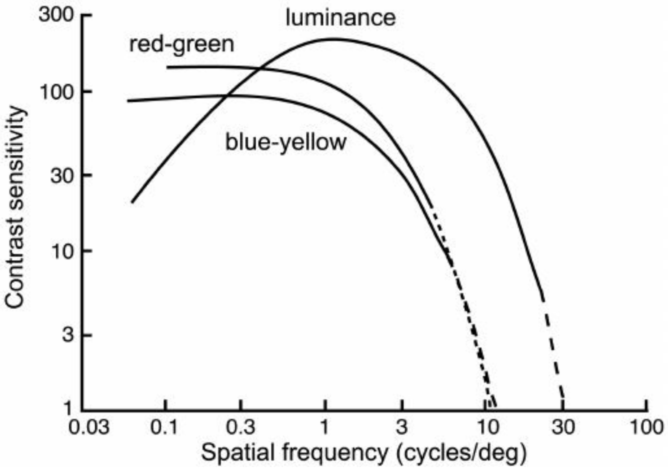


Fig 11. Contrast sensitivity curves for RG and YB (chromatic CS) and luminance (achromatic CS)[5]

2. Rationale and objectives of the study

Visual performance is considered essential for navigation in sea, land and air operations. All personnel entering or continuing in visually demanding operations in seafaring are carefully selected according to fitness standards.

A direct linkage between the methods for evaluating vision and the visual performance is still poorly founded, but some studies have indicated that CS may be more important than VA[77,78]. Evaluation of CS has the potential to improve the estimate of visual function and performance, but this still has to be proven by well-designed studies on relevant populations. Few studies, if any, have measured CS in personnel entering or serving in relevant occupations and evaluated the correlation between CS and visual performance.

The main objective for this thesis was to obtain more information about vision tests used for selection of personnel who perform work highly dependent on good visual function.

The specific aims included:

Paper I. To establish reference values of contrast sensitivity in young adults with normal visual acuity, and to compare two different test methods.

Paper II. To study the correlation between observation task performance and visual acuity, contrast sensitivity and environmental light in a simulated maritime study.

Paper III. To evaluate visual function under total sleep deprivation, especially for chromatic and achromatic contrast sensitivity.

3. MATERIALS AND METHODS

3.1 Study sample

3.1.1 Sample of Paper I

A total of 194 military recruits from the French Air Force and the Royal Norwegian Navy were invited to participate in the study. Fourteen candidates were excluded, as they did not meet one or more of the following inclusion criteria: age 18–26 years, best eye uncorrected VA logMAR 0.00 or better, normal CV by Ishihara's test and no previous refractive surgery in either eye. Thus, the study group included 180 subjects.

3.1.2 Sample of Paper II

In total, 74 cadets attending the RNoNA volunteered for the study. Due to malfunction in the first run of the simulator, nine cadets were excluded from the study. Another five cadets failed the Ishihara 24 plate CV test and were also excluded. Thus, 60 cadets (50 males and 10 females, with mean age 24.1 years (range 17.9 to 32.8; SD=2.9) completed the study. None reported somatic or mental health problems. Six cadets wore contact lenses, ten used glasses and three had undergone refractive surgery for myopia. The mean best eye VA in the study group was -0.10 (range -0.20 to 0.16; SD 0.09) at 85 cd/m^2 on a logMAR scale.

3.1.3 Sample of Paper III

In Paper III, two separate study weeks were planned. Eleven male fast patrol boat navigators from the Royal Norwegian Navy volunteered for the study. Their mean age was 26.8 years (range 23.1 to 30.6; SD 2.0). An ophthalmologist at the Institute of Aviation in Oslo examined the group before entering the study. The initial number of participants in the first week was eight navigators. Due to a mission deployment, three study subjects had to drop out from the last study week and were substituted by new navigators during the second study week.

3.2 Study design

3.2.1 Study design of Paper I

The study was an observational prospective cross section study, where individual data were recorded for CS and VA in a group of young healthy adults with VA better than 0.01 logMAR. Frequency CS data were used to compute ICS for all three CS test methods. The results, both recorded and computed, were used to describe reference values for CS and ICS for the group. ICS was used to study agreement between the three test methods.

3.2.2 Study design of Paper II

The study in Paper II was designed to be an experimental prospective cross-sectional study. The participants were examined in the same way as described in Paper I, by recording logMAR score and visual CS frequency data obtained by Optec 6500 and CVS 1000-E, and computing ICS for all the CS test methods. The experimental part in this paper was conducted using five identical fixed-base, full-scale Polaris simulators (Kongsberg Maritime AS, Horten, Norway) at the RNoNA. Skjold class simulator model was used, with hydrodynamic and performance characteristics like the real vessels. All bridges had a generic layout, with a 270-degree view-field (180 degrees forward view, 90 degrees aft). The participants did not use any electronic or paper based chart and simulator ran in autopilot in pre-programmed route at a speed of 20 knots/hour (37 km/h).

Along the planned course, three objects were distributed at randomized distances, orientation and sequence to allow for up to 20 observations at each run. Simulated external light was set at 50, 80 and 90 % relative darkness, as defined by the simulator settings, giving an illusion of photopic to low mesopic light conditions. The subjects were asked to identify and report each object they observed. The time of observation was noted allowing the distance for each observation to be calculated.

3.2.3 Study design of Paper III

The third study had a repeated measure design, collecting VA and CS ten times during 60 hours of total sleep deprivation. Individual collected data were analysed on group level and the first 24-hour period was compared with last 24-hour period.

3.3 Measurements used

3.3.1 Contrast sensitivity measurements in Paper I and II

Binocular CS was measured by two commercially available tests using sine wave gratings at different spatial frequencies. The Optec 6500 FACT (Functional Acuity Contrast Test) (Stereo Optical, Chicago, USA) was used for mesopic (3 cd/m^2) and photopic (85 cd/m^2) measurements at the spatial frequencies of 1.5 cpd, 6 cpd, 12 cpd and 18 cpd. Mesopic CS was measured after a ten minutes' dark adaptation, and then the test was repeated in photopic light. For the other test, we used the CSV-1000E (VectorVision, Greenville, Ohio, USA) for photopic (85 cd/m^2) CS measurements. This test also consists of sine wave gratings, but for the frequencies 3 cpd, 6 cpd, 12 cpd and 18 cpd. Index of contrast sensitivity[56] was calculated for each subject by using the results obtained in the three different CS measurements.

Index of contrast sensitivity was defined as the sum of the residual differences (positive or negative) from the population median in each frequency. The differences were weighted according to the presumed clinical importance of each frequency. Thus, 6 cpd was given the highest power (factor 3). The frequencies 3 cpd and 12 cpd received factor 2, while the remaining test frequencies were not weighted at all. A performance equivalent to the reference group median of all tested frequencies should yield an ICS value of zero.

$$\begin{aligned} ICS = {} & (1.5cpd - 1.5rcpd) + 2(3cpd - 3rcpd) + 3(6cpd - 6rcpd) \\ & + 2(12cpd - 12rcpd) + (18cpd - 18rcpd) \end{aligned}$$

Equation 1. Index of contrast sensitivity (ICS) is the sum of the residual differences for the recorded contrast sensitivity (CS) at each frequency (cpd) and a reference CS (rcpd). The reference CS (rcpd) is the median value collected in a reference population from Paper I

Median values to calculate ICS in Study I and II were collected in Study I[79], where reference percentiles also were reported. Index of contrast sensitivity is reported as logarithmic values in both papers.

3.3.2 Contrast sensitivity measurements in Paper III

In this study, we used VIGRA-C[80], a non-commercial system developed at the Norwegian University of Science and Technology using a high-resolution monitor. The system allows chromatic and achromatic sine wave frequency testing with a mean luminance of the monitor screen of 40 cd/m^2. We chose the frequencies of 2.0, 5.9 and 11.8 cpd for testing the achromatic CS, as human peak achromatic CS is found in this interval. To cover the expected peak chromatic CS, the frequencies of 0.6, 2.0 and 4.7 cpd were chosen to test the RG and YB CS. To facilitate the test procedure, Vigra-C was set up with ten predefined contrast levels at a constant luminance, enabling a stepwise examination of CS. The highest steps were defined to be above the expected level of resolution of human CS for each frequency tested.

3.3.3 Visual acuity measurements

In paper I and II we used the Optec 6500 EDTRS chart in long distance mode on a logMAR scale at photopic light conditions (85 cd/m^2). The chart has a maximum resolution at logMAR -0.20. In paper III, the CSV-1000EDTRS logMAR chart with a maximum resolution of -0.30 logMAR was used. The chart was read at 2.5 meters with a light level at 85 cd/m^2.

3.3.4 Colour vision measurments

To examine CV, Ishihara 24 plate pseudoisochromatic test in standardized daylight colour temperature of 6280° Kelvin was used in all three papers.

3.3.5 Observation performance measurements

In Paper II, the study participants were to observe three different objects distributed at random distance and orientation along a pre-planned course in a ship simulator.

Fig 12. The three targets used as objects for observation. The candidates were instructed to identify the objects, and observation distance in meters was calculated based on the time of observation.

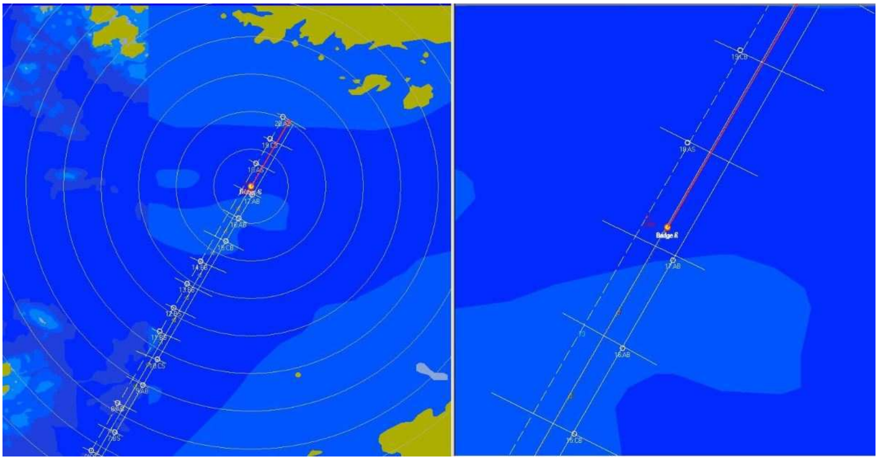


Fig 13. The map shows the pre-planned track for a simulated ship's course. Each object (fig 12) was placed on the port or starboard side of the course line in a randomized pattern.

The observation distance was calculated by the speed of the vessel and time of observation. The task was done three times under different environmental light conditions; low mesopic, mesopic and photopic light.

3.4 Statistical analyses

3.4.1 Statistical analyses used in Paper I

Descriptive statistics for each CS frequency and ICS for each of the CS tests were provided. Normality of data was considered by Shapiro-Wilk test. The agreement between the different methods was studied using the Bland-Altman technique[81]. Paired t-tests and Wilcoxon signed rank test were done to analyse the "differences of mean" between the ICS tests. Histograms of the "differences of mean" were used to evaluate the usability of Bland-Altman technique. PASW statistics 18.0.3 was used for all analyses (Predictive Analytics Software, SPSS Hong Kong).

3.4.2 Statistical analyses used in Paper II

Possible relationships between visual observation task performance and visual functions, age, sex, glasses and environmental light were studied by stepwise linear regression. LogMar VA and calculated ICS obtained in female and male cadets were compared using the nonparametric Mann-Whitney U test. The normality of visual data was tested by Shapiro-Wilk test. Statistical analyses were performed using IBM SPSS Statistics version 22.0 (IBM corp., Armonk, NY, USA).

3.4.3 Statistical analyses used in Paper III

In paper III, the Wilcoxon signed-rank test was used, as a normal distribution of the results could not be assumed. The analyses were made at a group level. As multiple comparisons were made, the level of statistical significance was set at 0.01. Statistical analyses were performed using IBM SPSS Statistics version 22.0 (IBM corp., Armonk, NY, USA).

3.5 Research etics

The study presented in Paper III was approved by the Regional Committee for Medical Research Ethics in Western Norway (06/453/2006) and the Phd project was approved in 2008 (2008/4759) and by the Norwegian Data Inspectorate (18918/2/KS 2008). All participants gave written consent, and all data containing personal identification at the University of Bergen were destroyed in 2008 for Paper III and in 2011 for Paper I and II. An opportunity to withdraw from the study at any point was given. All participants were granted immunity against the use of recorded data for the use of medical selection in the Armed Forces, both in Norway and France. The test subjects were not paid for participating in Paper I and II. In Paper III, the RNoN paid the participants ordinary salary.

4. SUMMARY OF RESULTS

4.1 Paper I

Visual acuity and CS for 180 recruits were collected and ICS was computed to describe cohort data and agreement between the tests. CS frequency data showed a highly skewed data sampling toward the high thresholds, especially on the low frequencies for the three test methods. Although the skewness and non-parametric distribution of the results were also evident in the calculated ICS, the results are reported as normative data for this age group according to the inclusion criteria. Agreement between the two photopic tests was found to have a fairly consistent “difference in mean” at all ICS scores. When comparing the mesopic test to the two photopic tests, the agreement was considered less evident, as the correlation between the tests was not consistent.

4.2 Paper II

In this study, no statistically significant correlation between visual task performance and VA or ICS was found. A highly significant improvement of identification distance was recorded for each stepwise increase in environmental light when comparing low mesopic, mesopic and photopic light settings. A statistically significant improvement was also found when identification distance was examined for each observation in each run, indicating a learning effect. Male subjects were capable of detecting targets significantly earlier than female subjects in all light conditions.

4.3 Paper III

A 60-hr sleep deprivation did apparently induce slight, but statistically significant increases in mean threshold for red-green contrast sensitivity at middle (2.0 cpd) and high frequencies (4.7 cpd). No such changes were detected in achromatic yellow-blue contrast sensitivity when comparing the first and last 24-hr test periods.

5. DISCUSSION

5.1 Methodological discussion

5.1.1 Study design

Paper I had an observational cross-sectional design. The objective was to describe reference visual function in a young adult population by VA, CS and ICS. The cohort data was the basis for studies of agreement between the three calculated ICS as well as giving reference ICS values to use in Paper II.

In Paper II, we used an observational cross section design with repeated measurements, where the test subjects repeatedly performed an observation task ten times in three different light settings. A repeated measure design may reduce the variance of estimates of observation distance and allows statistical inference with fewer subjects. To perform an observation task in a simulator is always an imitation of real world observations, and this limits the possibility to compare the results to other studies. Visual displays are often simplifications and the exactness may not be representative to actual maritime scenes. The positive side of performing the study in a simulator is the possibility to standardize the conditions and rule out the intrinsic of the ever-changing nature.

Paper III had a time series design where CS and VA were collected ten times during 6o hours sleep deprivation. Due to the expected diurnal variation in visual function, we chose to compare the first 24-hr period with the last 24-hr period, as this would level out the cyclic variation.

5.1.2 Study population

All studies included young healthy adults with vision defined as normal based on visual acuity and colour vision. The aim in Paper I was to give reference values for CS and ICS in a population selected for work highly dependent of visual function. Study subjects were selected accordingly to military requirements, which were stricter than the civilian statues at the time. The number of subjects included in the study was limited to the number of subjects available at both study sites and complied with the inclusion criteria. The inclusion criteria were best eye uncorrected visual acuity LogMAR 0.00 or better, normal colour vision and age between 18 to 25 years. The Norwegian cohort consisted of personnel selected for duty as conscripts in RNoN and in the Royal Norwegian Air Force. Conscript personnel are recruited from all parts of Norway after passing a medical screening process. At the time, female conscripts volunteered for the service, while men were called to service. The French cohort consisted of personnel applying for service in the French Air Force with the intention to become air pilots. In Paper II, we examined the cadets at RNoNA with normal CV, with no limitations regarding to VA. The aim was to have subjects with a larger variety in VA, but otherwise comparable to the study group in Paper I. Cadets have served in the Norwegian Armed Forces before entering the RNoNA. They are recruited mainly after service in RNoN, but may also represent other military branches. A strict medical selection screening process is not applied on all cadets, as other qualifications may be considered more important for the service.

The study population in Paper III was defined by the availability of experienced fast patrol boat male navigators taking part in another study[41]. The population sample was small due to availability of participants and simulator time. A larger cohort would have improved statistical power.

5.1.3 Visual tests

Visual functions may be assessed by several different methods for each of the different aspects of vision. We chose to include VA measured by EDTRS table and CS measured by sine-wave gratings.

The EDTRS visual acuity table is made according to Visual Acuity Measurement Standard by ICO[43], and is the preferred method for examining VA in scientific settings. The test allows statistical evaluation and a more fine-tuned score by its use of a logarithmic progression in the orthotypes. We used a scoring protocol giving credit of 0.02 logMAR units to each letter correctly read. The OPTEC 6500 EDTRS chart allows 60 letters to be identified, giving a maximum score of -0.20 logMAR. One misread letter, 59 correct identified letters, yields a score of -0.18 logMAR. The test-retest accuracy for EDTRS, when letter-scoring, is found to be 0.08 logMAR or four letters, gives a 95 % confidence interval of 0.10 logMAR[82]. In both Paper I and II we experienced subjects scoring -0.20 logMAR, indicating that the chart may not able to give full credit to subjects with excellent VA. In Paper II, this may represent a source for misinterpretation of the data, as six of the participants might have had a score better than -0.20 logMAR. The ceiling phenomena is not believed have influenced the results of the study due to the low linear relation between VA and observation (R square close to 0.0). In Paper III, the CSV-1000EDTRS maximum score was -0.30 logMAR, and no ceiling effect was experienced. Best corrected VA in the group was -0.24 logMAR.

No standards are agreed upon when it comes to CS tests, and this obviously reduces the possibility to compare the results obtained in different studies. Nevertheless, there are arguments for choosing sine-wave grading tests instead of contrast letter or symbol charts. As discussed earlier, sine-wave single frequencies are believed to give a better estimate of CS in accordance to the visual channel theory. In Paper I and II, we experienced ceiling effect at most frequencies and light levels for both OPTEC 6500 and CSV-1000E. The effect was most pronounced in Paper I, where up to 76 % made the highest score on 1.5 cpd (OPTEC 6500 85 cd/m^2). This obviously reduced the possibility to create a true expression of the CS of this population, and the results must be interpreted as specific for OPTEC 6500 and CSV-1000E. VectorVision give "Contrast Sensitivity Values and Norms" for the CSV-1000E based on three different populations. Presumably, young diabetic patients are used as the reference group at age 11-19 years. The article, by Prof J. Krasny at University Hospital in the Czech Republic, is not available, but the population means reported by VectorVision are close to the median values in our Paper I. The population norms for age 20-55 are described in a Food and Drug Administration (FDA) study (not available) on refractive surgery. Mean preoperative VA, presumably best corrected VA, for the subjects were -0.09 logMAR and average age 36 years. Mean CS for every cpd were slightly lower, except for 18 cpd, in this population than median values in our paper. VectorVision does not comment on a possible ceiling effect in the Czechoslovak article or in the FDA study. In contrast to the population norms given by VectorVision, our paper was based on inclusion of young people without any known disease and VA at least 0.00 logMAR.

