HCL:Baseline

Research Report

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Summary

By shifting the workplace from the conventional tower to a remote center the lack of daylight due to no outside windows might impact performance, safety and operator health negatively. Increased daytime sleepiness and reduced alertness could be a result of inadequate lighting (Cajochen, 2007, Najjar et al., 2014). As a possible measure an adequate lighting intervention designed after the Human Centric Lighting (HCL) guidelines could deliver proper daylight and act therefore as an effective countermeasure ensuring safety.

The purpose of the *HCL:Baseline* project was to quantify existing fatigue at remote and conventional tower, in regard to lighting conditions given. However, due to pandemic circumstances, the schedule and aim was revised. Within the research project did we conduct a study triplet. While study 1 aimed on a theoretical development of an HCL concept for remote, study 2 assessed actual lighting conditions in remote and conventional workplaces. In study 3 did we measure controllers in the field for fatigue among various shifts.

The results of the studies are integrated finally. It has been found that lighting conditions at the remote workplace are rather dark and unfavourable, as fatigue can be provoked. Moreover, the screen emitted much blue light which is potentially problematic for the circadian rhythm of the air traffic controllers. The HCL developed in study 1 could be beneficial for reducing current workplace flaws linked to fatigue. This seems to relevant in the light of the results gathered in study 3. The generic benefits of the HCL concept should be considered for future installations and other similar workplaces.

Sammanfattning

Genom att flytta arbetsplatsen från det konventionella tornet till en lokal med begränsat ljusinsläpp finns en möjlighet att bristen på dagsljus påverka prestanda, säkerhet och operatörens hälsa negativt. Ökad sömnighet på dagtid och minskad vakenhet är möjlig påverkan p.g.a. otillräcklig belysning (Cajochen, 2007, Najjar et al., 2014).

Det är möjligt att utforma ett belysningssystem efter riktlinjerna för Human Centric Lighting (HCL) som skulle kunna ge korrekt dagsljus vilket skulle motverka sömnighet och verka positivt för uppmärksamhet (alertness) och därmed inte påverka mänsklig prestanda och säkerhet negativt.

Syftet med *HCL:Baseline-projektet* var att kvantifiera befintlig trötthet vid ”remote TWR” tjänst och konventionella torn, med tanke på ljusförhållandena. På grund av pandemiska omständigheter justerades schemat och målet. Inom forskningsprojektet genomförde vi tre studier. Studie 1 syftade till en teoretisk utveckling av ett HCL-koncept för ”remote TWR”. Studie 2 angrep faktiska ljusförhållanden för ”remote TWR” och konventionella tornarbetsplatser. I studie 3 mätte vi operativa flygledare i fält för utmattning i olika skift.

Resultaten av de tre studierna integreras och vi finner att ljusförhållandena för ”remote TWR” arbetsplatsen är ganska mörka och ogynnsamma och en miljö där trötthet kan utvecklas. Dessutom avger skärmar mycket blått ljus vilket är potentiellt problematiskt för flygledarnas dygnsrytm. HCL konceptet som utvecklats i studie 1 kan vara till nytta för att motverka brister i existerande belysning som inte är optimal m.a.p. människans dygnsrytm och kognitiva förmågor. Resultaten i studie 3 stöder slutsatsen att en implementering av HCL konceptet skulle bidra till en förbättring av arbetsmiljön. Vidare bör HCL konceptet beaktas vid nyinstallationer och bedöms som relevant för arbetspositioner ämnade för övervakning och kontroll av processer ex. inom andra transportslag.

TABLE OF CONTENTS

REVISION HISTORY ... 2
1 INTRODUCTION ... 6
1.1 Motivation ... 6
1.2 Document Structure ... 7
2 EMPIRICAL BACKGROUND ... 8
2.1 Physics of Light ... 8
2.2 Biological Mechanism of Light ... 9
2.3 Relevant Factors of Light ... 10
2.3.1 Light Colour ... 10
2.3.2 Light Illuminance ... 11
2.3.3 Light Timing and Exposure Duration ... 12
2.3.4 Light Temporal Dynamics ... 12
2.3.5 Light Sources and Room Design ... 13
2.4 Integration and Conclusion ... 13
3 RESEARCH QUESTIONS AND AIM ... 15
4 STUDY 1 – LITERATURE-BASED HCL CONCEPT DEVELOPMENT ... 16
4.1 Towards a HCL Concept ... 16
4.2 Development of a HCL Concept ... 17
4.3 Prototypical HCL Concept ... 18
4.4 Benefit Analysis HCL Concept ... 21
5 STUDY 2 – LIGHTING COMPARISON ... 23
5.1 Method and Setup ... 23
5.2 Results ... 24
5.2.1 Conventional Tower Workplaces ... 24
5.2.2 Remote Tower Workplace ... 25
5.2.3 Merged Lighting Data of Remote and Conventional Workplace ... 26
5.2.4 Lighting Possibilities in Remote Tower ... 27
5.3 Discussion ... 28
6 STUDY 3 – AIR TRAFFIC CONTROLLER FIELD MEASUREMENTS ... 31
6.1 Method and Study Setup ... 31
6.1.1 Active Methods ... 31
6.1.2 Passive Methods ... 33
6.1.3 Study Procedure ... 34
6.1.4 Measurement Locations ... 34
6.1.5 Sample Characteristics ... 35
6.1.6 Statistical Analysis ... 36
6.2 Results ... 36
6.2.1 Sleep Behavioural Data ... 36
6.2.2 PANAS ... 36
6.2.3 H&ES Questionnaire ... 38
6.2.4 MSQ ... 40
6.2.5 ISA Workload ... 41
6.2.6 PVT ... 42
6.2.7 KSS ... 47
6.2.8 Lighting Sensor Wrist Band ... 49
6.3 Discussion ... 53

7 INTEGRATION AND OUTLOOK 55
REFERENCES 57
APPENDIX 62

1 INTRODUCTION

The *Human Centric Lighting (HCL) Baseline* project has the objective to quantify cognitive effects of lighting characteristics on the air traffic controllers in remote tower conditions. Human performance and safety respectively can be influenced by adaptive lighting conditions in several situations. To identify *"the right light at the right time and the right situation"* the *HCL:Baseline* project aimed to delivering data for answering that question. However, due to the unexpected pandemic situation in 2020, emerging during ongoing data collection, measurement schedule and research question were required to be adapted.

The project focused nevertheless on lighting at the conventional and the remote tower workplace. This is from a high relevance since the remote tower concept features distinct novel factors. These make it impossible to simple take existing lighting knowledge, but rather requires context-related studies for developing lighting concepts. This research gap shall be closed by means of the both projects *HCL:Baseline* and upcoming *HCL:Aurora*.

By shifting the workplace from the conventional rower to a remote tower center (RTC) the lack of daylight due to no outside windows might impact performance negatively, which was stated anecdotally by air traffic controllers already. Increased daytime sleepiness and reduced alertness could be a result of inadequate lighting, already shown in other domains (Cajochen, 2007; Najjar et al., 2014). An adequate lighting intervention designed following HCL guidelines could deliver improved access to daylight and act therefore as an effective countermeasure, to ensure performance, health and safety. Furthermore, the independent outside-lighting intervention at the remote tower workplace enables the opportunity to develop lighting systems which are ideal designed for human factors purposes. However, before any further HCL intervention is developed and designed, the effect of fatigue in conventional tower conditions needs to be quantified first. This is the aim of this project: The determination of a fatigue baseline, and quantification of lighting characteristics in several the conventional tower as well as remote tower workplaces.

1.1 Motivation

Within the last decades, awareness on lighting and its influence on the human body processes as well as work performance was shaped further. Empirical evidence was released indicating not only well-being, emotional and health effects, but also influences towards cognitive processes and work performance due to specific lighting conditions.

In our 24/7 society a constant demand of air traffic controllers is present. Operators are put into a situation, where shift work as well as night work is daily business. Shift and night work deteriorate alertness and performance and leads to stress to operators and the socio-technical system, since safety can be harmed. Moreover, by developing new workplaces basic cognitive functions should be considered from the beginning to prevent fatigue even under day shifts. These aspects require a counterweight and intelligent solutions which reduce fatigue and support alertness of operators to maintain aviation safety.