Several attempts have been made to describe CS by a single collective descriptor instead of using all the single frequency results. A collective descriptor would facilitate the use of sine-wave grating CS in clinical settings. In Paper I and II, we chose to follow up the concept of ICS as a new measure for CS. The idea behind ICS is to consider the presumed importance of the different CS frequencies. To the best of our knowledge, none of the collective descriptors, like "area under the curve" or normalized values, have been used in observation studies, neither have they been described for the populations we looked at.

5.1.4 Data analyses

In Paper I, the statistical analysis of the recorded data showed a high skewness towards the high threshold with a marked ceiling effect of the frequency data. The data reported are based on the non-normal distribution of the results[83] and the requirement to use median in the calculation of ICS. In addition, the calculated ICS showed skewness towards the high ICS-score. This was most evident in the photopic tests. To evaluate the comparability of ICS calculated from each of the tests, it is recommended[84] to do a Bland-Altman agreement study[81]. The method assesses two aspects of agreement: how the methods agree on average (mean) and how the results agree on individual level. The method is considered robust and may handle agreement if the distribution of the "differences of mean" is close to normal. In this paper, all three distributions were considered normal by inspection of the histograms.

Paper II used visual data recorded by the same methods as in Paper I. Index of contrast sensitivity was calculated using the median values for cpd frequencies collected in Paper I. Index of contrast sensitivity calculation is based on the median values for the specific cohort[56], but this will reduce the usefulness of ICS. One purpose of Paper I was to create a norm for median values for calculation of ICS that may be used in other studies or for individuals. If ICS values are supposed to be comparable over time and for different studies or examinations, median values must be treated as a constant. The observation data were collected in simulators where the ships sailed a pre-programmed track with visual targets positioned along the course. Ship speed was set to 20 knots (10.3 m/s) as this speed allowed some ground to be covered within the timeframe of 15 minutes. A faster speed would have made it possible to do more observations, but at the same time increase the margin of error when calculating the distance to the observed targets. All subjects could detect the ten first targets within the timeframe and the statistical analyses were based on this consideration.

In Paper III, visual data collection were done every 6th hour and repeated ten times. Contrast sensitivity was analysed on frequency level, as ICS was not introduced as a method at the time of data collection and analysis. Diurnal rhythms affect vision, and this was reflected in the statistical analyses. We chose to compare the first 24 hrs period with the last 24 hrs. This model will level out the expected circadian rhythm and give a possibility to detect changes of vision. Other procedures for analysis of visual changes were considered[85], but the limited number of subjects hampered the possibility to choose another approach.

5.1.5 External validity

This thesis adds to the knowledge of visual function in young navy personnel. The findings may apply in other services and in other countries for military personnel in the same age groups recruited for working in environments highly dependent on visual function.

Our findings may also be relevant for selection purposes of non-military personnel. The study populations were young and had good visual performance on VA, which make them comparable to civilian people selected for and introduced to perform working tasks with strict requirements on visual function.

5.2 General/main discussion

5.2.1 Vision and new navigation aids and methodes

The art of navigation has evolved and changed its character with the introduction of Integrated Navigation Systems (INS). Electronic Chart and Display Information Systems (ECDIS) have become mandatory and navigation is highly supported by navigation satellite systems like NAVSTAR Global positing system (GPS)[86]. However, an investigation report by the Norwegian Maritime Directorate[87] shows that incidents of grounding were not reduced from 2000 to 2011, in a period when ECDIS was implemented. *"ECDIS assisted grounding"* has been introduced by Marine Accident Investigation Branch[88], and it has been shown that the introduction of INS did not reduce the mental efforts of safe high speed navigation[89]. Navigation is still highly dependent on visual control of the surroundings, although automatic identification systems[90] and autonomous ships[91] are developing. Most of the accidents in maritime settings are attributed to human erroneous action[92], but few have been able to point at the direct cause of human error[9,93]. Norwegian regulations[94] and international standards[95] have recently been updated and the visual requirement (VA) for "a proper lookout" has been reduced to best corrected Snellen decimal visual acuity$\geq$0.5. The introduction of ECDIS and increased use colour coded visual displays have changed the way navigators work, and the ability to use colour coded signals as an aid in navigation and bridge work has not reduced the need for normal CV[24,96].

5.2.2 Vision and observation

Although it is evident that the quality of vision is relevant for the ability to observe, this is not well documented in the current literature.

Several methods to test visual capabilities may be described, and the results may evaluated according to different purposes or tasks. In maritime settings, Donderi[97] is one of few, according to Carter[98], who have studied vision and observation capabilities. The study task was to observe and identify life rafts afloat in a predefined search area. Environmental factors, such as light, wind, sea state and ships roll, were the most important predictors of detection percentage and detection distance of life rafts. In addition, colour vision deficiencies (CVD) and reduced letter contrast visual acuity were negatively correlated to detection percentage, but not to detection distance. High contrast VA did not correlate to any of the performance outcomes. A list of Performance-Shaping Factors[93] were used to analyse navigation accidents in the RNoN from 2004 to 2012, and visual fitness was assessed in all navigators involved. In one case, the officer on watch who failed to see landmarks had a severe reduction of high frequency CS[99].

Most visual observation studies look at the association between visual capabilities and driving performance. Performance is often estimated by self-reported driving outcomes, driving performance in simulators, but also by on-road motor vehicle crash indices. In a review[100], the impact of VA, CS, visual field, diplopia, and CV on safe driving were evaluated, and the conclusion was that the validity of the tests are insufficient. Wood and Black[101] reviewed the impact of ocular diseases, like cataract, glaucoma, age-related macular degeneration, hemianopia and diabetic retinopathy on driving performance. They stated that there is growing evidence to suggest that ocular disease is associated with driving performance, but it is unlikely that VA will be the best tool to assess visual performance. Blane[102] reviewed the impact of cataract on driving performance and found highly inconsistent results. In a study[103], twenty young subjects who were equipped with glasses giving average reduction in LogMAR VA from -0.13 to 0.54 had a 22 % reduction in task score. This method is not often used and the study is one of few that quantify the result of reduced VA. Another study found decimal VA < 0.2 compared to VA 1.0 to be the strongest predictor of self-reported reduced night driving performance (odds ratio 6)[104]. One study point out that a combination of VA and CS, examined by Pelli-Robson letter contrast sensitivity chart, had predictive value for the drivers' ability to detect road objects[105]. They reported that the best prediction was obtained by using the current standard, photopic VA in addition to mesopic VA and/or photopic CS. Contrast sensitivity was fund to be a significant performance predictor when studying highway-sign discriminability in a group of drivers[106].

The methodology of the studies varies and this reduces the possibility to interpret the results and to draw valuable conclusions. Owsley et al.[107] still claims that there is little evidence that VA screening tests enhance driving safety and performance.

5.2.3 Vision and sleep deprivation

Sleep deprivation is a challenge in the transport industry and is a known risk factor in maritime transport. Lack of sleep has been considered to play a role in a 82 % of the groundings happening between 0000 and 0600 a.m. investigated by Marine Accident Investigation Branch[9]. In all these cases, contributing to 35 % of all groundings, the watch keeper had fallen asleep. The same findings have been reported by Norwegian Maritime Directorate in 2011, were 25 % of the groundings were due to “falling asleep on watch”[87]. National authorities are focusing on sleepiness (the tendency to fall asleep) and fatigue (a feeling of tiredness or lack of energy) in the statutory regulations. In the Ship Safety and Security Act regulations, they state the need for sleep both on daily and weekly basis[108]:

“*Time of rest must be at least 10 hrs every 24 hrs and 77 hrs at every 168 hrs”*.

Sleep deprivation is a condition that occurs in the absence of sleep. Sleep is a basic human need and the effect of sleep deprivation is associated with a large number of adverse outcomes, both in short and long terms[35]. In the frame of this thesis, the short-term adverse effects are the most relevant.

A group of navigators who took part in a 60-hrs sleep deprivation study in a simulator study observed and classified other ships in the area of operation[41]. A significant reduction in visual observation performance was found as an effect of both time ($p<0.001$) and circadian rhythm ($p<0.001$). The subjects also had reduced saccadic velocity[109]. Sleep deprivation reduces tear film osmolality, reduces the tear film break up time and reduces the tear secretion[110]. A reduced tear film function is associated with reduced CS[111]. Blink rate increased by sleep deprivation[112] and may also be a possible indicator of fatigue[113]. In two 64-hrs sleep deprivation studies, there were some evidence for exophoria[114], decreased saccadic velocity and increased latency of pupillary constriction[115]. Even for some evidence of visual and oculomotor deterioration there are, to my knowledge, no studies indicating increased accident rates due to decreased visual function. Accident investigations seldom check visual function and this may be a contributing fact to the lack of knowledge on how often reduced visual function may have been a contributing factor[93]. The most likely cause of accidents due to sleep deprivation is not visual impairment, but “the navigator falling asleep” and reduced cognitive performance. Cognitive performance has been shown to deteriorate with sleep deprivation, resulting in negative influence on task shifting ability and increased number of lapses[116], impaired thinking and decision making[117] and reduced executive functions[118].

5.2.4 Accessing visual fitness

> *The wool test allows 50 per cent of dangerously colour-blind to pass and of those rejected 50 per cent are not dangerously colour-blind.*
>
> Edridge-Green[m][119]

Medical maritime fitness standards are issued for mainly two purposes; to ensure that the seafarer has the capacities and fitness for the work and to ensure that the seafarer is not suffering from any medical condition likely to be aggravated by service at sea, make the seafarer unfit for such service or endanger the health or safety of other persons. By Norwegian law, the "*Anti-Discrimination Act*" states the equal opportunity to work and the duty of public authorities and employers to make active equality efforts[120]. Lawful differential treatment is only possible if "*it has an objective purpose, it is necessary to achieve the purpose and the negative impact of the differential treatment on the person whose position will worsen is reasonably proportionate in view of the intended result*". With the law in mind, it is fair to ask on what reason do we select or exclude people from specific work and positions. Are we able to justify the laws and regulations issued by international organisations or national authorities? Already in the early days of regulations, it was acknowledged that the end product of standards often was influenced by political guidance and negotiations between the parts involved[20,121]. And it is evident that groups or individuals with expertise and high academic status influenced the development of statues[70,119,122], making statues and regulations quite diversified[123].

Ever since the start of issuing fitness standards there has been a concern wheatear or not the standards reflect the purpose and by what means the standards should be effectuated.

---

[m] Edridge-Green, Frederick William (1863 - 1953), made an original study of colour blindness, won a gold medal with his MD thesis on this subject, attacking the Holmgren wool-test. He later invented the Edridge-Green lantern.

The requirement for CV in the transport industry came in the second half of 19th century[67] after railway and maritime incidents were associated with colour vision deficiencies[65,124] and due to increased knowledge of CV[122]. The procedures used for CV testing have changed and most of them have been disputed: "*Edridge-Green lantern is obviously a test for all seasons that can be interpreted as the examiner wishes*"[76].

The fail-pass criteria have also been discussed. In 1910, second mate John Trattles finally got his certificate as first mate. He passed the Holmgren wool test in 1904, subsequently failing the test three times and passing it three times until 1909. His case was debated in House of Lords before he got his approval, and a new lantern test was developed[76]. The issue of pass/fail and the Law proclaiming equal opportunity have been addressed several times[96,125].

An expert panel, a Delphi group, in International Commission on Illumination developed a standard for CV testing in 2001[70], trying to classify and quantify CVD according to the perceived requirement for safe function in transportation industry. The expert panel was highly qualified, but still only provided level five evidence: *Expert opinion based on physiology, bench research*[126]. Until recently there has been few better alternatives to this approach, but the development of computerized colour vision testing give a possibility for increased accuracy in diagnostic testing of colour vision deficiency[24]. Task performance studies has been performed for air pilots[69] and for London train drivers[24], resulting in an ease in the standard for air traffic pilots.

A requirement for excellent vision in a military setting was, to my knowledge, first addressed in 1863[20]. The development of rifled muskets in mid-1850 gave the soldier an opportunity to aim at, fire and hit a target on a long rage compared to the smooth bore muskets used earlier. The new army requirement was the ability to identify and shoot at an object at 600 feet. In Great Britain, no eyesight qualifications were required for merchant navigators until 1899 and the discussion for implementing requirements were much the same as for CV[122,124,127]. At the same time, in the Royal Navy apparently no rules applied, and "*the examining officers must be guided by their own judgment*"[127], though it was suggested implementation for VA in 1894[125].

As for colour vision requirements, the fitness standard for VA should be made after a task performance study. In the maritime setting, such task performance studies are still missing[128]. A Cochrane review on vision screening of older drivers to prevent road traffic injuries and deaths stated that there is a need to develop valid and reliable tools of vision screening that can predict driving performance. Today, there is a lack of methodologically sound studies to assess the effects of vision screening tests on subsequent motor vehicle crash reduction[129].

6. CONCLUSIONS

The main findings in the first study (Paper I) was the description of population norms for CS and ICS in a young adult population with normal VA, and the degree of agreement between calculated ICS for each of the test methods. There was apparently little agreement between the mesopic and the two photopic tests. Lacks of agreement reduce the possibility to interpret the result of the mesopic and the photopic tests interchangeably. All the recorded and calculated results were skewed towards high visual function and for CS there was a ceiling effect, indicating that both the OPTEC 6500 and the CSV-1000E is not sensitive for high CS performance. This may not be considered a major disadvantage in medical selection purposes, such as a marked floor effect would have been. In medical selection, the aim is to examine the visual fitness of a candidate related to a relevant work task, and the cut off value of the test must be inside the test limits, ceiling or floor, if the minimum visual requirement should predict task performance.

The aim of the second study (Paper II) was to evaluate the validity of VA and ICS as predictors of observation task performance. Identification distance in a ship simulator was not significantly correlated to VA or to ICS, presumably due to uniform and high level visual function in the study group.

In the third study (Paper III), the aim was to evaluate the effect on CS after total sleep deprivation. Except for a significant increase in threshold for high and middle frequency red-green CS, the study showed no distinct and readily explained changes of CS during 60 hrs sleep deprivation. Apparently, prolonged sleep deprivation does not cause clinically or occupationally significant changes of CS in otherwise healthy subjects with normal VA.

7. A look out on the future

There is a need to further develop valid and reliable tools for visual assessment that can improve prediction of task performance in many occupations and situations, hereunder also in maritime transportation.

Evidence-based guidelines securing sound and fair visual fitness standards in medical selection can only be achieved by performing high quality trials and systematic reviews.

References

1 McMahon, D. G., Iuvone, P. M. & Tosini, G. Circadian organization of the mammalian retina: from gene regulation to physiology and diseases. *Prog Retin Eye Res* **39**, 58-76, doi:10.1016/j.preteyeres.2013.12.001 (2014).

2 Good-Lite. (Good-Lite Company, 1155 Jansen Farm Drive Elgin, IL 60123).

3 Colblindor. *Farnsworth-Munsell 100 HueColor Vision Test*, <http://www.color-blindness.com/farnsworth-munsell-100-hue-color-vision-test/> (2017).

4 Kolb, H., Nelson, R., Fernadez, E. & Jones, B. *Webvison.* (The University of Utah, 585 Komas, Salt Lake City, Utah 84108, 2017).

5 Researchgate.net. (https://www.researchgate.net).

6 SciELO.org. (Scientific Electronic Library Online 2011).

7 Ginesu, G., Massidda, F. & Giusto, D. D. A multi-factors approach for image quality assessment based on a human visual system model. *Signal Process-Image* **21**, 316-333, doi:DOI 10.1016/j.image.2005.11.005 (2006).

8 Greenlaw, L. *The Hungry Ocean: A Swordboat Captain's Journey.* 288 (Hyperion Books, 2000).

9 Marine Accident Investigation Branch. Bridge watchkeeping safety study. (2004).

10 International Maritime Organization. Recommendation on basic prinsiples and operational guidance relating to navigational watchkeeping. (IMO, 1973).

11 Nærings- og handelsdepartementet. Forskrift om helseundersøkelse av arbeidstakere på skip (2001).

12 Colenbrander, A. The Historical Evolution of Visual Acuity Measurement. *Visual Impairment Research* **10**, 57-66, doi:10.1080/13882350802632401 (2009).

13 Rayson, M. P. Fitness for work: the need for conducting a job analysis. *Occup Med (Lond)* **50**, 434-436, doi:10.1093/occmed/50.6.434 (2000).

14 International Labour Organization. Guidelines on the medical examinations of seafarers. Report No. 978-92-2-125097-5, (International Labour Organization, UN, 2011).

15 GARD AS. *Gard Enhanced PEME program for Filipino Seafarers is expanding* <http://www.gard.no/ikbViewer/page/news-and-publications/news?p_document_id=2438903> (2009).

16 Guyatt, G. H. *et al.* GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. *BMJ* **336**, 924-926, doi:10.1136/bmj.39489.470347.AD (2008).

17 Balasubramanian, R. & Agarwal, D. Delphi technique-A review. *International Journal of Public Health Dentistry* **3**, 16-25 (2013).

18 Dalkey, N. An experimental study of group opinion. *Futures* **1**, 408-426, doi:10.1016/s0016-3287(69)80025-x (1969).

19 Jeste, D. V. *et al.* Expert consensus on characteristics of wisdom: a Delphi method study. *Gerontologist* **50**, 668-680, doi:10.1093/geront/gnq022 (2010).

20 Longmore, T. *The optical manual or Handbook of instructions for guidance of surgeons in testing the range and quality of vision of recruits and others seeking employment in the military services of Great Britan, and in distinguishing and dealing with optical defects among the officers and men already engaged in them.* 3rd. edn, 184 (Published by Authority, 1885).

21 Beard, B. L., Hisle, W. A. & Ahumada, A. Occupational vision standards: A review. *Report for FAA AAR-100* (2002).

22 Valberg, A. *Light Vision Color.* (John Wiley & Sons, Ltd, 2005).
23 Baylor, D. A., Lamb, T. D. & Yau, K. W. Responses of retinal rods to single photons. *J Physiol* **288**, 613-634 (1979).
24 Barbur, J. L. & Rodriguez-Carmona, M. Colour vision requirements in visually demanding occupations. *Br Med Bull* **122**, 51-77, doi:10.1093/bmb/ldx007 (2017).
25 Kocaoglu, O. P. *et al.* Photoreceptor disc shedding in the living human eye. *Biomedical optics express* **7**, 4554-4568, doi:10.1364/BOE.7.004554 (2016).
26 Usrey, W. M. & Alitto, H. J. Visual Functions of the Thalamus. *Annu Rev Vis Sci* **1**, 351-371, doi:10.1146/annurev-vision-082114-035920 (2015).
27 Campbell, F. W. & Robson, J. G. Application of Fourier analysis to the visibility of gratings. *J Physiol* **197**, 551-566 (1968).
28 Ginsburg, A. P Specifying relevant spatial information for image evaluation and display design: An explanation of how we see certain objects. Proceedings of the SID Vol 21/3 219-227. (1980).
29 Cahill, G. M. & Besharse, J. C. Circadian Rhythmicity in Vertebrate Retinas - Regulation by a Photoreceptor Oscillator. *Progress in Retinal and Eye Research* **14**, 267-291, doi:Doi 10.1016/1350-9462(94)00001-Y (1995).
30 Tassi, P., Pellerin, N., Moessinger, M., Hoeft, A. & Muzet, A. Visual resolution in humans fluctuates over the 24h period. *Chronobiol Int* **17**, 187-195 (2000).
31 Tassi, P., Pellerin, N., Moessinger, M., Eschenlauer, R. & Muzet, A. Variation of visual detection over the 24-hour period in humans. *Chronobiol Int* **17**, 795-805 (2000).
32 Balkema, G. W., Cusick, K. & Nguyen, T. H. Diurnal variation in synaptic ribbon length and visual threshold. *Vis Neurosci* **18**, 789-797 (2001).
33 Hwang, C. K. *et al.* Circadian rhythm of contrast sensitivity is regulated by a dopamine-neuronal PAS-domain protein 2-adenylyl cyclase 1 signaling pathway in retinal ganglion cells. *J Neurosci* **33**, 14989-14997, doi:10.1523/JNEUROSCI.2039-13.2013 (2013).
34 Chokroverty, S. in *Sleep Disorders Medicine: Basic Science, Technical Considerations and Clinical Aspects* (ed Sudhansu Chokroverty) 5-27 (Springer New York, 2017).
35 Chokroverty, S. *Sleep Disorders Medicine.* (Springer New York, 2017).
36 Rea, M. S., Figueiro, M. G., Bierman, A. & Bullough, J. D. Circadian light. *J Circadian Rhythms* **8**, 2, doi:10.1186/1740-3391-8-2 (2010).
37 Paul, A. Effects of Sleep Deprivation on Visual Function. *Aerospace medicine* **36**, 617-620 (1965).
38 Quant, J. R. The effect of sleep deprivation and sustained military operations on near visual performance. *Aviat Space Environ Med* **63**, 172-176 (1992).
39 Koefoed, V. F., Assmus, J., Gould, K. S., Hovding, G. & Moen, B. E. Contrast sensitivity and the effect of 60-hour sleep deprivation. *Acta Ophthalmol* **93**, 284-288, doi:10.1111/aos.12536 (2015).
40 Jackson, M. L. *et al.* The effect of acute sleep deprivation on visual evoked potentials in professional drivers. *Sleep* **31**, 1261-1269 (2008).
41 Gould, K. S. *et al.* Effects of 60 hours of total sleep deprivation on two methods of high-speed ship navigation. *Ergonomics* **52**, 1469-1486, doi:10.1080/00140130903272611 (2009).
42 Roge, J. & Gabaude, C. Deterioration of the useful visual field with age and sleep deprivation: insight from signal detection theory. *Perceptual and motor skills* **109**, 270-284, doi:10.2466/PMS.109.1.270-284 (2009).

43 International Council of Ophthalmology. Visual Acuity Measurement Standard. (ICO, 1984).

44 Elliott, D. B., Yang, K. C. & Whitaker, D. Visual acuity changes throughout adulthood in normal, healthy eyes: seeing beyond 6/6. *Optom Vis Sci* **72**, 186-191 (1995).

45 Bailey, I. L. & Lovie, J. E. New design principles for visual acuity letter charts. *Am J Optom Physiol Opt* **53**, 740-745 (1976).

46 Michelson A.A. *Studies in Optics*. (University of Chicago Press, 1927).

47 Schade, O. H., Sr. Optical and photoelectric analog of the eye. *J Opt Soc Am* **46**, 721-739 (1956).

48 Graham, N. & Nachmias, J. Detection of grating patterns containing two spatial frequencies: a comparison of single-channel and multiple-channels models. *Vision Res* **11**, 251-259 (1971).

49 Pelli, D. G., Robson, J. G. & Wilkins, A. The design of a new letter chart for measuring contrast sensitivity. *Clinical Vision Sciences* **2**, 187-199 (1987).

50 Regan, D. Low-Contrast Letter Charts and Sinewave Grating Tests in Ophthalmological and Neurological Disorders. *Clinical Vision Sciences* **2**, 235-& (1988).

51 Arditi, A. Improving the design of the letter contrast sensitivity test. *Invest Ophthalmol Vis Sci* **46**, 2225-2229, doi:10.1167/iovs.04-1198 (2005).

52 Leguire, L. Do letter charts measure contrast sensitivity? *Clinical vision sciences* **6**, 391-400 (1991).

53 Rohaly, A. M. & Owsley, C. Modeling the contrast-sensitivity functions of older adults. *J Opt Soc Am A* **10**, 1591-1599 (1993).

54 Pelli, D. G. & Robson, J. G. Are letters better than gratings? *Clin. Vision Sci* **6** (1991).

55 Ginsburg, A. Suprathreshold Contrast Sensitivity Vision Test Chart. (Vision Sciences Research Corp., 1991).

56 Haughom, B. & Strand, T. E. Sine wave mesopic contrast sensitivity - defining the normal range in a young population. *Acta Ophthalmol* **91**, 176-182, doi:10.1111/j.1755-3768.2011.02323.x (2013).

57 Wachler, B. S. & Krueger, R. R. Normalized contrast sensitivity values. *J Refract Surg* **14**, 463-466 (1998).

58 Hohberger, B., Laemmer, R., Adler, W., Juenemann, A. G. & Horn, F. K. Measuring contrast sensitivity in normal subjects with OPTEC 6500: influence of age and glare. *Graefes Arch Clin Exp Ophthalmol* **245**, 1805-1814, doi:10.1007/s00417-007-0662-x (2007).

59 Maclean WC. Surgeon-General Sir Thomas Longmore, C.B. *British Medical Journal* **2**, 936-937 (1895).

60 McIntosh, R. (2017).

61 Johansen, O. *Øyelegekunstens historie i Norge*. (Universitetsforlaget, 1978).

62 Helsedirektoratet. *Førerkort – veileder til helsekrav*, <https://helsedirektoratet.no/retningslinjer/forerkortveilederen/seksjon?Tittel=syn-9-13-helsekrav-10650#synsstyrke-(helsekrav-til-førerkort)> (2016).

63 Ginsburg, A. P. Contrast sensitivity and functional vision. *International ophthalmology clinics* **43**, 5-15 (2003).

64 Wilson, G. *Researches in colour-blindness: With a supplement on the danger attending the present system of railway and marine coloured signals 1818-1859*. Reprinted from 1855 edition edn, (Sutherland & Know, 1855).

65 Holmgren, F. *Color-blindness in its relation to accidents by rail and sea*. (1878).

66 Mollon, J. D. & Cavonius, L. R. The Lagerlunda collision and the introduction of color vision testing. *Surv Ophthalmol* **57**, 178-194, doi:10.1016/j.survophthal.2011.10.003 (2012).

67 Vingrys, A. J. & Cole, B. L. Origins of Color-Vision Standards within the Transport Industry. *Ophthalmic and Physiological Optics* **6**, 369-375, doi:10.1111/j.1475-1313.1986.tb01155.x (1986).

68 French, A., Rose, K., Cornell, E. & Thompson, K. The evolution of colour vision testing. *Australian Orthoptic Journal* **40**, 7 (2008).

69 Safety Regulation Group. Minimum Colour Vision Requirements for Professional Flight Crew. Recommendations for new colour vision standards., (Federal Aviation Administration, 2009).

70 International commission on illumination. International recommendations for colour vision requirements for transport. (CIE).

71 Bailey, K. G. H. & Carter, T. Consistency of secondary colour vision tests in transport industries. *Occup Med (Lond)* **66**, 268-275, doi:10.1093/occmed/kqw012 (2016).

72 Carter, T. & Barbur, J. Colour vision assessment for maritime navigation lookout report. (Maritime and Coastguard Agency, 2016).

73 Rodriguez-Carmona, M., O'Neill-Biba, M. & Barbur, J. L. Assessing the severity of color vision loss with implications for aviation and other occupational environments. *Aviat Space Environ Med* **83**, 19-29 (2012).

74 Murphy, R. *Comparing Color Vision Testing Using the Farnsworth-Munsell 100-Hue, Ishihara Compatible, and Digital TCV Software* Master of Science thesis, Pacific University, Oregon, (2015).

75 Kinnear, P. R. Proposals for scoring and assessing the 100-Hue test. *Vision Res* **10**, 423-433, doi:http://dx.doi.org/10.1016/0042-6989(70)90123-9 (1970).

76 Cole, B. L. & Vingrys, A. J. A survey and evaluation of lantern tests of color vision. *Am J Optom Physiol Opt* **59**, 346-374 (1982).

77 Ginsburg, A. P., Easterly, J. & Evans, D. W. Contrast Sensitivity Predicts Target Detection Field Performance of Pilots. *Proceedings of the Human Factors Society Annual Meeting* **27**, 269-273, doi:10.1177/154193128302700319 (2016).

78 Donderi, D. C. Visual-Acuity, Color-Vision, and Visual-Search Performance at Sea. *Human factors* **36**, 129-144, doi:10.1177/001872089403600108 (1994).

79 Koefoed, V. F., Baste, V., Roumes, C. & Hovding, G. Contrast sensitivity measured by two different test methods in healthy, young adults with normal visual acuity. *Acta Ophthalmol* **93**, 154-161, doi:10.1111/aos.12487 (2015).

80 VigraC - Users manual.

81 Bland, J. M. & Altman, D. G. Measuring agreement in method comparison studies. *Stat Methods Med Res* **8**, 135-160, doi:10.1177/096228029900800204 (1999).

82 Bailey, I. L. & Lovie-Kitchin, J. E. Visual acuity testing. From the laboratory to the clinic. *Vision Res* **90**, 2-9, doi:10.1016/j.visres.2013.05.004 (2013).

83 Armstrong, R. A., Davies, L. N., Dunne, M. C. & Gilmartin, B. Statistical guidelines for clinical studies of human vision. *Ophthalmic Physiol Opt* **31**, 123-136, doi:10.1111/j.1475-1313.2010.00815.x (2011).

84 Bunce, C. Correlation, agreement, and Bland-Altman analysis: statistical analysis of method comparison studies. *American journal of ophthalmology* **148**, 4-6, doi:10.1016/j.ajo.2008.09.032 (2009).

85 Refinetti, R., Lissen, G. C. & Halberg, F. Procedures for numerical analysis of circadian rhythms. *Biological rhythm research* **38**, 275-325, doi:10.1080/09291010600903692 (2007).

86 Hareide, O. S., Ostnes, R. & Mjelde, F. V. Understanding the Eye of the Navigator. (Royal Norwegian Naval Academy, 2016).

87 Norwegian Maritime Directorate. Ulykkesutvikling 2000 - 2010. (NMD, 2011).

88 Marine Accident Investigation Branch. Report on the investigation of the grounding of CFL Performer, Haisborough Sand, North Sea. Report No. 21/2008, (Marine Accident Investigation Branch, Carlton House, Carlton Place, Southampton, United Kingdom, SO15 2DZ, 2008).

89 Gould, K. *Faster, better, safer? Studies of safety, workload and performance in naval high-speed ship navigation* Ph. D. thesis, University of Bergen, (2009).

90 Last, P., Kroker, M. & Linsen, L. Generating real-time objects for a bridge ship-handling simulator based on automatic identification system data. *Simulation Modelling Practice and Theory* **72**, 69-87, doi:10.1016/j.simpat.2016.12.011 (2017).

91 Maritime Unmanned navigation through Intelligence in Networks. *The Autonomous Ship*, <http://www.unmanned-ship.org/munin/about/the-autonomus-ship/> (2017).

92 European Maritime Safety Agency. Annual Overview of Marine Casualties and Incidents 2016. (EMSA, 2016).

93 Gould, K. S., Roed, B. K., Koefoed, V. F., Bridger, R. S. & Moen, B. E. Performance-shaping factors associated with navigation accidents in the Royal Norwegian Navy. *Military Psychology* **18**, S111-S129 (2006).

94 Nærings- og fiskeridepartementet. Forskrift om helseundersøkelse av arbeidstakere på norske skip og flyttbare innretninger. (2014).

95 International maritime Organization. International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW 95). (1997).

96 Cole, B. L. The handicap of abnormal colour vision. *Clin Exp Optom* **87**, 258-275, doi:ceo874258 [pii] (2004).

97 Donderi, D. C. Visual acuity, color vision, and visual search performance at sea. *Hum Factors* **36**, 129-144, doi:10.1177/001872089403600108 (1994).

98 Carter, T. Mapping the knowledge base for maritime health: 4 safety and performance at sea. *International maritime health* **62**, 236-244 (2011).

99 Report after grounding: KNM Trondheim. (Norwegian Armed Forces, Joint Head Quarter, 2006).

100 Thorslund, B. & Strand, N. Vision measurability and its impact on safe driving: a literature review. *Scandinavian Journal of Optometry and Visual Science* **9**, 1-9 (2016).

101 Wood, J. M. & Black, A. A. Ocular disease and driving. *Clin Exp Optom* **99**, 395-401, doi:10.1111/cxo.12391 (2016).

102 Blane, A. Through the Looking Glass: A Review of the Literature Investigating the Impact of Glaucoma on Crash Risk, Driving Performance, and Driver Self-Regulation in Older Drivers. *J Glaucoma* **25**, 113-121, doi:10.1097/IJG.0000000000000193 (2016).

103 Lee, S. S., Wood, J. M. & Black, A. A. Blur, eye movements and performance on a driving visual recognition slide test. *Ophthalmic Physiol Opt* **35**, 522-529, doi:10.1111/opo.12230 (2015).

104 McGwin, G., Chapman, V. & Owsley, C. Visual risk factors for driving difficulty among older drivers. *Accident Anal Prev* **32**, 735-744, doi:Doi 10.1016/S0001-4575(99)00123-2 (2000).

105 Wood, J. M. & Owens, D. A. Standard measures of visual acuity do not predict drivers' recognition performance under day or night conditions. *Optom Vis Sci* **82**, 698-705 (2005).

106 Evans, D. W. & Ginsburg, A. P. Contrast sensitivity predicts age-related differences in highway-sign discriminability. *Hum Factors* **27**, 637-642, doi:10.1177/001872088502700602 (1985).

107 Owsley, C., Wood, J. M. & McGwin, G., Jr. A roadmap for interpreting the literature on vision and driving. *Surv Ophthalmol* **60**, 250-262, doi:10.1016/j.survophthal.2015.01.005 (2015).

108 Nærings- og fiskeridepartementet. Ship Safety and Security Act. (2007).

109 Hirvonen, K. *et al.* Improving the saccade peak velocity measurement for detecting fatigue. *J Neurosci Methods* **187**, 199-206, doi:10.1016/j.jneumeth.2010.01.010 (2010).

110 Lee, Y. B. *et al.* Sleep deprivation reduces tear secretion and impairs the tear film. *Invest Ophthalmol Vis Sci* **55**, 3525-3531, doi:10.1167/iovs.14-13881 (2014).

111 Koh, S. *et al.* The Effect of Ocular Surface Regularity on Contrast Sensitivity and Straylight in Dry EyeContrast Sensitivity and Straylight in Dry Eye. *Investigative Ophthalmology & Visual Science* **58**, 2647-2651 (2017).

112 Barbato, G. *et al.* Effects of sleep deprivation on spontaneous eye blink rate and alpha EEG power. *Biol Psychiatry* **38**, 340-341, doi:10.1016/0006-3223(95)00098-2 (1995).

113 Stern, J. A., Boyer, D. & Schroeder, D. Blink rate: a possible measure of fatigue. *Hum Factors* **36**, 285-297, doi:10.1177/001872089403600209 (1994).

114 Horne, J. A. Binocular convergence in man during total sleep deprivation. *Biological psychology* **3**, 309-319, doi:http://dx.doi.org/10.1016/0301-0511(75)90029-0 (1975).

115 Rowland, L. M. *et al.* Oculomotor responses during partial and total sleep deprivation. *Aviat Space Environ Med* **76**, C104-113 (2005).

116 Heuer, H., Kleinsorge, T., Klein, W. & Kohlisch, O. Total sleep deprivation increases the costs of shifting between simple cognitive tasks. *Acta Psychol* **117**, 29-64, doi:10.1016/j.actpsy.2004.04.005 (2004).

117 Harrison, Y. & Horne, J. A. One night of sleep loss impairs innovative thinking and flexible decision making. *Organ Behav Hum Decis Process* **78**, 128-145, doi:10.1006/obhd.1999.2827 (1999).

118 Nilsson, J. P. *et al.* Less effective executive functioning after one night's sleep deprivation. *J Sleep Res* **14**, 1-6, doi:10.1111/j.1365-2869.2005.00442.x (2005).

119 Edridge-Green, F. W. Merchant Shipping. Standard of Rejection for Colour-Blindness in Seamen. *Br J Ophthalmol* **6**, 126-128 (1922).

120 Barne- og likestillingsdepartementet. Act on prohibition of discrimination based on ethnicity, religion, etc. [Anti-discrimination Act] (2017).

121 Brailey, W. A. On The Tests Of Vision Which Should Be Applied To Sailors. *The British Medical Journal* **2**, 1008-1009 (1883).

122 Snellen, E. The Testing Of Colour-Sense And Vision, Especially With Regard To Sailors. *The British Medical Journal* **2**, 1009-1011 (1883).

123 Schepers, B. Medical Examinations to Assess Fitness for Maritime Services – an International Comparision in *The International symposium on maritime helath.* (eds H Saarni & W Gardner) 68-99 (Turku regional Institute of occcupational health). ISBN 953-801-855-5

124 British Medical Association On The Eyesight Question. The eyesight of seamen. *British Medical Journal*, 343 (1897).

125 Vingrys, A. J. & Cole, B. L. Are colour vision standards justified for the transport industry? *Ophthalmic Physiol Opt* **8**, 257-274 (1988).

126 Oxford Centre for Evidence. *Levels of Evidence*, <http://www.cebm.net/oxford-centre-evidence-based-medicine-levels-evidence-march-2009/> (2009).

127 Caley, H., Landolt, E. & Mackay, G. A Discussion On Visual Tests. *The British Medical Journal* **2**, 766-770, doi:10.2307/20261860 (1899).

128 Carter, T. The need for international seafarer medical fitness standards. *International maritime health* **60**, 1-5 (2009).

129 Desapriya, E. *et al.* Vision screening of older drivers for preventing road traffic injuries and fatalities. *The Cochrane database of systematic reviews*, CD006252, doi:10.1002/14651858.CD006252.pub4 (2014).