High-level regulations anticipated these challenges and require an adapted fatigue management. In air traffic control, the regulation EU 373/2017 brings up the need for focus on fatigue among operators in air traffic control. The regulations require measures to identify and manage the effect of fatigue on safety of operations. By this, awareness of negative effects due to fatigue is created and data to develop further is collected. Further, the EASA rulemaking group recently conducted a survey with the aim to gather feedback and information about ongoing and planned remote aerodrome air traffic services implementations/operations within Europe. A feedback that was provided by one of the European Civil Aviation Authorities concerning a specific remote aerodrome air traffic service implementation suggested that improvements should be considered with regard to lighting (*too dark*) and rostering (*only one air traffic controller in the room at night*), to reduce the risk of fatigue. This demonstrates that the interplay of lighting and fatigue receives more and more attention as a potent performance factor and fatigue countermeasure.

1.2 Document Structure

The following chapter 2 will describe further the empirical background of lighting and the HCL concept, especially in the frame of aviation and remote tower. Thereafter, chapter 3 aims on research questions and the study triplet. As noted above, the pandemic situation altered execution and plan of the study, hence, a separate section onto its impact is delivered as well. Consequently, the following chapter 4, 5 and 6 deliver an overview on all three studies that were conducted. Results are discussed separately, but all results are finally in chapter 7 integrated and embedded into empirical evidence. Further research questions and an outlook is given.

2 EMPIRICAL BACKGROUND

By shifting the workplace from the conventional rower to a RTC the lack of daylight could lead to safety-critical operator challenges. Most prominent and obvious, daytime sleepiness but circadian disruption could be a result of inadequate lighting (Cajochen, 2007). Moreover, reduced alertness and increased fatigue could be an outcome as well. Studies on that topic are available that show a connection between inadequate lighting and fatigue (Caldwell et al., 2012). Own previous research projects on the topic, showed a negative effect of low light conditions on the flight deck on human alertness and performance. After installing a proper lighting intervention, alertness and performance increased again (Peukert & Wiggerich, 2016). However, so far there is still a lack of empirical evidence for effects of lighting in air traffic control and RTC workplaces. That is one argument to carry out this baseline study and shape knowledge for further development.

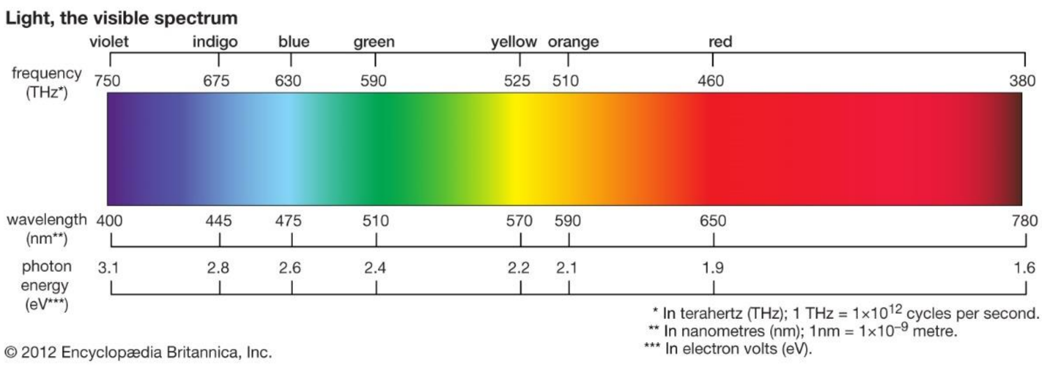
Several discussions with air traffic controllers at the RTC Sundsvall confirmed this assumption on a subjective basis as well. Hence, we are aiming for establishing a baseline, comparison study between the conventional rower and the remote tower workplace. To quantify the subjective feelings of air traffic controllers, the results shall act as the framework for the next step: A HCL intervention, to battle negative effects due to inadequate lighting and lack of daylight during work.

2.1 Physics of Light

Lux and lumen are the most basic units of measurement in lighting technology. Thereby Lux indicates the illuminance, i.e. the luminous flux that strikes onto a surface. This luminous flux is measured in the unit lumen. It expresses how large the luminous flux in all directions radiated power of the light source in the visible range is. A distinction is also made between horizontal and vertical illuminance.