Acta Ophthalmologica

ACTA OPHTHALMOLOGICA 2015

Contrast sensitivity measured by two different test methods in healthy, young adults with normal visual acuity

Vilhelm F. Koefoed,[1] Valborg Baste,[2] Corinne Roumes[3] and Gunnar Høvding[1]

[1]Department of Clinical Medicine, Faculty of Medicine and Dentistry, University of Bergen, Bergen, Norway
[2]Department of Global Public Health and Primary Care, Faculty of Medicine and Dentistry, University of Bergen, Bergen, Norway
[3]Institut de Recherche Biomédicale des Armées, Brétigny sur Orge, France

ABSTRACT.
Purpose: **This study reports contrast sensitivity (CS) reference values obtained by two different test methods in a strictly selected population of healthy, young adults with normal uncorrected visual acuity. Based on these results, the index of contrast sensitivity (ICS) is calculated, aiming to establish ICS reference values for this population and to evaluate the possible usefulness of ICS as a tool to compare the degree of agreement between different CS test methods.**
Methods: **Military recruits with best eye uncorrected visual acuity 0.00 LogMAR or better, normal colour vision and age 18–25 years were included in a study to record contrast sensitivity using Optec 6500 (FACT) at spatial frequencies of 1.5, 3, 6, 12 and 18 cpd in photopic and mesopic light and CSV-1000E at spatial frequencies of 3, 6, 12 and 18 cpd in photopic light. Index of contrast sensitivity was calculated based on data from the three tests, and the Bland–Altman technique was used to analyse the agreement between ICS obtained by the different test methods.**
Results: **A total of 180 recruits were included. Contrast sensitivity frequency data for all tests were highly skewed with a marked ceiling effect for the photopic tests. The median ICS for Optec 6500 at 85 cd/m^2 was −0.15 (95% percentile 0.45), compared with −0.00 (95% percentile 1.62) for Optec at 3 cd/m^2 and 0.30 (95% percentile 1.20) FOR CSV-1000E. The mean difference between ICS$_{FACT85}$ and ICS$_{CSV}$ was −0.43 (95% CI −0.56 to −0.30, $p < 0.00$) with limits of agreement (LoA) within −2.10 and 1.22. The regression line on the difference of average was near to zero ($R^2 = 0.03$).**
Conclusion: **The results provide reference CS and ICS values in a young, adult population with normal visual acuity. The agreement between the photopic tests indicated that they may be used interchangeably. There was little agreement between the mesopic and photopic tests. The mesopic test seemed best suited to differentiate between candidates and may therefore possibly be useful for medical selection purposes.**

Key words: contrast sensitivity – medical selection – mesopic vision – photopic vision – visual function – visual quality

Acta Ophthalmol. 2015: 93: 154–161

doi: 10.1111/aos.12487

Introduction

Assessment of contrast sensitivity (CS) is now generally believed to give information about the visual capacity beyond that obtained by high-contrast visual acuity tests (HCVA). This has been indicated by among others Ginsburg et al. (1982), who found contrast sensitivity to correlate better than visual acuity in predicting a pilot's ability to detect a small, semi-isolated, air-to-ground target. A review paper by Owsley & McGwin (2010) cites numerous studies reporting significant associations between impaired contrast sensitivity and reduced driving performance.

Contrast sensitivity may be examined by different methods, and this diversity is reflected in the previously published studies on the normal distribution of contrast sensitivity in healthy populations. Grimson et al. (2002) used the small letter contrast test (SLCT) when measuring contrast sensitivity in a group of naval pilot students. They also compared these results with those obtained in aviation and non-aviation personnel aged 21–54 years. Kelly et al. (2012) tested a group of adults (mean age 26.4, SD 4.7) and children using CSV-1000, primarily to find values of repeatability. Using the same test method in a large, randomly selected population of men aged 35–80 years, Sia et al. (2013) found that CS declined with increasing age in all spatial frequencies tested. Franco et al. (2010) used the Bland–

Altman technique to compare the CS obtained by CSV-1000 and Vision Contrast Test System 6500(VCTS) in 105 subjects (mean age 21.4 years, SD 1.9) with best-corrected Snellen visual acuity (BCVA) ≥0.8. Hohberger et al. (2007) measured contrast sensitivity in a group of 61 hospital employees and patients aged ≥18 years using the Optec 6500 (Stereo Optical Co., Inc., Chicago, IL, USA) based on the Functional Acuity Contrast Test (FACT). Haughom & Strand (2013) examined aviation pilots aged 17–54 years, assessing their contrast sensitivity on five frequencies in mesopic and photopic light conditions by Optec 6500. They also introduced the term “index of contrast sensitivity (ICS)”, which they believed to be a useful collective descriptor of the different contrast sensitivity frequencies and suggested that ICS may be accepted as a generalized parameter for contrast sensitivity assessment.

The concept of ICS is a follow-up on an idea by Wachler & Krueger (1998) of using and reporting normalized contrast sensitivity values. They stated that difficulties to interpret contrast sensitivity curves might be overcome by reporting the obtained contrast sensitivity as a factor of the population mean for each test frequency. Another solution is to report the area under the curve (AUC) as a measure of contrast sensitivity. One challenge using these methods is to evaluate the impact of each frequency and its importance on visual performance. Previous studies have indicated different clinical significance of the various frequencies. Ginsburg et al. (1982) found the best predictive value at the peak of the contrast sensitivity curve, that is, 6 cpd, while another study (Evans & Ginsburg 1985) stressed the importance of 1.5 and 12 cpd, which seemed to correlate best with the visual performance. Acknowledging the presumed increased importance of 6 cpd and adjacent frequencies, the ICS gives more power to these frequencies (Haughom & Strand 2013).

A review by Owsley & McGwin (2010) on the research performed on contrast sensitivity states that CS screening tests which can be more readily translated into licensing policies need to be developed. As a step towards this goal, this study aimed to present reference CS and ICS values obtained in photopic and mesopic light for a strictly selected population. A further aim was to use the ICS values to analyse the agreement between the Optec 6500/FACT and CSV-1000E contrast sensitivity tests.

Materials and Methods

Subjects

A total of 194 military recruits from the French Air Force and the Royal Norwegian Navy were invited to participate in the study. Fourteen candidates were excluded, as they did not meet one or more of the following inclusion criteria: age 18–26 years, best eye uncorrected visual acuity (BVA) LogMAR 0.00 or better, normal colour vision by Ishihara’s test and no previous refractive surgery in either eye. Thus, the study group included 180 subjects.

Measurements

Contrast sensitivity

Binocular contrast sensitivity (CS) was measured by two commercially available tests using sine wave gratings with different spatial frequencies. The Optec 6500/FACT (Functional Acuity Contrast Test) from Stereo Optical, Chicago, USA, was used for mesopic (3 candela/m^2 (cd/m^2) and photopic (85 cd/m^2) measurements with the spatial frequencies of 1.5 cpd (cycles per degree of visual angle) (threshold range 0.045–2.00), 3 cpd (threshold range 0.70–2.20), 6 cpd (threshold range 0.78–2.26), 12 cpd (threshold range 0.60–2.08) and 18 cpd (threshold range 0.30–1.81) in far vision mode. Mesopic CS was first measured after 10-min dark adaptation, and then the test was repeated in photopic light. All the study participants (n = 180) were tested the same examiner. The data obtained were plotted using the EyeView™ software (Vision Sciences Research Corporation, Walnut Creek, CA, USA). The other test used the CSV-1OOOE (VectorVision, Greenville OH, USA) for photopic (85 cd/m^2) contrast sensitivity with 2.5-m viewing distance. The test consists of sinoidal grated patches for the frequencies 3 cpd (threshold range 0.70–2.08), 6 cpd (threshold range 0.91–2.29), 12 cpd (threshold range 0.61–1.99) and 18 cpd (threshold range 0.17–1.55). Immediately after the Optec 6500 tests were completed, the CSV-1OOOE test was performed by a second examiner on all participants except one (n = 179). During the tests, the participants were encouraged to respond, but not to guess. A forced choice and a strict time limit were not employed.

The first examiner also measured the BVA of each participant using the Optec 6500/EDTRS chart in far distance mode on a LogMAR scale at photopic light conditions (85 cd/m^2). The chart has a minimum resolution at LogMAR −0.20. A third examiner recorded the colour vision using the Ishihara 24-plate pseudoisochromatic test in standardized daylight of 6280 degree K light (Illuminator for Pseudoisochromatic Tests with Easel, Richmond Products, http://www.richmondproducts.com/).

Using the results and median values obtained in our three different contrast sensitivity measurements, the ICS was calculated for each participant. As recommended by Haughom & Strand (2013), ICS was defined as the sum of the residual differences (positive or negative) from the median in each frequency. The differences were weighted according to the presumed clinical importance of each frequency. Thus, 6 cpd was given the highest power (factor 3). The frequencies 3 and 12 cpd received factor 2, while the remaining test frequencies were not weighted. A performance equivalent to the median in all tested frequencies should yield an ICS value of zero.

Statistical analysis

Descriptive statistics for each frequency and ICS for each of the contrast vision tests were provided. Normality of data was assessed by Shapiro–Wilk test and through skewness and kurtosis. The agreement between the different test methods was studied using the technique described by Bland & Altman (1999), which has been recommended when conducting comparative studies of clinical test in ophthalmology (McAlinden et al. 2011). Limits of agreement (LoA) were calculated as ±1.96 standard deviation of the differences of the mean. Paired t-tests were conducted to analyse the mean differences between the ICS tests. PASW statistics 18.0.3 was used for all analyses (Predictive Analytics Software; SPSS, Hong Kong, China).

Table 1. Log contrast sensitivity values for Optec 6500 (FACT) in photopic and mesopic light and for CSV-1000E in photopic light.

	Optec 6500 FACT 85 cd/m^2				Optec 6500 FACT 3 cd/m^2				CVS-1000E 85 cd/m^2			
Spatial frequency (cpd)	Median	Mode	95% percentile	Range results	Median	Mode	95% percentile	Range results	Median	Mode	95% percentile	Range results
1.5	2.00	2.00	2.00	0.30	1.85	1.85	2.00	0.44				
3	2.06	2.06	2.20	0.30	2.06	2.06	2.20	0.60	1.93	1.78	2.08	0.45
6	2.26	2.26	2.26	0.31	2.11	2.11	2.26	1.06	2.14	2.29	2.29	0.59
12	2.08	2.08	2.08	0.90	1.63	1.78	2.08	1.48	1.84	1.99	1.99	0.91
18	1.65	1.65	1.81	1.03	1.08	1.08	1.52	1.51	1.25	1.55	1.55	0.91

Research ethics

The study adhered to the Declaration of Helsinki. The participants were informed about the objectives and conditions of the study and had to sign a formula of consent. The Regional Committee for Medical Research Ethics, Western Norway and the Norwegian Social Science Data Services approved the study protocol. The test subjects were not paid for participating in the study, and they could withdraw from the study at any point. Individual data from the study were not revealed to the Armed Forces and could not be used for medical selection of the candidates.

Results

Study population

The study group consisted of 172 male and eight female recruits (47 French and 133 Norwegian) with mean age 20.95 (range 18–25, SD 1.16). The French recruits were slightly older than the Norwegian participants (mean age 21.8 and 20.6 years, respectively), while the BVA did not differ significantly in the two groups. The mean BVA in the whole study group was −0.13 (range −0.20–0.00, SD = 0.05, 75% and 95% percentile −0.11 and −0.14, respectively). Mode was −0.18.

Frequency distribution

The individual frequency data showed a non-symmetrical distribution for all measurements, evident both by visual inspection of distribution curves (not published) and by statistical evaluation of single frequency data (Table 1). The frequency samples for Optec 6500/FACT at 85 cd/m^2 were highly skewed towards the high end of the test range, showing a marked ceiling effect. This was evident for all frequencies except 18 cpd, and most pronounced for the three lowest frequencies (1.5–6 cpd), where all participants scored within the three patches with highest threshold values. At 1.5 cpd, 138 of 180 made the highest score, while 118 of 180 made the maximal score at 6 cpd. Reducing light emission to 3 cd/m^2 in the Optec 6500/FACT induced a wider spread of the test results. Still, a ceiling effect existed, most pronounced at the lower frequencies with skewness towards the high thresholds. None of the participants failed the test by not being able to detect the gratings with the lowest level, but the results showed a wider spread in the high frequencies, where only three subjects made highest score at 18 cpd, and ten just made the entry level (Fig. 1). The results obtained in the 179 participants examined by the CSV-1000E test were skewed towards the high-threshold end for all frequencies, most pronounced at 3 and 6 cpd.

Index of contrast sensitivity

The ICS calculated by all three test methods were considered not normally distributed (Figs 2–4) and by Shapiro–Wilk test ($p < 0.001$). The median ICS based on FACT 85 cd/m^2 (ICS_{FACT85}) was −0.15, with mode 0.16 and 95% percentile 0.45. For ICS calculated from FACT 3 cd/m^2 (ICS_{FACT3}), the median was −0.00, mode −0.37 and 95% percentile 1.62. Using CSV-1000E, ICS_{CSV} median was 0.30, mode 1.20 and 95% percentile 1.35. ICS percentiles for all three ICS is presented in Table 2.

Agreement

The agreement between ICS calculations based on our three test methods were analysed using Bland–Altman plots and by calculating the LoA and by paired sample *t*-test and Wilcoxon signed-rank test. Wilcoxon signed-rank test did not differ from paired sample *t*-test (p-values not reported) indicating the ability to use parametric methods to evaluating agreement.

ICS_{FACT85} compared with ICS_{CSV} showed a mean difference on the average of the two tests of −0.43 with 95%

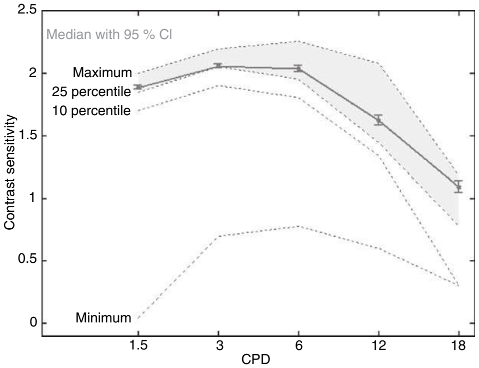


Fig. 1. The figure illustrate the ceiling effect in this cohort at 3 cd/m2 for Optec 6500, most pronounced for the lower frequencies. The shaded area represent the highest 75% of the scores. The test score ranges are indicated by Maximum and Minimum. Median score for the cohort with 95% confidence intervals is shown by the solid line.

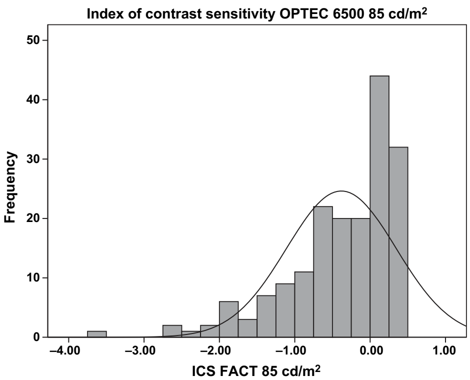


Fig. 2. Distribution of calculated index of contrast sensitivity for Optec 6500 at photopic light.

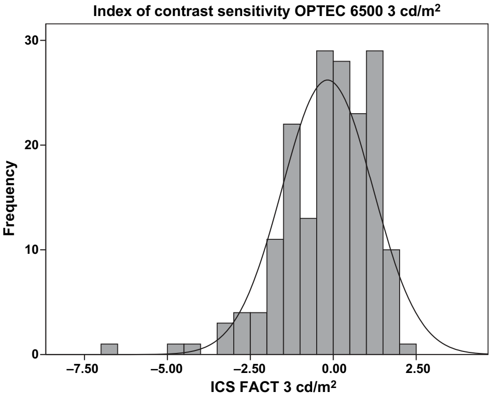


Fig. 3. Distribution of calculated index of contrast sensitivity for Optec 6500 at mesopic light.

LoA within −2.10 and 1.22. The lower average score on $\mathrm{ICS}_{\mathrm{FACT85}}$ was consistent as mean of differences of the pair was significantly different (paired *t*-test, 95% CI −0.56 to −0.30, $p < 0.00$). The trend analyses showed a fairly consistent correlation between the two measurements with a near to zero regression line ($R^2 = 0.03$). See Fig. 5.

When comparing $\mathrm{ICS}_{\mathrm{FACT85}}$ and $\mathrm{ICS}_{\mathrm{FACT3}}$, the mean difference was −0.22 (95% CI −0.36 to −0.08, $p = 0.002$) and LoA were −2.18 and 1.75. There was a marked trend of increasing difference at increased average score ($R^2 = 0.52$). See Fig. 6. $\mathrm{ICS}_{\mathrm{FACT3}}$ and $\mathrm{ICS}_{\mathrm{CSV}}$ showed a significant mean difference of 0.20 (95% CI 0.01–0.40, $p = 0.04$), but the regression line indicated lack of agreement throughout the test range ($R^2 = 0.23$). The LoA were fairly wide (−2.32 and 2.76), but the clinical implications of this are still to be investigated. See Fig. 7.

Discussion

The purpose of the study was to describe the population norms of contrast sensitivity measured by two different test methods in a young, healthy population selected for duty with high visual demands. Several occupations have strict visual qualification limits with requirements of high visual acuity, both corrected and uncorrected. Applicants for such jobs are typically below 25 years of age and meet visual selection criteria of 1.0 at Snellens table.

The relevance of high-contrast visual acuity measured by Snellen or other equivalent test is debated, and Ginsburg (2003) has argued in detail why CS is more relevant when evaluating visual function. Several different commercial tests are available to test contrast sensitivity, but Amesbury & Schallhorn (2003) states that the clinical relevance of CS is not well understood. In addition, there is little consensus regarding the best method to test CS. Unlike tests for other elements of vision, there are no universally recognized standard test method to measure CS. The CS tests currently available use either gratings or ortotypes as targets. There are a variety of grating charts for CS testing. In this study, we have chosen to evaluate two commercially available systems using charts with sine wave grating in different spatial frequencies, the Optec 6500/FACT and CSV-1000E. In order for these tests to be relevant for interchangeably use and medical selection purposes, they have to yield fairly similar results, and the tests must show relevance to real-life situations.

Previously, normal data for the Optec 6500/FACT and the CSV-1000E have been published by Owsley et al. (1983), Wachler & Krueger (1998), Adams & Courage (2002), Swamy (2002), Hohberger et al. (2007) and Haughom & Strand (2013). These studies had relatively wide inclusion criteria regarding age and/or visual acuity, and none of them estimated agreement with other test methods. Wachler & Krueger (1998), Swamy (2002) and Haughom & Strand (2013) described normality by parametric methods, while Hohberger et al. (2007) used AUC as a measure of CS.

In our strictly selected population, we report CS for each frequency and ICS reference values examined in the tests. The calculated ICS values were used to estimate the agreement between the test methods. All three tests showed skewness of data and a marked ceiling effect. This was most prominent in the photopic tests and in low frequencies. Thus, in FACT 85 cd/m^2, 75% of the participants made the highest score at 1.5 and 65% at 6 cpd. In FACT 3 cd/m^2, only three made the highest score and ten just made the entry level at 18 cpd. Skewness combined with only minor differences within the study group suggested the use of nonparametric methods for describing normal data (Armstrong et al. 2011). In our study, the population was limited to the age group most relevant for medical selection to posi-

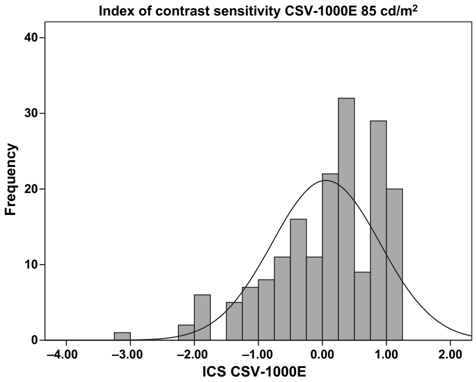


Fig. 4. Distribution of calculated index of contrast sensitivity for CSV-1000E at photopic light.

Table 2. Index of contrast sensitivity log values including percentiles 10–95% for the three methods.

	ICS FACT 85 cd	ICS FACT 3 cd	ICS CSV-1000E
Index of contrast sensitivity			
Median	−0.15	−0.00	0.30
Mean	−0.38	−0.17	0.06
Std. deviation	0.73	1.37	0.85
Percentiles			
10	−1.47	−1.73	−1.19
25	−0.74	−1.04	−0.45
50	−0.15	0.00	0.30
75	0.16	0.88	0.75
90	0.30	1.33	1.05
95	0.45	1.62	1.20

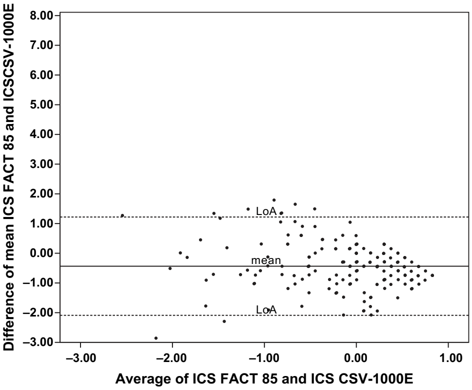


Fig. 5. Bland–Altman plot (plot of difference of the two methods) comparing ICS_{FACT85} and ICS_{CSV} in 179 subjects. Mean difference is −0.43 with limits of agreement (LoA) at −2.10 and 1.22.

tions with high visual demands, and all participants had visual acuity within the limits of acceptance to duty as a naval pilot. Differences regarding both study populations and statistical methods prevent direct comparison between our results and those previously reported.

Percentiles may also describe the levels of achieved score. The skewness and ceiling effect also reduces the usefulness of this method. As shown in Table 1, the 95% percentile was equivalent to highest score and mode for a majority of the frequencies except in the high FACT 3 cd/m^2 frequencies. Such a pronounced ceiling effect has previously been claimed to limit the usefulness of CS tests (Pesudovs et al. 2004; Buhren et al. 2006). This is correct if the purpose is to detect subtle loss or change of CS. However, CS tests may conceivably also be used in strictly selected populations to correlate the visual ability of each individual related to task performance, hopefully establishing a CS cut-off value at the lowest acceptable performance. Participants making high visual score must all be expected to be in the high CS performance group. For such selection purposes, the ceiling effect is not as problematic as a marked floor effect would have been. In our study, all participants made the entry level on each frequency and the flooring effect was not present.

The pronounced single frequency ceiling effect will influence ICS by reducing the score in the high performance area. The clinical implication is considered small, as long as the flooring effect is not evident. When calculating ICS for all three tests, the distribution of ICS made it possible to establish useful percentiles in the range from 10 to 100%. ICS normal data have been presented by Haughom & Strand (2013), but their population characteristics differed from ours to such an extent that the value of comparing the study results is low. As they point out, normal data are only relevant for similar populations.

The present study aimed to evaluate whether the three tests can be used interchangeably to measure contrast sensitivity. One method can be used as a substitute for another if they yield similar results. Agreement studies by Pesudovs et al. (2004) compared Vistech and FACT wall charts in a normal population of 33 subjects, testing for intraclass correlation and establishing Bland–Altman limits for each frequency. Similar studies were also published by Hong et al. (2010) and Franco et al. (2010), who looked at agreement and repeatability between Optec 6500/FACT (85 cd/m^2) and Vision Contrast Test System 6500 (120 cd/m^2). All these studies found low correlations in-

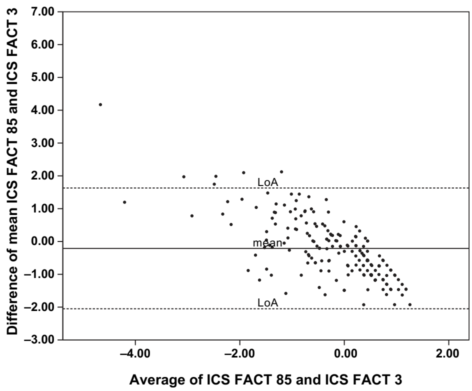


Fig. 6. Bland–Altman plot (plot of difference of the two methods) comparing $\text{ICS}_{\text{FACT85}}$ and $\text{ICS}_{\text{FACT3}}$ in 180 subjects. Mean difference is −0.22 with limits of agreement (LoA) at −2.18 and 1.75.

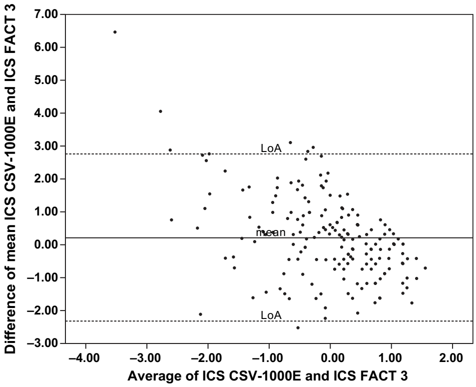


Fig. 7. Bland-Altman plot (plot of difference of the two methods) comparing and ICSCSV ICSFACT3 in 179 subjects. Mean difference is 0.20 with limits of agreement (LoA) at −2.32 and 2.76.

between tests. In our study, we have used the calculated ICS values to evaluate the agreement between the examined test methods. By definition, ICS was still not normally distributed, but transformation made the data close enough to normal distribution to allow agreement study by the Bland–Altman method. The method is believed to be fairly robust, and according to Bunce (2009), an inspection of histogram is sufficient to decide this.

The interpretation of the agreement analysis is based on clinical considerations. The relevance of ICS has never been tested in real-life or in simulated situations, and the clinical importance of a difference in mean on average of 0.43, as when comparing $\text{ICS}_{\text{FACT85}}$ and ICS_{CSV}, is still open to question. The same considerations must be made when evaluating the 95% levels of agreement. The LoA were fairly wide, −2.20 and 1.34, but the clinical implication of this is still to be investigated. $\text{ICS}_{\text{FACT3}}$ agreement to $\text{ICS}_{\text{FACT85}}$ and to ICS_{CSV} showed a different pattern. Evidently, the $\text{ICS}_{\text{FACT 3}}$ frequently differs from $\text{ICS}_{\text{FACT85}}$ and ICS_{CSV}, making it unsuitable to be used interchangeably with the two other tests.

A major difference between the photopic ($\text{ICS}_{\text{FACT85}}$ and ICS_{CSV}) and the mesopic ($\text{ICS}_{\text{FACT3}}$) test is the spread of results. The photopic tests showed a range of 4.06 and 4.68, compared with 8.97 in the mesopic test. This was partly due to one outlier in the Norwegian cohort. This recruit had low scores on high frequencies in FACT 3 cd/m^2, just making the entry level of the test. His visual acuity LogMAR score was −0.04 in one eye and 0.04 in the fellow eye. He did not report any eye condition that could explain the low ICS score. In a review, Fan-Paul et al. (2002) points out the occurrence of dark vision disturbances after refractive surgery, but if this was the case in our study is unknown. Previous refractive surgery was an exclusion criterion in our study, but this was only checked by the obtained self-reports. Another possible explanation is the phenomena of night myopia, which is only partly understood (Artal et al. 2012). The phenomenon is elusive and only present in very low light conditions (<0.02 cd/m^2) and up to 30 min of dark adaption. Our participants were not exposed to such conditions, and night myopia therefore probably does explain the reduced mesopic performance of this recruit. The increased range in test results may indicate that mesopic tests are more sensitive to dark vision disturbances then photopic tests.

The lack of objective control of the self-reports may be a weakness in this study. The French cohort was all selected for duty as aviators and had undergone ophthalmological examination at admission to duty. The Norwegian participants were screened by naval physicians prior inclusion in the study, and this cohort thus reflects a less vigorously examined population.

During the study, none of the participants wore corrective lenses. Although visual acuity 0.00 LogMAR is normally not considered an indication for using corrective lenses, it is well known that young adults frequently have a corrected visual acuity better than LogMAR 0.00 (Elliott et al. 1995; Colenbrander 2008) . Haughom & Strand (2013) found that slightly undercorrected myopia decreased the CS performance in both photopic and mesopic conditions. In an ordinary selection process, visual acuity 0.00 LogMAR is sufficient for entering any kind of work in maritime or aviation industry. We might have found even higher levels of CS if we had fitted the study population with optimal corrective lenses, but this would have created a non-realistic setting in our further studies and in relevant use of the data in other settings.

Agreement CS studies often include repeatability studies. The outcomes of these studies have been divergent, but often indicating low repeatability. Pesudovs et al. (2004) found low test–retest repeatability in FACT measured by intraclass correlation coefficient (ICC) and coefficient of repeatability (CoR). There were no significant differences between mean test and retest scores, but the average test–retest ICC was 0.34, and the average CoR was 0.35. Ideally, ICC should be close to one and CoR as near zero as possible. Kelly et al. (2012) investigated CSV-1000 and found estimates for ICC and CoR indicating low repeatability for all frequencies. On the other hand, Pomerance & Evans (1994) found acceptable CoR (mean 0.19) for CSV-1000. Hong et al. (2010) reported acceptable ICC (mean 0.85) for FACT, but poorer results for CoR (0.27). According to Miller (2008), the test–retest reliability should be estimated using a time interval that mirrors the actual use of the test, rather than trying to maximize the value of the coefficient. Our study design did not allow us to do reliability tests in what could be regarded as a relevant timeframe. Pesudovs et al. (2004) and Kelly et al. (2012) discuss in detail possible reasons for the difference in repeatability. They indicate that the main reason may be difference in test procedure. In our study, we asked the candidates not to guess when they could not positively identify the gratings. If the observer suspected guessing, the candidate made another try after the test procedure had been clarified. This was also performed if the results indicated that the candidate had not understood the test procedure. In our study, Optec 6500/FACT and CVS-1000E tests were performed by two different examiners. This may account for test differences due to systematic variations between the observers. Kelly et al. (2012) did not consider interobserver variation to be a major issue, as repeatability of CS data obtained by one or two examiners did not differ significantly. On the other hand, Elliott & Whitaker (1992) found highly significant differences between optometrists measuring both VA and CS. As stated by Miller (2008), increasing number of study participants will decrease the variation due to examiners or subjects. The narrow confidence intervals on the LoA in the present study indicate a low variance. ICC reported in other studies is not valid for use in evaluation of ICS, as these studies are performed on single frequency reports. In further studies using the ICS, it is therefore necessary to establish estimates of the repeatability coefficient.

Conclusion

Reference values for Optec 6500/FACT (85 cd/m^2 and 3 cd/m$^{2)}$ and CVS-1000E (85 cd/m^2) were established in a young, healthy population with uncorrected visual acuity 0.00 LogMAR or better. The data showed a marked ceiling effect for all frequencies of photopic and most frequencies of mesopic vision. Reference values for ICS based on the frequency data in the same population were calculated, and agreement between ICS for each test was tested. The agreement between the photopic tests was promising, but so far evidence for clinical use of ICS is missing. There was little agreement between mesopic and photopic CS tests. The mesopic test seemed to differentiate better between the candidates and may thus be most useful for medical selection purposes.

References

Adams RJ & Courage ML (2002): Using a single test to measure human contrast sensitivity from early childhood to maturity. Vision Res **42**: 1205–1210.

Amesbury EC & Schallhorn SC (2003): Contrast sensitivity and limits of vision. Int Ophthalmol Clin **43**: 31–42.

Armstrong RA, Davies LN, Dunne MC & Gilmartin B (2011): Statistical guidelines for clinical studies of human vision. Ophthalmic Physiol Opt **31**: 123–136.

Artal P, Schwarz C, Canovas C & Mira-Agudelo A (2012): Night myopia studied with an adaptive optics visula analyzer. PLoS One **7**: e40239.

Bland JM & Altman DG (1999): Measuring agreement in method comparison studies. Stat Methods Med Res **8**: 135–160.

Buhren J, Terzi E, Bach M, Wesemann W & Kohnen T (2006): Measuring contrast sensitivity under different lighting conditions: comparison of three tests. Optom Vis Sci **83**: 290–298.

Bunce C (2009): Correlation, agreement, and Bland-Altman analysis: statistical analysis of method comparison studies. Am J Ophthalmol **148**: 4–6.

Colenbrander A (2008): The historical evolution of visual acuity measurement. Vis Impair Res **10**: 57–66.

Elliott DB & Whitaker D (1992): Clinical contrast sensitivity chart evaluation. Ophthalmic Physiol Opt **12**: 275–280.

Elliott DB, Yang KC & Whitaker D (1995): Visual acuity changes throughout adulthood in normal, healthy eyes: seeing beyond 6/6. Optom Vis Sci **72**: 186–191.

Evans DW & Ginsburg AP (1985): Contrast sensitivity predicts age-related differences in highway-sign discriminability. Hum Factors **27**: 637–642.

Fan-Paul NI, Li J, Miller JS & Florakis GJ (2002): Night vision disturbances after corneal refractive surgery. Surv Ophthalmol **47**: 533–546.

Franco S, Silva AC, Carvalho AS, Macedo AS & Lira M (2010): Comparison of the VCTS-6500 and the CSV-1000 tests for visual contrast sensitivity testing. Neurotoxicology **31**: 758–761.

Ginsburg AP (2003): Contrast sensitivity and functional vision. Int Ophthalmol Clin **43**: 5–15.

Ginsburg AP, Evans DW, Sekule R & Harp SA (1982): Contrast sensitivity predicts pilots' performance in aircraft simulators. Am J Optom Physiol Opt **59**: 105–109.

Grimson JM, Schallhorn SC & Kaupp SE (2002): Contrast sensitivity: establishing normative data for use in screening prospective naval pilots. Aviat Space Environ Med **73**: 28–35.

Haughom B & Strand TE (2013): Sine wave mesopic contrast sensitivity – defining the normal range in a young population. Acta Ophthalmol **91**: 176–182.

Hohberger B, Laemmer R, Adler W, Juenemann AG & Horn FK (2007): Measuring contrast sensitivity in normal subjects with OPTEC 6500: influence of age and glare. Graefes Arch Clin Exp Ophthalmol **245**: 1805–1814.

Hong YT, Kim SW, Kim EK & Kim TI (2010): Contrast sensitivity measurement with 2 contrast sensitivity tests in normal eyes and eyes with cataract. J Cataract Refract Surg **36**: 547–552.

Kelly SA, Pang Y & Klemencic S (2012): Reliability of the CSV-1000 in adults and children. Optom Vis Sci **89**: 1172–1181.

McAlinden C, Khadka J & Pesudovs K (2011): Statistical methods for conducting agreement (comparison of clinical tests) and precision (repeatability or reproducibility) studies in optometry and ophthalmology. Ophthalmic Physiol Opt **31**: 330–338.

Miller M (2008): Reliability. Encyclopedia of educational psychology. Thousand Oaks, CA: SAGE Publications, Inc.

Owsley C & McGwin G Jr (2010): Vision and driving. Vision Res **50**: 2348–2361.

Owsley C, Sekuler R & Siemsen D (1983): Contrast sensitivity throughout adulthood. Vision Res **23**: 689–699.

Pesudovs K, Hazel CA, Doran RM & Elliott DB (2004): The usefulness of Vistech and FACT contrast sensitivity charts for cataract and refractive surgery outcomes research. Br J Ophthalmol **88**: 11–16.

Pomerance GN & Evans DW (1994): Test-retest reliability of the CSV-1000 contrast test and its relationship to glaucoma therapy. Invest Ophthalmol Vis Sci **35**: 3357–3361.

Sia DI, Martin S, Wittert G & Casson RJ (2013): Age-related change in contrast sensitivity among Australian male adults: Florey Adult Male Ageing Study. Acta Ophthalmol **91**: 312–317.

Swamy S (2002): Contrast sensitivity in IAF aircrew. Ind J Aerospace Med **46**: 7–22.

Wachler BSB & Krueger RR (1998): Normalized contrast sensitivity values. J Refract Surg **14**: 463–466.

Received on November 11th, 2013.
Accepted on May 24th, 2014.

Correspondence:
Vilhelm F. Koefoed
Department of Clinical Medicine
Faculty of Medicine and Dentistry
University of Bergen
PO Box 7800
N-5020 Bergen
Norway
Tel: +47 55504891
Fax: +47 55504890
Email: v@koefoed.no

We would like to acknowledge Irene Berg, senior engineer at Institute of Aviation medicine and Hjalmar Johansen, commander (R) in The Royal Norwegian Navy, for assistance in data collection. Assistance from Ecole de l'air, Salon de Provence and Justin Plantier, Institut de Médicine Aerospatiale have been valuable for gathering data in the French Air Force. The Royal Norwegian training school and the Norwegian Armed Forces Medical Services assisted in collecting data in the Norwegian cohort. The studies have been performed with support from the Royal Norwegian Navy and Norwegian Centre of Maritime Medicine.

Acta Ophthalmologica

Correlation between observation task performance and visual acuity, contrast sensitivity and environmental light in a simulated maritime study

Vilhelm F. Koefoed,[1] Jörg Assmuss[2] and Gunnar Høvding[1]

[1]Department of Clinical Medicine, Faculty of Medicine, University of Bergen, Bergen, Norway
[2]Uni Research Helse, Bergen, Norway

ABSTRACT.

Purpose: **To examine the relevance of visual acuity (VA) and index of contrast sensitivity (ICS) as predictors for visual observation task performance in a maritime environment.**

Methods: **Sixty naval cadets were recruited to a study on observation tasks in a simulated maritime environment under three different light settings. Their ICS were computed based on contrast sensitivity (CS) data recorded by Optec 6500 and CSV-1000E CS tests. The correlation between object identification distance and VA/ICS was examined by stepwise linear regression.**

Results: **The object detection distance was significantly correlated to the level of environmental light ($p < 0.001$), but not to the VA or ICS recorded in the test subjects. Female cadets had a significantly shorter target identification range than the male cadets.**

Conclusion: **Neither CS nor VA were found to be significantly correlated to observation task performance. This apparent absence of proven predictive value of visual parameters for observation tasks in a maritime environment may presumably be ascribed to the normal and uniform visual capacity in all our study subjects.**

Key words: contrast sensitivity – index of contrast sensitivity – visual function – visual performance

Acta Ophthalmol.

doi: 10.1111/aos.13673

Introduction

According to international convention, it is required that ‘every vessel shall at all times maintain a proper lookout by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision, stranding and other hazards to navigation’ (International Maritime Organization 1972). In *Guidelines on medical examination of seafarers* by the International Labour Organization (2011), the internationally agreed minimum occupational requirements are stated. As shown by Schepers (1991), the requirements are practised differently in different countries. In Norway, personnel acting as lookouts or mariners should previously have a best corrected decimal visual acuity (BCVA) of 1.0 or better tested by a Snellen chart in both eyes (NHD 2001), but this requirement was recently reduced to BCVA ≥0.5 in both eyes (NFD 2014).

Visual minimum requirements were developed during the last half of 19th century and were apparently set by both political and scientific considerations (Langmore 1885). This duality is still reflected in the new regulations (International Labour Organization 2011), where governmental organizations, employers and employees have agreed on minimum standards. To the best of our knowledge, little research has been performed on visual requirements for seafarers. A study by Donderi (1994) using contrast sensitivity (CS) letter charts (Regan 1988) showed a significant relationship between low-contrast visual acuity (LCVA) and visual performance at sea, but found no significant correlation between high-contrast visual acuity (HCVA) and visual performance. On the other hand, several studies on the relationship between CS and performance in other occupations or car driving have been published (Owsley & McGwin 2010; Yazdan-Ashoori & Ten Hove 2010). In a study on US Air Force pilots, Ginsburg et al. (1982) found CS to be a better predictor than visual acuity (VA) to detect air-to-ground targets in an aircraft simulator. Owsley & Sloane (1987) reported CS and age to be stronger predictors than VA to estimate visual performance in a picture observation study. Using pictures in a study on simulated visual search performance in 55 selected and trained Canadian military technicians, Stager & Hameluck (1986) also found CS to be a better predictor than VA. In an experimental study on road safety, Wood & Owens (2005) found photopic VA to be of limited value in predicting performance, while improved prediction was obtained by combining photopic VA and photopic CS or mesopic VA.