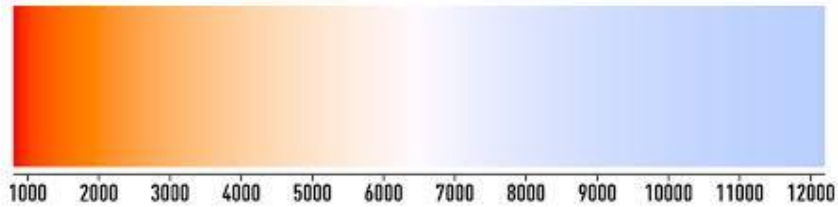
How brightly an illuminated object appears to the human eye is determined by the luminance described. It is expressed in candelas per unit area (cd/m^2). Besides illuminance and luminance, light colour is another relevant size of the lighting technology. Light created from a light source has its own colour, which is caused by the wavelength (*nm*) of the light spectrum (figure 1).

Figure 1. Visible spectrum of light with corresponding wavelength.



The colour temperature of a light source to be assigned to the light colour can be determined by means of a "Planck's radiator". This mediates between light colour and temperature in Kelvin (*K*). The higher the temperature, the cooler and whiter the light colour (figure 2).

Figure 2. Light colour with corresponding temperature in K.



Independent of the light colour, the characteristic is light reproduction of a light source. The light rendering describes the spectral reflectance of a light source on colour objects. This is expressed how colours appear due to the light source and how this is perceived by the human. To describe the colour rendering of a light source, the colour rendering index *Ra* is used. A value of 100 is considered as optimal. For the lighting of interiors, the Ra should not fall below the value 80, to ensure natural colour perception.

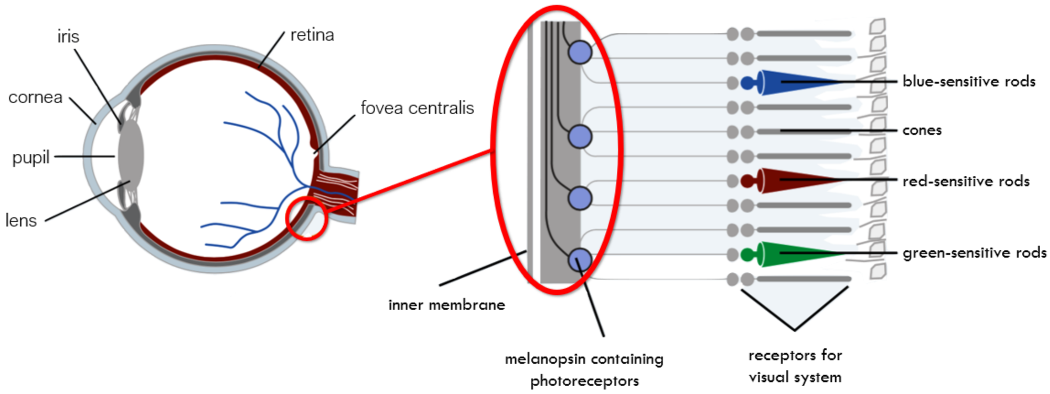
To facilitate the recognition of objects in their three-dimensionality and with structures and to make surfaces possible, the interplay of light and shadow is indispensable. In lighting technology this is called modelling. The formation of shadows depends on the direction of the light sources and their beam angle and placement in the room. Modelling has a great influence on the effect of a room: A room tends to look more like a monotonous and expressive, when illuminated by diffuse light and hardly any shadows exist, which could give contour to the room and its furnishings. Another fundamental aspect of lighting technology are glare properties. Light can act through direct glare, caused, for example, by too high luminance or unfavourably installed lights, or reflected glare disturb. Reflected glare can occur when light is reflected on shiny surfaces.

All these aspects need to be considered by designing lighting for RTC.

2.2 Biological Mechanism of Light

As the previously indicated, the primary need for light is to ensure visual perception of objects through the human eye. For that task, the human retina in the eye consists ganglion cells as well as the photoreceptors rods and cones that mediate by means of biochemical and physical processes light photons to a cognitive representation of the outside (figure 3). The picture we see is processes through various brain areas until a full mental picture is created.

Figure 3. Biological background of retina in the human eye.



In addition to the ganglion cells, which primarily serve to process information from rods and cones, there is a third type of ganglion cells that are themselves light-sensitive and have a direct influence on the circadian system (Berson et al., 2002). These cells – called intrinsically photosensitive retinal ganglion cells (*ipRGC*) - are, next to the visual effects of light, from a great interest for non-visual and psychological effects of light on the human.

The ipRGCs react with maximum sensitivity to short-wave light in the blue spectral range between 460 and 490 nm and have their own photo pigment, melanopsin (Hattar et al., 2002). Only about 1-3% of ganglion cells belong to this special cell type (Berson, 2003). Their main concentration is in the lower and nasal part of the retina (Rüger et al., 2005). The axons move from the cell bodies of the ipRGC via the retinohypothalamic tract directly into the nucleus suprachiasmaticus (*SCN*). The SCN is a nucleus in the anterior part of the hypothalamus, immediately above the optic nerve junction and laterally to the anterior tip of the III ventricle. It is considered to be the most important timer for the human circadian rhythm (Roenneberg et al., 2003). Starting from the SCN, the information is transmitted without switching from the contralateral peripheral retina via the paraventricular nuclei and the cervical superiors ganglion to the pineal gland (epiphysis), which regulates the release of human sleeping hormone melatonin (Lockley et al., 2007).

2.3 Relevant Factors of Light

The *right light at the right time in the right situation* can lead to psychophysiological activation, fatigue reduction and an improvement in alertness (Cajochen, 2007; Najjar et al., 2014). The desired biological and cognitive lighting effects depend highly on factors, such as the light spectrum and its intensity, but also on timing and exposure duration of the human. The following sections give an overview about evidence available.

2.3.1 Light Colour

In line with the biological findings presented in the section before, Smolders and de Kort (2014) for example, summarise reports that show that light colour affects subjective measures such as the feeling of alertness, the experienced need for rest or a break, and the self-report on one's own performance.

Borragán et al. (2017) describe that *blue-enriched light* seems to be most effective for increasing alertness and cognitive functions in the wavelength range 420 to 520 nm. In a field study, researchers compared how alertness, mood, performance, evening tiredness, concentration and eye complaints, among other things, differ between employees who worked for four weeks under light with a colour temperature of either 4000 K (white light) or 17000 K (Viola et al., 2008). They found that the 17000 K condition resulted in a significant improvement in all the variables just mentioned. It can be concluded that blue-enriched light has a positive effect on mood, fatigue, concentration and alertness. Furthermore, the authors registered that blue-enriched light does not have a subjectively noticeable disadvantage in terms of eye strain. Instead, the subjects reported even reduced eye strain and less discomfort such as tired eyes and blurred vision. The study also noted that the participants night sleep improved. The authors explain that increased activation during the day with the help of the blue-enriched light could have led to the circadian rhythms of the subjects now having stronger amplitudes in the long term. This led to increased melatonin secretion at night, which in turn is responsible for better sleep. The result could also be exclusively due to increased activity during the day (Viola et al., 2008). The results lead to the conclusion that blue-enriched light has an activating effect on humans and can be used for the purpose of increasing alertness and activation.

Light can inhibit human melatonin secretion. If this is to be prevented, e.g. to maintain a melatonin balance that is as natural as possible during the night shift, this can be achieved by using light with a reduced blue component. In one study, it was found that a reduction in colour temperature can lead to a less disturbed melatonin secretion without impairing the cognitive performance or mood of the persons studied. For example, a colour temperature of 1700 K showed significantly less disturbed melatonin secretion compared to a colour temperature of 6300 K (Hoffmann et al., 2008).

It can be concluded that blue-enriched light of high colour temperature or light of short wavelength in the range between 420 and 520 nm can be used to specifically prevent or delay the natural melatonin secretion and thus counteract a tendency to sleep. The opposite effect can be achieved by using light of longer wavelengths and lower colour temperatures. In other words, in order not to disturb the human circadian rhythm, e.g. during a night shift, melatonin production can take place almost undisturbed by using light with a reduced blue component. A shift in the circadian rhythm is prevented. Melatonin as a sleep mediator can help maintain or restore the circadian rhythm (Cajochen, 2007). Besides light colour, illuminance also plays a role in regulating melatonin secretion.