Contrast sensitivity (CS) can be examined by different methods, such as charts displaying letters or symbols at different contrast levels compared to the background (Rabin & Wicks 1996) or sine-wave gratings in different spatial frequencies (Campbell & Robson 1968). The interpretation of measured CS values has been a major obstacle in previous efforts to employ CS as a selection criterion for personnel employed in tasks highly dependent on visual performance. Some studies imply that the high-frequency area is most important, others emphasize the middle frequencies and some stress the importance of the lower frequencies (Ginsburg et al. 1982; Evans & Ginsburg 1985; Stager & Hameluck 1986). This inspired Haughom & Strand (2013) to describe CS by the so-called index of contrast sensitivity (ICS), which takes all measured frequencies into account, weighting them according to believed importance. Reference values for two different cohorts have been established for this collated index by Haughom & Strand (2013) and Koefoed et al. (2015). As far as we know, no studies validating ICS against visual performance in simulated situations or in real world have previously been published.

The aim of this study was to examine the relationship between visual observation task performance in simulated maritime environments and recorded VA and CS/ICS.

Subjects and Methods

Study subjects

Subjects were cadets attending the Royal Norwegian Navy Academy (RNoNA) with normal colour vision. Cadets have served in the Norwegian Armed Forces before entering the RNoNA. They are recruited mainly after service in RNoN, but may also represent other military branches. A strict medical selection screening process is not applied on all cadets as other qualifications may be considered as more important for the service. Cadets entering nautical education are required to have BCVA ≥1.0 and uncorrected VA ≥0.5 in one eye and 0.3 in the other. For other cadets, the requirements are BCVA ≥1.0 and VA ≥0.1 uncorrected in both eyes.

Observation task

In order to examine whether CS is a reliable predictor for visual observation task performance, the study had to be controlled for environmental factors. It was therefore carried out in simulators, securing the same environmental test conditions (light, sound, temperature and visual stimuli) for all subjects.

The experiments were conducted using five identical fixed-base, full-scale Polaris bridge simulators (Kongsberg Maritime AS, Horten, Norway) at the RNoNA. Skjold-class simulator models were used, with hydrodynamic and performance characteristics similar to the real vessel. All bridges had a generic layout, with a 270-degree field of vision (180 degrees forward view, 90 degrees aft). The subjects did not use any electronic- or paper-based charts. The simulator ran in autopilot in a preprogrammed route at a speed of 20 knots/hr (37 km/hr).

Along the planned course (Fig. 1), three different objects (Fig. 2) were distributed at randomized distances, orientations and sequences to allow for up to 20 observations at each run. The study subjects were asked to identify and verbally report each object they observed. The time a target was identified was recorded by a secretary, which allowed the identification distance to be calculated in metres, hereafter named ‘time-points’. Three different runs with 15 min time limitation were performed with no repetition. The most important environmental factor used was simulated external light at 90%, 80% and 50% relative darkness, defined by the simulator settings, which gave an illusion of low mesopic, mesopic and photopic light conditions. A 10 min dark vision adaptation was applied before the first run in low mesopic light, followed by runs in mesopic and photopic light levels. Simulated engine noise, but no wind or current, was employed.

Visual assessment

Binocular contrast sensitivity (CS) was measured by two commercially available tests using sine-wave gratings in different spatial frequencies. The Optec 6500/FACT (Functional Acuity Contrast Test; Stereo Optical, Chicago, IL, USA) was used for mesopic (3 candela/m^2 (cd/m^2)) and photopic (85 cd/m^2) measurements at the spatial frequencies of 1.5, 3, 6, 12 and 18 cpd (cycles per degree visual angle). Mesopic CS was first measured after 10 min dark adaptation, and then, the test was repeated in photopic light. The same examiner tested all the study subjects. The data obtained were plotted using the EyeView™ software. The other test used the CSV-1000E (VectorVision, Greenville, OH, USA) for photopic (85 cd/m^2) CS measurements. The test consists of sine-wave gratings for the frequencies 3, 6, 12 and 18 cpd. A second examiner performed this test immediately after the Optec 6500 tests were completed. During the tests, the subjects were encouraged to respond, but not to guess. A forced choice and a strict time limit were not employed.

The first examiner also measured the monocular best eye visual acuity (VA) of each subject using the Optec 6500/EDTRS chart in long distance mode on a logMAR scale at photopic light conditions (85 cd/m^2). The chart has a minimum resolution at −0.20 logMAR.

A third examiner recorded the colour vision using the Ishihara 24-plate pseudoisochromatic test in standardized daylight colour temperature of 6280° Kelvin using the illuminator for pseudoisochromatic tests with Easel (Richmond Products, Albuquerque, NM, USA).

Using the results obtained in our three different CS measurements, the ICS was calculated for each subject. As recommended by Haughom & Strand (2013), ICS was defined as the sum of the residual differences (positive or negative) from the population median in each frequency. The differences were weighted according to the presumed clinical importance of each frequency. Thus, 6 cpd was given the highest power (factor 3). The frequencies 3 and 12 cpd received factor 2, while the remaining test frequencies were not weighted at all.

$$\begin{aligned}\mathrm{ICS} = {} & (1.5\mathrm{cpd} - 1.5\mathrm{rcpd}) + 2(3\mathrm{cpd} \\ & - 3\mathrm{rcpd}) + 3(6\mathrm{cpd} - 6\mathrm{rcpd}) \\ & + 2(12\mathrm{cpd} - 12\mathrm{rcpd}) \\ & + (18\mathrm{cpd} - 18\mathrm{rcpd}).\end{aligned}$$

Median values (rcpd) to calculate ICS were collected in a previous study by Koefoed et al. (2015), where reference percentiles also were reported. A performance equivalent to the median of all tested frequencies in the reference cohort should yield an ICS value of zero.

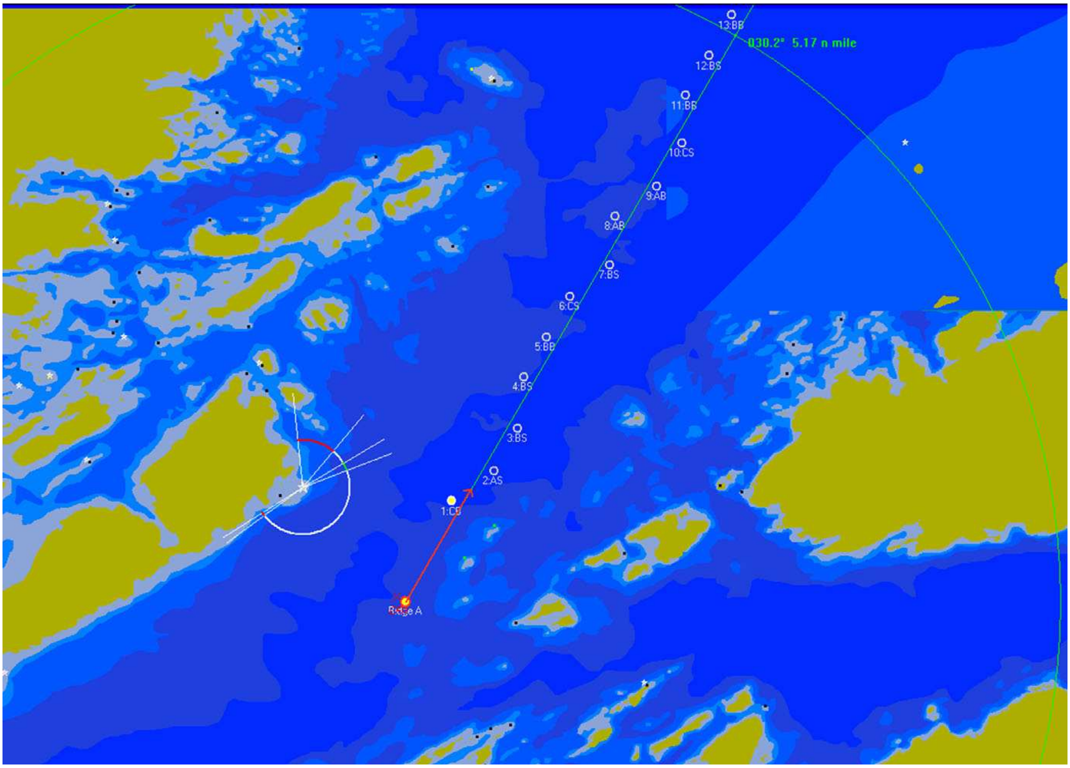


Fig. 1. The map shows the preplanned track for a simulated ship's course. Each object (Fig. 2) was placed on the port (left) or starboard (right) side of the course line in a randomized pattern.

Fig. 2. The three targets used as objects for observation. The test subjects were instructed to identify the objects, and observation distance was calculated based on time of observation.

Statistical analyses

The possible relationship between visual capability and visual performance was studied by stepwise linear regression using identification distance as a dependent variable. Age, gender, visual descriptor (VA and ICS), spectacles, time-points and light conditions were independent variables. The low mesopic light condition was a fixed variable. For the identification distance, we used the first ten observations in each light setting. Male and female VA (logMAR) and calculated ICS performance were compared by gender using the Mann–Whitney *U*-test. The normality of visual data was tested by Shapiro–Wilk test. A *t*-test was used to test for gender differences in performance and effect of difference in time-points. The level of significance was set at 0.05. Statistical analyses were performed using IBM SPSS Statistics version 22.0 (IBM corp., Armonk, NY, USA).

Research ethics

This study adhered to the Declaration of Helsinki. The subjects were informed about the objectives and conditions of the study and had to sign a formula of consent. A physician was on call throughout the study, in case of adverse health effects occurring in the study group. The Regional Committee for Medical Research Ethics, Western Norway and the Norwegian Social Science Data Services approved the study protocol. The test subjects were not paid for participating in the study, and they could withdraw from the study at any point. Individual data from the study were not revealed to the Armed Forces and could not be used for medical selection of the candidates.

Results

Subjects

A total of 74 cadets attending the RNoNA volunteered for the study. Due to malfunction in the first run of the simulator, nine cadets had to be excluded from the study. Another five cadets failing the Ishihara 24 plate colour vision test were also excluded. Thus, ten female and 50 male cadets

Table 1. Visual acuity logMAR (VA) and indexes of contrast sensitivity (ICS; log values) for the study population.

	Visual acuity logMAR	Index of contrast sensitivity Optec 6500 3 cd/m^2	Index of contrast sensitivity Optec 6500 85 cd/m^2	Index of contrast sensitivity CSV-1000E 85 cd/m^2
Subjects				
Valid	60	60	60	60
Missing	0	0	0	0
Mean	−0.10	−1.53	−0.85	−0.32
Median	−0.12	−1.72	−0.46	−0.075
SD	0.086	1.83	1.51	1.18
Range	0.36	9.94	6.79	4.51
Minimum	−0.20	−8.03	−6.35	−3.16
Maximum	0.16	1.91	0.44	1.35

SD = standard deviation.

with mean age of 24.1 years (range 18–33; SD 2.9) fulfilled the study. The proportion of female and male cadets trained as navigators did not differ significantly. None reported somatic or mental health problems. Six cadets wore contact lenses, ten wore spectacles and three had undergone refractive surgery for myopia. A complete set of CS measurements (Table 1 and Fig. 3) and independent variables were obtained from all 60 test subjects. The mean best eye corrected VA in the study group was −0.10 (range −0.20 to 0.16; SD 0.09) at 85 cd/m^2 on a logMAR scale. Neither VA (p = 0.74) nor CS (p = 0.29 to 0.76) differed significantly between female and male cadets. None of the visual tests showed a normal distribution according to Shapiro–Wilk test. Visual acuity (VA) was skewed towards the highest resolution of OPTEC 6500 at −0.20 LogMAR, indicating a ceiling effect of the test. Also, the calculated ICS values indicated skewness towards the high end of CS.

Task performance

No statistically significant correlations between observation task performance and VA or ICS were found (Table 2 and Fig. 4). The performance is indicated by a linear trend line. Inspections of the trend lines indicate no significant correlation between observation distance and VA or ICS ($R^2 < 0.04$ for all). A highly significant improvement of identification distance was recorded for each stepwise increase in environmental light settings when comparing low mesopic, mesopic and photopic light settings (p < 0.001). A statistically significant improvement was also found when identification distance was examined for each observation (time-points) in each run (p < 0.001). The correct identification rate of the observed objects did not differ significantly from time-point one to time-point ten, indicating that the increased observation distance during each run was a learning effect. Male subjects were capable of detecting targets earlier than female subjects in all light conditions correlated to VA and the three different ICS values (p = 0.010 to 0.016). The correct identification rate showed no statistically significant gender difference. Correct identifications rates were 87% in low mesopic light level, 96% in mesopic light level and 95% in photopic light level.

Discussion

The present study aimed to examine the possible correlation between CS and the ability to make observations in a maritime environment. Although it is evident that the quality of vision must be relevant for visual performance at sea, a statistically significant correlation between identification distance and the level of CS expressed by ICS could not be shown. The subjects in our study had been selected for military duty and they all had normal VA (mean logMAR score −0.10, range logMAR −0.20 to 0.16). Most likely, the lack of significant correlations between visual characteristics and observation task performance in our study was mainly caused by the uniform and normal visual function in all our study subjects.

The observation performance in a similar high-vision study group was described in a flight simulator study by Ginsburg et al. (1983), where 11 pilots observed air-to-ground targets. A statistically significant correlation (r = 0.83, p < 0.01) between identification distance in low visibility conditions and peak CS region in scotopic (0.15 cd/m^2) light was found. A highly significant association between several spatial frequencies and detection range was reported, but unfortunately, only the result in the ‘peak region’ of a single frequency was published. Visual acuity (VA) was not significantly correlated to identification distance.

In a later real-world study performed in a maritime setting, Donderi (1994) to some degree confirmed the findings of Ginsburg et al. (1983). The study task was to observe and identify life rafts afloat in a predefined search area. The mean VA in the test group was slightly better than Snellen VA 1.0. The study showed that environmental factors, such as light level, wind, sea state and skips roll, were the most important predictors of detection percentage and detection distance of life rafts. Deficient colour vision and reduced LCVA were also negatively correlated to detection percentage, but not to detection distance. High-contrast visual acuity (HCVA) did not correlate to any of the performance outcomes.

Conceivably, studies including subjects with a wider range of VA and CS might reveal a wider range of responses, giving increased opportunity to detect clinically significant correlations. Wood & Owens (2005) found that a combination of VA and CS, as tested with Pelli–Robson chart, had predictive value for the drivers’ ability to detect road objects. They found that the best predictor for detecting road objects was photopic VA in combination with either mesopic VA and/or photopic CS. Their study population differed from ours, having an age span of approximately 50 years and BCVA decimal acuity ≥0.5. Contrast sensitivity (CS) was found to be a significant performance predictor in a group of drivers with significant differences in sine-wave CS when Evans & Ginsburg (1985) studied highway-sign discrimination. Their two study groups had mean Snellen decimal BCVA of 1.15 and 1.21, respectively. This nonsignificant VA difference between the groups may probably explain the lack of VA as a predictor of visual performance also

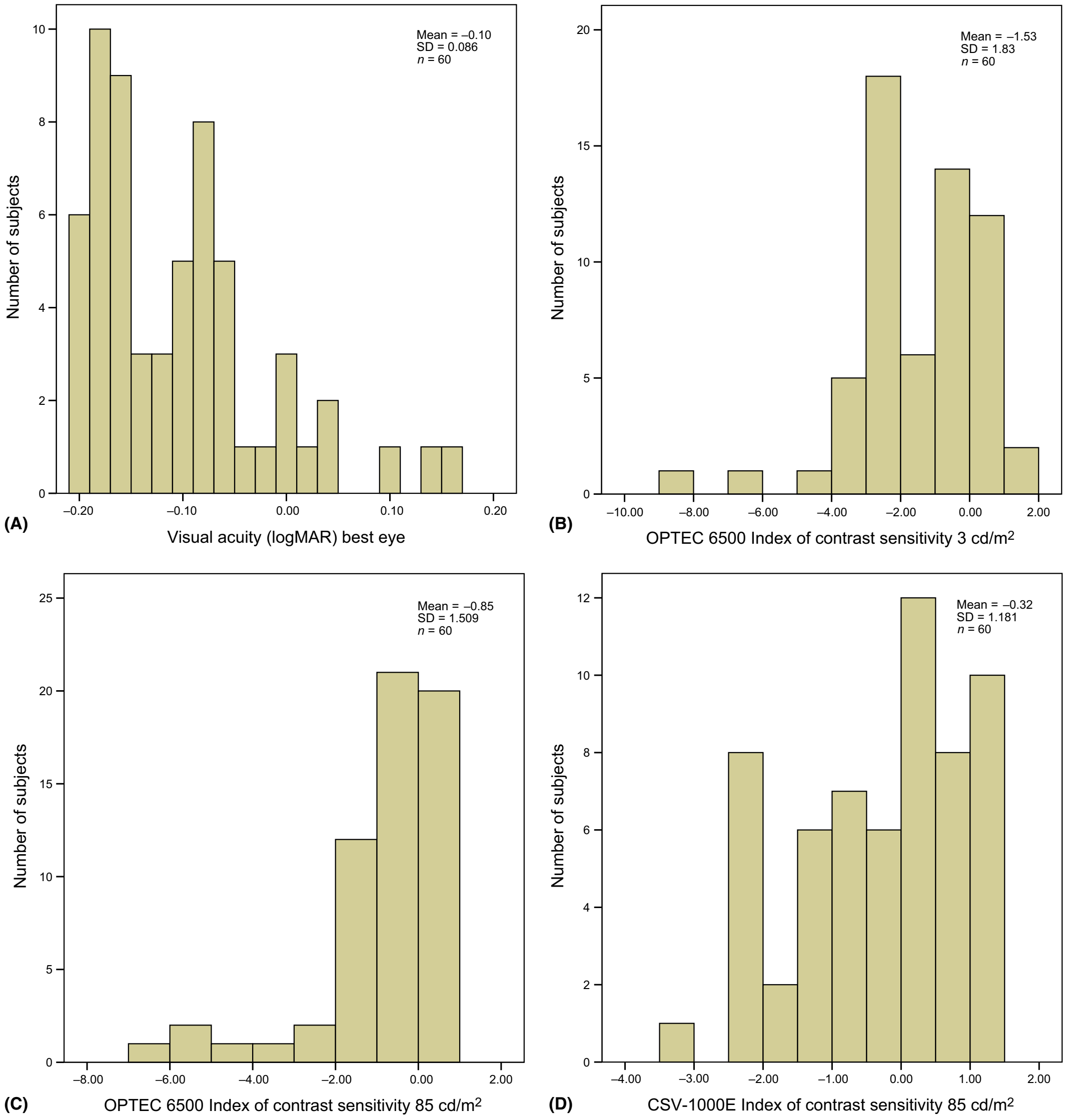


Fig. 3. Distribution of visual acuity (A) and indexes of contrast sensitivity (B–D). None of the visual tests showed normal distribution, and all had skewness towards a high-performance result. An ICS value = 0.0 indicates a contrast sensitivity equal to the median of the reference population (Koefoed et al. 2015). ICD = index of contrast sensitivity, SD = standard deviation.

in that study. McGwin et al. (2000) found decimal acuity of <0.2 compared to 1.0 to be the strongest predictor of self-reported reduced night driving performance in an adjusted logistic regression model (odds ratio 6), indicating the need for a large difference in VA to obtain significant predictive value of this parameter.