The fact that exposure to very bright light in the evening has a suppressive effect on the pineal gland hormone melatonin is shown, for example, by a study by Gooley et al. (2011). The researchers observed a delay of up to 90 minutes in the release of melatonin in 99 percent of the subjects exposed to BL before bedtime. The authors conclude that evening exposure to bright light shortens the body's own representation of the night duration. It can be concluded that evening light exposure has a negative effect on night sleep by inhibiting the release of the sleep-promoting hormone melatonin. If this melatonin suppression takes place over a long, sustained period of time, it can have a serious impact on health. Disturbed melatonin production, e.g. through inhibition by light, can lead to sleep disorders, weaken the immune system and in turn promote tumour growth (Blask, 2009). To protect and promote health in the long term, an undisturbed melatonin balance should therefore be ensured.

2.3.2 Light Illuminance

The activating properties of light can help people to work attentively and with concentration. Bright light with a high illuminance (BL) can be used to solve cognitive serving tasks compared with dimmed light (DL) can be more effective than that of dimmed light (Campbell & Dawson, 1990; Daurat et al., 1993). Several studies have shown the effects of increased performance and better ability to maintain vigilance for longer periods.

Studies show that cold light with high illuminance levels can increase alertness and have an activating effect (Cajochen, 2007). For complex tasks, however, which require problem-solving skills, performance can be reduced by cold and bright lighting (Borragán et al., 2017). Light has a fatigue-suppressing effect that can be useful for long working hours both during the day and at night to keep human performance at a consistently high level. Bright light can counteract the feeling of fatigue during the day (Smolders & de Kort, 2014). This effect is moderated by the condition of the individual. For example, people could benefit more from the effect of bright light when they are tired than people who consider their current alertness and vitality to be very high.

The design of dynamic lighting is largely based on natural daylight because natural daylight has a strong activating effect. This is due to the combination of illuminance and light colour. While both illuminance and the most similar colour temperature are enormously high outdoors, interior lighting can only achieve a similar biological effect to natural daylight by using very high similar colour temperatures. This means that light with a high blue component needs to be used to compensate for illuminance levels, which tend to be lower indoors than outdoors.

2.3.3 Light Timing and Exposure Duration

Both the time and duration of exposure to light are crucial for achieving a biological effect of light. Effects of light can be enhanced by applying at the right time. On the other hand, risks are also associated with the use of light at an inappropriate time.

It has been reported that exposure to light at night affects human physiology by altering heart rate and core body temperature, an indicator for the circadian rhythm (Borragán et al., 2017). Effects have been shown that light modulates brain functions by both night and daytime exposure. The time of exposure to light does not only change the state of activation of an individual in the short term. Rather, light is able to influence the circadian rhythm of a person, with the expression of this shift being moderated by the time of exposure. Humans react highly sensitively to phase shift effects of light in the first hours of the biological night, and even small changes in daily light exposure in the late evening hours can have a significant impact on the concentration of melatonin in the blood and the setting of the circadian pacemaker (Zeitzer et al., 2000). Light in the evening thus reduces the propensity and quality of sleep.

In the setting of a simulated night shift, researchers observed that light exposure to BL of 1500 lx in the early morning or in the last hours of the night induces more significant positive effects on performance and alertness than exposure in the first hours of the night (Foret et al., 1998). It can be concluded that BL can be used especially during the early morning hours to activate individuals and increase their performance at work. The degree to which light can have an activating effect also depends on the lighting to which a person was previously exposed. If an individual was in a darker environment for a prolonged period of time before being exposed to supposedly biologically effective light and was adapted to this state, the person reacts much more sensitively to light (DIN SPEC 67600:2013-04). The same biological effect may require different illuminance levels or colour spectra. This so-called aspect of lighting history should be considered when developing a lighting concept as well.

2.3.4 Light Temporal Dynamics

According to DIN SPEC 67600, the pace of lighting changes should not cause lighting changes to be too rapid. Changes every second give rise to visual perception problems and flicker effects. To avoid this, lighting changes should occur every few minutes or even hours. How the dynamics of a lighting solution with biologically effective light should be designed depends crucially on the context. Generally, it should be aimed to support the circadian rhythm by biologically effective lighting. However, there are cases where a deviation from this may be necessary or more appropriate, for example in shift work (DIN SPEC 67600:2013-04). Even though shift work is critically assessed by the World Health Organisation (WHO) because of its rhythm which deviates from nature (Straif et al., n.d.), it cannot be avoided in aviation. In shift work, the question arises of how biologically effective lighting can be used most effectively. According to DIN SPEC 67600, there are two ways of using biologically effective lighting in shift work. The first is to shift the circadian phases. The other option is to stabilise the circadian phases with focused activation in critical situations.