So far, there is no generally accepted ‘gold standard’ method to measure and report CS. A valid comparison between our results and those presented in the above-mentioned papers is therefore not readily carried out, as CS and VA were examined by different principles and methods. Ginsburg et al. (1983) and Evans & Ginsburg (1985) studied observation performance correlated to sine-wave single frequencies, Donderi (1994) used a low-contrast acuity chart based on Snellen-type letters printed with varying levels of optotype/background contrast, as described by Regan (1988). Wood & Owens (2005) and McGwin et al. (2000) used a Pelli–Robson chart (Pelli et al. 1987), a low-

Table 2. Identification distance according to visual acuity (VA) and index of contrast sensitivity (ICS) by three different test modes, gender and light levels using stepwise linear regression in a combined model with low mesopic light as fixed variable. The effects of age and glasses were nonsignificant and were not included in the table (β = regression slope. SE = standard error).

Visual measurement/ visual descriptor	Visual acuity $_{(\text{logMAR})}$			$\text{ICS}_{\text{Optec 6500 3 cd/m}^2}$			$\text{ICS}_{\text{Optec 6500 85 cd/m}^2}$			$\text{ICS}_{\text{csv-1000E 85 cd/m}^2}$		
Variable	β	SE	p-value	β	SE	p-value	β	SE	p-value	β	SE	p-value
Low mesopic light	303.11	338.42	0.37	−6.34	14.68	0.67	−5.65	18.96	0.77	−16.94	23.00	0.46
Mesopic light	731.91	13.09	<0.001	731.89	13.09	<0.001	732.34	13.08	<0.001	731.91	13.09	<0.001
Photopic light	1427.07	19.30	<0.001	1426.96	19.29	<0.001	1427.45	19.31	<0.001	1426.96	19.29	<0.001
Time-points	19.65	2.04	<0.001	19.67	2.04	<0.001	19.63	2.04	<0.001	19.68	2.04	<0.001
Gender Women = 1	−191.14	75.35	0.014	−188.15	75.87	0.016	−202.34	75.95	0.010	−196.15	75.62	0.012

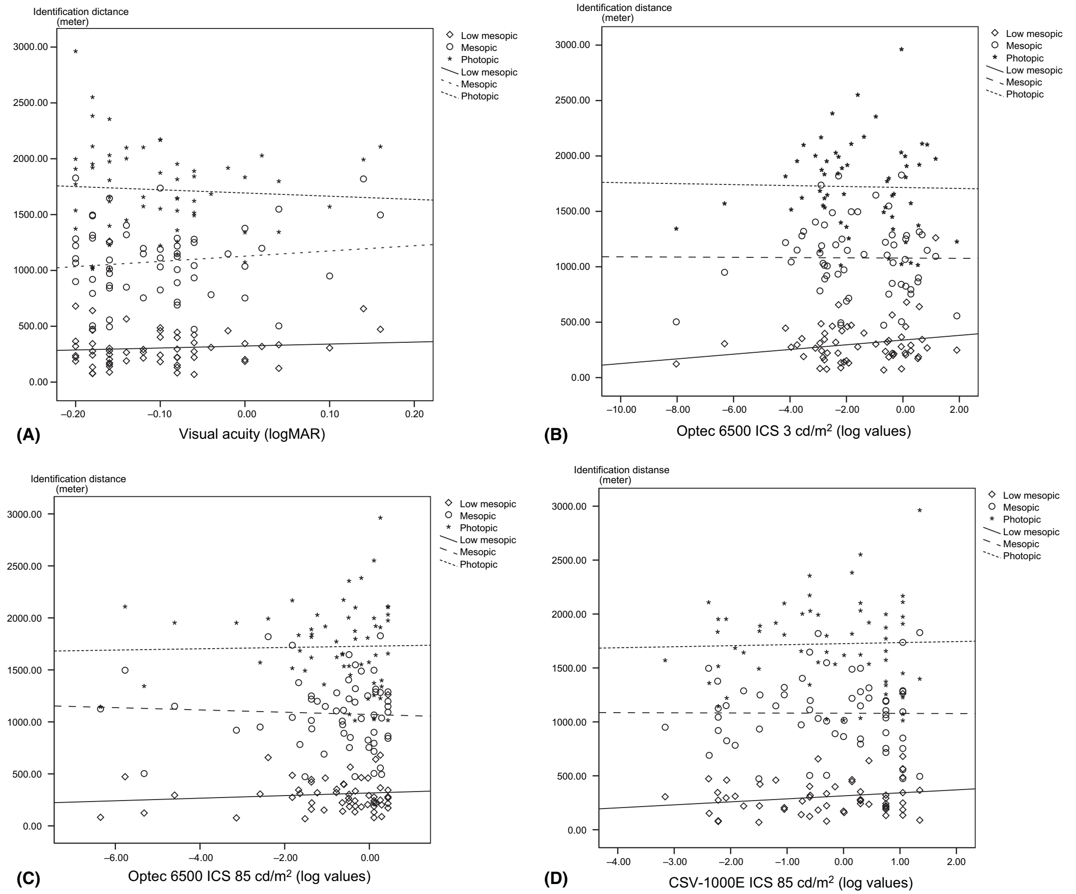


Fig. 4. Object observation distance according to visual acuity (logMAR) and index of contrast sensitivity (ICS) in three different environmental light settings (low mesopic, mesopic and photopic). A linear trend line indicates the observation task performance. Inspections of the trend lines indicate no significant correlation between observation distance and VA or ICS ($R^2 < 0.04$ for all). Reduced logMAR score indicates improved VA, while increased ICS indicates improved contrast sensitivity. Each dot represents mean value of observation distance for a study subject. Scatter plot A represents calculated identification distance related to VA. Scatter plot B represents identification distance calculated for ICS values obtained with Optec 6500 at 3 cd/m^2, scatter plot C with Optec 6500 at 85 cd/m^2 and scatter plot D with CSV-1000E at 85 cd/m^2.

contrast letter identification chart quite similar to the test used by Donderi (1994). However, Regan (1988), Leguire (1991) and Rohaly & Owsley (1993) have on the other hand debated the usability of letter charts (LC) for measuring CS. In the present study, we chose to use ICS as a measure for CS, aiming to evaluate the relevance of this collated index in a simulated task observation study.

In our study, both VA and CS were very similar in female and male subjects. Despite this, the recorded mean target identification distance was significantly shorter in the female cadets. Our main hypothesis for this finding is a presumed gender difference in decision criterion as there was no difference in true identification rate. As previously suggested by Venkatesh & Morris (2000) and Mitchell & Walsh (2004), females may require a higher degree of positive identification before decision is made, resulting on a shorter identification distance.

Conclusion

Visual object observation performance in a simulated maritime environment was recorded, and the correlation between identification distance and CS was examined. For subjects with normal visual function, the results showed that object observation range was significantly correlated to environmental light conditions, but not to VA or ICS. The apparent nonsignificant correlation between object identification distance and visual function was believed to be due to the uniform levels of VA and CS in our test subjects.

References

Campbell FW & Robson JG (1968): Application of Fourier analysis to the visibility of gratings. J Physiol **197**: 551–566.

Donderi DC (1994): Visual acuity, color vision, and visual search performance at sea. Hum Factors **36**: 129–144.

Evans DW & Ginsburg AP (1985): Contrast sensitivity predicts age-related differences in highway-sign discriminability. Hum Factors **27**: 637–642.

Ginsburg AP, Evans DW, Sekule R & Harp SA (1982): Contrast sensitivity predicts pilots' performance in aircraft simulators. Am J Optom Physiol Opt **59**: 105–109.

Ginsburg AP, Easterly J & Evans DW (1983): Contrast sensitivity predicts target detection field performance of pilots. Proc Hum Fact Ergon Soc Annu Meet **27**: 269–273.

Haughom B & Strand TE (2013): Sine wave mesopic contrast sensitivity – defining the normal range in a young population. Acta Ophthalmol **91**: 176–182.

International Labour Organization (2011): Guidelines on the medical examinations of seafarers. Geneva: International Labour Organization, UN.

International Maritime Organization (1972): Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs). London: International Maritime Organization.

Koefoed VF, Baste V, Roumes C & Hovding G (2015): Contrast sensitivity measured by two different test methods in healthy, young adults with normal visual acuity. Acta Ophthalmol **93**: 154–161.

Langmore T (1885): The optical manual or Handbook of instructions for guidance of surgeons in testing the range and quality of vision of recruits and others seeking employment in the military services of Great Britain, and in distinguishing and dealing with optical defects among the officers and men already engaged in them. London: Published by Authority.

Leguire L (1991): Do letter charts measure contrast sensitivity? Clin Vis Sci **6**: 391–400.

McGwin G, Chapman V & Owsley C (2000): Visual risk factors for driving difficulty among older drivers. Accident Anal Prev **32**: 735–744.

Mitchell V-W & Walsh G (2004): Gender differences in German consumer decision-making styles. J Consum Behav **3**: 331–346.

NFD (2014): Forskrift om helseundersøkelse av arbeidstakere på norske skip og flyttbare innretninger. In: fiskeridepartementet N-o (ed.) FOR-2014-06-05-805.

NHD (2001): Forskrift om helseundersøkelse av arbeidstakere på skip. In: handelsdepartementet) NN-o (ed.) FOR-2001-10-19-1309.

Owsley C & McGwin G Jr (2010): Vision and driving. Vision Res **50**: 2348–2361.

Owsley C & Sloane ME (1987): Contrast sensitivity, acuity, and the perception of 'real-world' targets. Br J Ophthalmol **71**: 791–796.

Pelli DG, Robson JG & Wilkins A (1987): The design of a new letter chart for measuring contrast sensitivity. Clin Vis Sci **2**: 187–199.

Rabin J & Wicks J (1996): Measuring resolution in the contrast domain: the small letter contrast test. Optom Vis Sci **73**: 398–403.

Regan D (1988): Low-contrast letter charts and sinewave grating tests in ophthalmological and neurological disorders. Clin Vis Sci **2**: 235.

Rohaly AM & Owsley C (1993): Modeling the contrast-sensitivity functions of older adults. J Opt Soc Am A **10**: 1591–1599.

Schepers B (1991): Medical examinations to assess fitness for maritime service - an international comparison. In: Saarni H & Gardner W (eds.) The International symposium on maritime health. Turku, Finland: Turku regional Institute of Occupational Health 68–99.

Stager P & Hameluck D (1986): Contrast sensitivity and visual detection in search and rescue. Downsview, ON: Defence and Civil Institute of Environmental Medicine.

Venkatesh V & Morris MG (2000): Why don't men ever stop to ask for directions? Gender, social influence, and their role in technology acceptance and usage behavior MIS Q **24**: 115.

Wood JM & Owens DA (2005): Standard measures of visual acuity do not predict drivers' recognition performance under day or night conditions. Optom Vis Sci **82**: 698–705.

Yazdan-Ashoori P & Ten Hove M (2010): Vision and driving: Canada. J Neuroophthalmol **30**: 177–185.

Received on February 20th, 2017.
Accepted on November 15th, 2017.

Correspondence:
Vilhelm F. Koefoed
Department of Clinical Medicine
Faculty of Medicine
University of Bergen
5020 Haukeland University Hospital
Bergen
Norway
Tel: +4790727527
Fax: +4755504150
Email: v@koefoed.no

We would like to acknowledge Irene Berg, senior engineer at Institute of Aviation medicine, and Hjalmar Johansen, commander (R) in The Royal Norwegian Navy, for assistance in data collection. Commander Petter Lunde and Commander Frode Voll Mjelde played a vital role in the study by running the simulators during the study. Assistance from Corinne Roumes and Justin Plantier, Institut de Médicine Aerospatiale has been valuable for evaluating the performance in the simulators. The studies have been performed with support from the Royal Norwegian Navy and Norwegian Centre of Maritime Medicine.

Acta Ophthalmologica

Contrast sensitivity and the effect of 60-hour sleep deprivation

Vilhelm F. Koefoed,[1] Jörg Aßmus,[2] Kristian S. Gould,[3] Gunnar Hövding[1] and Bente E. Moen[4]

[1]Department of Clinical Medicine, Faculty of Medicine and Dentistry, University of Bergen, Bergen, Norway
[2]Uni Health, Bergen, Norway
[3]Statoil ASA, Stavanger, Norway
[4]Department of Global Public Health and Primary Care, Faculty of Medicine and Dentistry, University of Bergen, Bergen, Norway

ABSTRACT.
Purpose: **The study aimed to evaluate the possible influence of prolonged sleep deprivation on achromatic and chromatic (red–green and blue–yellow) contrast sensitivity (CS).**
Methods: **During 60-hr sleep deprivation, CS was measured in 11 naval officers every sixth hour using videographic (Vigra-C) sine-wave-generated stimuli.**
Results: **When comparing the CS measurements obtained in the first and last 24 hr of the study, no statistically significant mean changes of achromatic CS (2.0, 5.9 and 11.8 cpd) or yellow–blue CS (0.6, 2.0 and 4.7 cpd) were found, while a significantly increased mean red–green CS at 2.0 and 4.7 cpd was recorded in the last 24 hr ($p = 0.003$ in both). The variance of achromatic and chromatic CS measurements in the group did not differ significantly in the first and last 24 hr test periods.**
Conclusions: **Prolonged sleep deprivation does apparently not cause clinically or occupationally significant changes of contrast sensitivity in otherwise healthy subjects with normal visual acuity.**

Key words: contrast sensitivity – eye – fatigue – sleep deprivation – visual function

Acta Ophthalmol. 2015: 93: 284–288

doi: 10.1111/aos.12536

Introduction

Previous studies on the effects of sleep deprivation or fatigue on visual functions have usually involved subjects performing monotonous tasks, for example reading for hours, while examiners study the effect on visual-motor processes like accommodation (Miller et al. 1983; Pigion & Miller 1985; Ehrlich 1987; Owens & Wolf-Kelly 1987), oculomotor performance, such as visual search and saccadic tasks (De Gennaro et al. 2000, 2001; Gould et al. 2009) and visual field (Roge et al. 2003).

Only a few studies have evaluated visual function after prolonged sleep deprivation. In a study including 20 students, a minor loss of visual acuity after 46 hr without sleep and a total recovery after 4 hr of sleep were reported by Paul (1965). Quant (1992) studied contrast sensitivity (CS) in six army service men performing simulated military missions during 65 hr of total sleep deprivation. Following 36 hr of sleep deprivation, a significantly reduced near-vision CS at 6 cpd (cycles per degree of visual angle) was recorded ($p = 0.03$). To the best of our knowledge, there are very few studies on colour vision after sleep deprivation and no such studies on chromatic CS.

The present study aimed to examine the effect of prolonged total sleep deprivation on both achromatic and chromatic CS. Different types of CS tests are available, commonly using sinusoidal test patterns of different spatial frequencies and relative contrast. As total sleep deprivation might conceivably cause reduced CS, thereby possibly also influencing visual acuity and colour vision, our results may yield information relevant for the working conditions and operational requirements for subjects working under extreme conditions with little or no possibility to rest, such as military operations, naval seafaring and commercial fishing.

Materials and methods

Study design

Contrast sensitivity measurements were obtained as part of a larger research project, in which the effect of sleep deprivation on performance in two high-speed navigation systems was studied. The main results have been published elsewhere (Gould et al. 2009), but information relevant for the study of CS is only reported in the present paper. The design for the navigation study by Gould et al. (2009) required two separate test periods, and this gave an opportunity to increase the number of measurements. The CS measurements were made during two test periods separated by a period of 10 weeks. Within a 6-hr test cycle (preparation – simulator navigation –

questionnaires – visual tests – rest), the participants underwent an 80-min session of visual tests in a low-light test laboratory, of which only the CS tests are reported here (Fig. 1). At the completion of each test cycle, the participants had a 90-min break to eat and rest, but not to sleep, before the next test cycle started. During these breaks, the participants were allowed to read, watch films, use the Internet and walk (but not run). The study comprised a total of 10 repetitions of the same test cycle. Those showing signs of falling asleep were prompted to stay awake by a research assistant. To ensure realistic study conditions, the participants were allowed caffeinated beverages and tobacco not exceeding the number of units they consumed on an ordinary working day according to information obtained at the time of recruitment. Caffeine units were administered in the form of 4 g instant coffee sachets.

Test subjects

Eleven male fast patrol boat (FPB) navigators from the Royal Norwegian Navy volunteered for the study. Their mean age was 26.8 years (range 23.1–30.6; SD = 2.0). The group was examined by an ophthalmologist at the Institute of Aviation Medicine, Norwegian Armed Forces in Oslo before entering the study. None of them reported somatic or mental health problems, including sleep disorders or abnormal sleep habits, and no medication was currently used. Three of the participants used snuff during the study, but no one smoked. Two normally used contact lenses, one used glasses, and one had undergone refractive surgery. During the study, the contact lens users wore glasses. Their mean best corrected visual acuity (BCVA) was −0.11 (range −0.24 to −0.04, SD = 0.09) OD and −0.12 (range −0.22 to −0.16, SD = 0.12) OS at 80 cd/m^2 on a logMAR scale using the CSV-1000ETDRS (Vector Vision, Greenville, OH, USA) visual test.

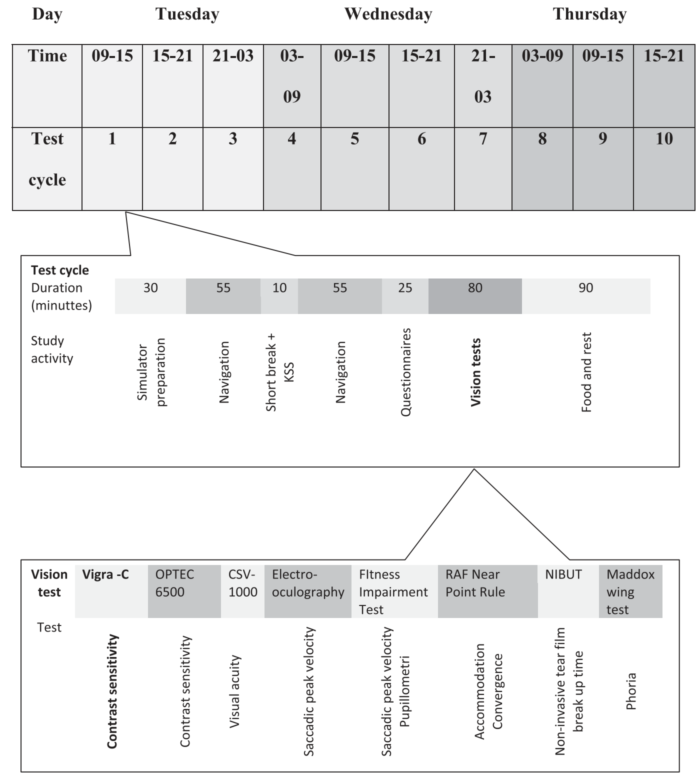
The test subjects were provided general background information, and written informed consent was obtained 6 months prior to the study. Two weeks before entering the study, the participants received prestudy instructions and a letter with detailed information about the study (Gould et al. 2009).

Five of the test subjects originally recruited in a group of eight participated in both study periods, while the remaining three subjects from the first period had to attend an upcoming naval mission and were replaced by three other officers in the second test period. In this paper, only the measurements obtained in the first test cycle of each of the 11 participants are included.

Contrast sensitivity measurements

Spatial CS was measured using horizontal sinusoidal gratings displayed on a calibrated (g-corrected) 30-bit videographic system (VIGRA-C) developed at the Norwegian University of Science and Technology (Gjerde 1997; Fosse & Valberg 2001). The VIGRA-C display was a 19-inch Mitsubishi high-resolution monitor (HL7955SFKL) with 100-Hz frame rate. To maintain stable light adaptation throughout the test, a white wall behind the monitor was illuminated by a halogen lamp. This enabled the participants to look at a neutral background between each threshold setting to avoid eye strain by continuously concentrating on the monitor screen.

CS was defined as $1/C$, where C is the Michelson constant of a luminance grating defined by $C = (L_{\max} - L_{\min})/(L_{\max} + L_{\min})$, $L_{\max}$ and $L_{\min}$ being the maximal and minimal luminance of the grating bars. The chromatic sensitivity measurement was according to a modulation of Michelson constant of the *L*-, *M*- and *S*-cones (Valberg 2005, p. 196). The CS measurements on the VIGRA-C system were made in a dimly illuminated room (<5 cd). The mean luminance of the monitor screen was 40 cd/m^2, and the sinusoidal gratings were displayed in an angle of 16°, at a distance of 1 m. The sinusoidal gratings were identified by the cycles per degree (cpd) of visual angle at 1 m.



Day	Tuesday				Wednesday			Thursday		
Time	09-15	15-21	21-03	03-09	09-15	15-21	21-03	03-09	09-15	15-21
Test cycle	1	2	3	4	5	6	7	8	9	10

Test cycle							
Duration (minuttes)	30	55	10	55	25	80	90
Study activity	Simulator preparation	Navigation	Short break + KSS	Navigation	Questionnaires	**Vision tests**	Food and rest

Vision test	**Vigra -C**	OPTEC 6500	CSV-1000	Electro-oculography	FItness Impairment Test	RAF Near Point Rule	NIBUT	Maddox wing test
Test	**Contrast sensitivity**	Contrast sensitivity	Visual acuity	Saccadic peak velocity	Saccadic peak velocity Pupillometri	Accommodation Convergence	Non-invasive tear film break up time	Phoria

Fig. 1. Day, time and sequence for visual examinations. Within each of the 10 test cycles we had 80 min to perform visual tests. Of a total of eight visual tests, only the contrast sensitivity test done by Vigra-C is reported in this study.

Table 1. Vigra-C contrast steps and contrast test range for each of the measured frequencies, both for achromatic and chromatic contrast sensitivity.

	Achromatic			Red–Green			Yellow–Blue		
Frequencies (cpd)	2.0	5.9	11.8	0.6	2.0	4.7	0.6	2.0	4.7
Vigra-C contrast step	0.05	0.06	0.20	0.08	0.15	0.25	0.10	0.30	0.90
Vigra-C test range	0.05–1.0	0.06–1.5	0.2–5.0	0.08–1.44	0.15–4.05	0.25–7.25	0.1–3.0	0.3–12.0	0.9–25.2

The frequencies of 2.0, 5.9 and 11.8 cpd were selected for testing the achromatic CS (Table 1), because human peak achromatic CS is found in this interval (Valberg 2005, p 187). To cover the expected peak chromatic CS (Valberg 2005, p. 195), the frequencies of 0.6, 2.0 and 4.7 cpd were chosen to test the red–green and blue–yellow contrast sensitivity. To facilitate the test procedure, Vigra-C was set up with 10 predefined contrast levels at a constant luminance, enabling a stepwise examination of CS. The highest steps were defined to be above the expected level of resolution of human CS for each frequency tested.

Recognition threshold was determined binocularly in all CS measurements by an ascending method of limits. Starting each test with an invisible grating, the examiner gradually increased the contrast in a stepwise fashion until the grating became visible, allowing the participant to report whether it was fine, medium or broad. A printout of a fine, a medium and a broad grating was fixed to the frame of the screen to help the test subjects to make the correct identification. Spatial frequency was changed in a pseudorandom sequence, presenting each grating three times at every time-point.

Statistical analysis

The possible changes of achromatic and chromatic CS during prolonged sleep deprivation were studied by comparing the mean values and mean variances obtained during the first and last 24-hr study periods (Fig. 2). Each of these periods included four cycle points and 12 data values. If one value was missing at each time-point, it was replaced by the mean of the two remaining values. More than one missing value at each time-point would have excluded the participant from this part of the study, but no such exclusions had to be made. In analysis, we used all the available data. The Wilcoxon signed-rank test was used, as a normal distribution of the results could not be assumed. The analyses were made at a group level. As multiple comparisons were made, the level of statistical significance was set at 0.01. Statistical analyses were performed using IBM SPSS Statistics version 22.0 (IBM corp., Amronk, NY, USA).

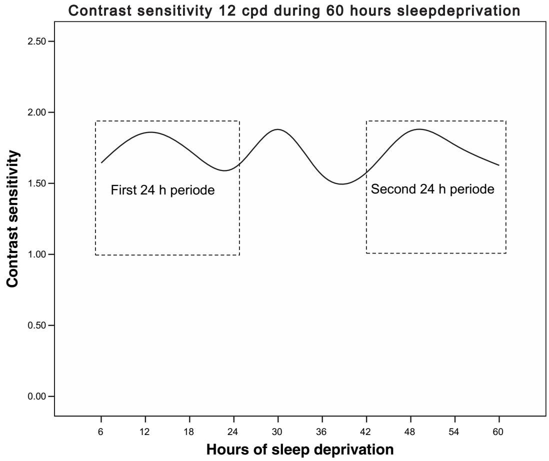


Fig. 2. Example of contrast sensitivity results and the variation at different time points for one test person. The two frames indicate the two time periods used for analyses.

Research ethics

The study adhered to the Declaration of Helsinki. The participants were informed about the objectives and conditions of the study. A physician was on call throughout the study, in case of adverse health reactions in any of the participants. The study protocol was approved by the Regional Committee for Medical Research Ethics, Western Norway and the Norwegian Social Science Data Services (REK 06/453). The participants received their regular salary from the Royal Norwegian Navy during participation in the study.

Results

A complete set of CS measurements was obtained from all 11 test subjects. Five participants used coffee during the study, their mean coffee consumption being 4.7 units (range 2–10, SD = 3.2) per day. None of the test subjects was smoking, but three used snuff.

No statistically significant changes of mean achromatic CS at the frequencies 2, 5.9 and 11.8 cpd were recorded during 60-hr sleep deprivation. However, when comparing the results obtained in the first and last 24-hr study periods, a significant increase in mean red–green CS at 2.0 cpd ($p = 0.003$) and 4.7 cpd ($p = 0.003$) was noted in the last period (Table 2).

At the chosen 1% level of statistical significance, the variance of achromatic and chromatic CS measurements did not differ significantly in the first and last 24-hr test periods. At a 5% significance level, achromatic 11.8 cpd variance increased ($p = 0.03$) while yellow–blue 2.0 cpd variance decreased ($p < 0.05$; Table 2).

Discussion

The present study showed no statistically significant changes of mean achromatic CS during 60 hrs of total sleep deprivation. This was not completely in line with the results reported by Quant (1992), who found a minor loss of CS

Table 2. Mean and variance of the first and last 24-hr periods for achromatic and chromatic contrast sensitivity. Significant differences tested by Wilcoxon test. The results indicate improved Red-Green contrast sensitivity in the two higher frequencies.

	First 24-hr period	Last 24-hr period	p-Value
2 cpd			
Mean	2.55	2.55	0.48
Variance	0.01	0.01	0.86
6 cpd			
Mean	2.44	2.41	0.21
Variance	0.01	0.02	0.21
12 cpd			
Mean	1.97	1.96	0.08
Variance	0.01	0.03	0.03*
0.5 cpd Yellow–Blue			
Mean	2.21	2.17	0.06
Variance	0.03	0.03	0.79
2 cpd Yellow–Blue			
Mean	1.80	1.78	0.33
Variance	0.02	0.01	>0.05*
5 cpd Yellow–Blue			
Mean	1.32	1.32	0.66
Variance	0.02	0.02	0.93
0.5 cpd Red–Green			
Mean	3.03	3.02	0.72
Variance	0.01	0.06	0.54
2 cpd Red–Green			
Mean	2.81	3.02	0.003**
Variance	0.01	0.01	0.69
5 cpd Red–Green			
Mean	2.57	2.82	0.003**
Variance	0.01	0.02	0.37

**Significant at 1 %, *significant at 5%.

at 6 cpd on a near-vision test following 36 hr of sleep deprivation. She concluded that the visual system appeared to be remarkably resilient to the effects of sleep deprivation, but also stressed the importance of the 6 cpd frequency and the implications such a reduction might have. Her paper had certain important limitations, including a small study group and no detailed description of the statistical methods used. She also stressed the weaknesses of her test method (Vistech 6000 near chart; Vistech Consultants, Inc., Dayton, OH, USA), recommending further studies to employ more sophisticated tools.

In our study, the location in the simulator at the RNoN Academy secured stable environments regarding light, noise and temperature exposure. The Vigra-C system has been well described by Gjerde (1997), yielding reliable results regarding both test and retest and compared to other test systems. It is not commercially available and needs more technical expertise to run than the commonly available tests.

Previous papers have expressed different opinions on the scientific value of the commonly used sine-wave patch charts for CS measurements. A study by Pomerance & Evans (1994) indicated good repeatability both at retesting and between tests. This was questioned by Pesudovs et al. (2004), who found poor test–retest repeatability, presumably caused by large steps between each CS level on the charts. They also found the tests to suffer from insufficient range of contrast levels, resulting in ceiling and flooring effects, that is, participants frequently having CS above or below the test range. In our study, we used the Vigra-C, which is a dynamic system enabling us to measure a broader range of contrast levels with finer steps between each level, as well as to record chromatic CS.

Following one night's sleep deprivation, an earlier case study including one colour-normal and one protanope participant showed a reduced performance of the colour-normal when identifying colours on a video display terminal, and poor performance of the protanope during the CN lantern test (Hovis & Ramaswamy 2007). These findings were not supported by the present recordings of chromatic CS, where mean red–green CS at 2.0 and 4.7 cpd showed a slight but statistically significant increase during the last 24-hr test period. Despite favourable test conditions, our study could not readily explain this recorded increased mean red–green CS during sleep deprivation. However, it may probably be attributed to our limited number of test subjects, which was the main weakness of our study. A new study including more participants and increased number of test time-points and repetitions might possibly clarify whether or not this apparent effect is truly present.

At a statistical significance level of 1%, no significantly increased mean variances of CS recordings were found after prolonged sleep deprivation. However, the achromatic 11.8 cpd variance was apparently slightly increased ($p = 0.03$), while the mean yellow–blue 2.0 cpd variance appeared to be slightly decreased ($p < 0.05$). Also, these discrepancies may well be due to our limited number of test subjects. On the other hand, there may also be other explanations for possible changes in CS variance, including factors other than changes strictly caused by altered CS. Our study was designed to minimize the effects of circadian rhythms, but prolonged sleep deprivation may conceivably influence the circadian system as well as mental and visual functions on different levels. The circadian system is complex and only partly understood (Roenneberg & Merrow 2005). Circadian rhythm disruption may act on a central level (Rea et al. 2010) and possibly also on a retinal level involving melatonin and dopamine (Tosini et al. 2008), retinal rod shedding (Teirstein et al. 1980) and gene expression (Li et al. 2005). Diurnal visual changes occur with maximal visual resolution and detection before midday and a minimum after midnight (Tassi et al. 2000a,b). In a study on mice, Balkema et al. (2001) found a maximal sensitivity 2 hr after light onset and a minimal sensitivity 4 hr later, also corresponding to the length of the synaptic ribbons. Jackson et al. (2008) measured human visually evoked potentials following 27-hr sleep deprivation. Their main findings were no effects on early visual processing, but distinct effects on higher-order cognitive processing, evidenced by slower reaction time and increased number of omission errors in the sleep-deprived group. Such effects may possibly influence the degree of variance recorded during CS tests. A paper by Roge & Gabaude (2009) on visual field performance after sleep deprivation has indicated that the participants' decision criteria when responding to a signal detection task may be altered. Gould et al. (2009) described a reduced visual task performance of the participants in the present study and suggested that this could be explained by reduced cognitive resources. The slight changes of CS values and CS variance indicated in some of our tests may possibly also reflect changes in higher cognitive functions and/or use of altered decision criteria occurring after prolonged sleep deprivation.

Conclusion

Up to 60-hr sleep deprivation did apparently induced slight, but statistically significant increases in mean CS for red–green CS at 2.0 cpd ($p = 0.003$)

and 4.7 cpd (p = 0.003), while no mean changes in achromatic CS or yellow–blue CS were found when comparing the first and last 24-hr test periods. Distinct and readily explained changes of CS variance during prolonged sleep deprivation were not recorded. Based on our limited number of test subjects, prolonged sleep deprivation does apparently not cause clinically or occupationally significant changes of contrast sensitivity in otherwise healthy subjects with normal visual acuity.

References

Balkema GW, Cusick K & Nguyen TH (2001): Diurnal variation in synaptic ribbon length and visual threshold. Vis Neurosci **18**: 789–797.

De Gennaro L, Ferrara M, Urbani L & Bertini M (2000): Oculomotor impairment after 1 night of total sleep deprivation: a dissociation between measures of speed and accuracy. Clin Neurophysiol **111**: 1771–1778.

De Gennaro L, Ferrara M, Curcio G & Bertini M (2001): Visual search performance across 40 h of continuous wakefulness: measures of speed and accuracy and relation with oculomotor performance. Physiol Behav **74**: 197–204.

Ehrlich DL (1987): Near vision stress – vergence adaption and accommodative fatigue. Ophthalmic Physiol Opt **7**: 353–357.

Fosse P & Valberg A (2001): Contrast sensitivity and reading in subjects with age-related macular degeneration. Vis Impair Res **3**: 111–124.

Gjerde T (1997): Evaluering av et videografisk (VIGRA) system for synstesting NTNU. Thesis. Trondheim, Norway: Norwegian University of Science and Technology (NTNU).

Gould KS, Hirvonen K, Koefoed VF, Roed BK, Sallinen M, Holm A, Bridger RS & Moen BE (2009): Effects of 60 hours of total sleep deprivation on two methods of high-speed ship navigation. Ergonomics **52**: 1469–1486.

Hovis JK & Ramaswamy S (2007): Color vision and fatigue: an incidental finding. Aviat Space Environ Med **78**: 1068–1071.

Jackson ML, Croft RJ, Owens K, Pierce RJ, Kennedy GA, Crewther D & Howard ME (2008): The effect of acute sleep deprivation on visual evoked potentials in professional drivers. Sleep **31**: 1261–1269.

Li P, Temple S, Gao Y, Haimberger TJ, Hawryshyn CW & Li L (2005): Circadian rhythms of behavioral cone sensitivity and long wavelength opsin mRNA expression: a correlation study in zebrafish. J Exp Biol **208**: 497–504.

Miller RJ, Pigion R, Wesner MF & Patterson JG (1983): Accommodation fatigue and dark focus: the effects of accommodation-free visual work as assessed by two psychophysical methods. Percept Psychophys **34**: 532–540.

Moen BE, Koefoed VF, Bondevik K & Haukenes I (2008): A survey of occupational health in the Royal Norvegian Navy. Int Marit Health **59**: 35–44.

Owens DA & Wolf-Kelly K (1987): Near work, visual fatigue, and variations of oculomotor tonus. Invest Ophthalmol Vis Sci **28**: 743–749.

Paul A (1965): Effects of sleep deprivation on visual function. Aerosp Med **36**: 617–620.

Pesudovs K, Hazel CA, Doran RM & Elliott DB (2004): The usefulness of Vistech and FACT contrast sensitivity charts for cataract and refractive surgery outcomes research. Br J Ophthalmol **88**: 11–16.

Pigion RG & Miller RJ (1985): Fatigue of accommodation: changes in accommodation after visual work. Am J Optom Physiol Opt **62**: 853–863.

Pomerance GN & Evans DW (1994): Test–retest reliability of the CSV-1000 contrast test and its relationship to glaucoma therapy. Invest Ophthalmol Vis Sci **35**: 3357–3361.

Quant JR (1992): The effect of sleep deprivation and sustained military operations on near visual performance. Aviat Space Environ Med **63**: 172–176.

Rea MS, Figueiro MG, Bierman A & Bullough JD (2010): Circadian light. J Circadian Rhythms **8**: 2.

Roenneberg T & Merrow M (2005): Circadian clocks – the fall and rise of physiology. Nat Rev Mol Cell Biol **6**: 965–971.

Roge J & Gabaude C (2009): Deterioration of the useful visual field with age and sleep deprivation: insight from signal detection theory. Percept Mot Skills **109**: 270–284.

Roge J, Pebayle T, el Hannachi S & Muzet A (2003): Effect of sleep deprivation and driving duration on the useful visual field in younger and older subjects during simulator driving. Vision Res **43**: 1465–1472.

Tassi P, Pellerin N, Moessinger M, Eschenlauer R & Muzet A (2000a): Variation of visual detection over the 24-hour period in humans. Chronobiol Int **17**: 795–805.

Tassi P, Pellerin N, Moessinger M, Hoeft A & Muzet A (2000b): Visual resolution in humans fluctuates over the 24 h period. Chronobiol Int **17**: 187–195.

Teirstein PS, Goldman A & O'Brien PJ (1980): Evidence for both local and central regulation of rat rod outer segment disc shedding. Invest Ophthalmol Vis Sci **19**: 1268–1273.

Tosini G, Pozdeyev N, Sakamoto K & Iuvone PM (2008): The circadian clock system in the mammalian retina. BioEssays **30**: 624–633.

Valberg A (2005): Light vision color. ISBN 0 470 84902 9 (Hardback). England: John Wiley & Sons, Ltd 187–196.

Received on November 11th, 2013.
Accepted on July 10th, 2014.

Correspondence:
Vilhelm F. Koefoed
Department of Clinical Medicine
Faculty of Medicine and Dentistry
University of Bergen
PO Box 7804
NO-5020 Bergen
Norway
Tel: +4755504891
Fax: +4755504890
Email: v@koefoed.no

The authors wish to thank the FPB navigators from the 22nd and Skjold FPB squadrons who participated in this study. Inger Rudvin played a vital role in this study by helping to set up the Vigra-C and conduct the majority of measurements. Institute of Aviation Medicine, Norwegian Armed Forces, assisted in pretest ophthalmological examination. This work was partly funded by the Royal Norwegian Navy through the research programme in the Royal Norwegian Navy at the University of Bergen and Norwegian Centre of Maritime Medicine (Moen et al. 2008).

NORDIC ECOLABEL
241 PRINTED MATTER 731

Graphic design: Communication Division, UIB / Print: Skipnes Kommunikasjon AS

uib.no

ISBN: 978-82-308-3682-8