2.3.5 Light Sources and Room Design

Apart from illuminance, light colour and temporal dynamics, physical lighting location and design should be well selected to achieve the desired biological effect. DIN SPEC 67600 points out that the biological effect of light is greater where light falls on the field of vision over a large area, i.e. from light sources with a larger solid angle. Solid angles smaller than 0.1 sr are negligible; between 0.1 sr and 0.5 sr, the biological effect increases with increasing solid angle. It is recommended to use solid angles greater than 0.5 sr, which for the observer are caused by large bright surfaces. Windows or backlit transparent surfaces, for example, can be used for this purpose (DIN SPEC 67600:2013-04). It is also emphasised that the direction of light has a significant influence on the lighting effect. It is recommended that "two-dimensional lighting of bright areas in the upper part of the visual field (upper part of walls and ceilings) should be aimed for" (DIN SPEC 67600:2013-04). In addition, avoidance of glare is important for such design measures. Further is it recommended that biologically effective lighting should also be designed to ensure that light falls as naturally as possible, i.e. from above and from the front of the room. In this case, illuminance levels of between 500 and 1200 lx are sufficient to produce a melanopic lighting effect.

It should also be noted that biological lighting effects are generated by each individual light source. So, it is not only room lighting that matters. Instead, the biological effects emanating from self-luminous objects such as control displays, screens etc. need to be considered as well (DIN SPEC 67600:2013-04). The same applies to the design of the room furnishings. Depending on how objects are arranged in the room, this results in different lighting requirements. For the purposes of this project, it is assumed that the remote tower workstation is a workstation at a desk with several monitors. Besides control displays, large panoramic screens are a special feature. These provide controllers with visual information about traffic at the airport. Live images of the airport are transmitted on these screens to simulate the tower view. Where workplaces are arranged differently, this needs to be integrated into the lighting concept.

2.4 Integration and Conclusion

Lighting effects can be used to create both visual and non-visual, biological, and emotional effects. It is therefore possible to consider immediate, but also long-term changes only by means of a lighting design. A lighting concept can therefore be responsible for making employees feel more comfortable at their workplace, increasing their motivation to work performance.

As described above, light colour, light illuminance, light timing, light exposure duration, light temporal dynamics and light sources as well as room design influence the extend of how lighting effects on the operator. The whole entirety of these factors as well as the effects of lighting on the human are merged into the HCL concept. HCL describes a holistic lighting concept, that includes a dynamic change of light colour and intensity based on time of day and person individual factors. By simulating the natural sun as good as possible, many positive effects linked to daylight sun can be gained (Bodrogi et al., 2017).

Further, by dynamic changes of lighting intensity and colour, based on operators chronotype, shifttype and time of day, positive effects on health, performance and safety could be established. Applying HCL seems to be a promising measure against reduced alertness and increased fatigue at the remote rower workplace. Since HCL and lighting play a vital role our circadian rhythm, it is therefore important for well-being and long-term health of the operators (Cronström, 2018).

However, as mentioned before, a baseline study to investigate the status and problem extent is lacking so far. A next step shall then include the development of a holistic HCL concept in remote tower operations. Another use case for HCL in RTC could emerge due to a latitude discrepancy of actual RTC location and remotely controlled airfield location. With a shift in latitude, the daylight hours are also changing, depending on the time of year. With polar night in the winter and the midnight sun in the summertime, the northern airports that will be remotely controlled (Kiruna, Umeå) are relevant. These airports will be controlled from the RTC in Stockholm. For instance, the winter season in Stockholm means 6:15 hours of daylight, while in Kiruna only 35 minutes occur (2nd of January 2019). This discrepancy could lead to an artificial induced night shift for the air traffic controller that works during a regular day shift at the RTC. As a result, a social jetlag (circadian disruption) with sleep disturbances, increased fatigue and performance decrement could occur. A HCL concept, adapted to the latitude of the RTC location and time of year, could act as countermeasure against potential negative effects and enrich the workplace for the operator on the long run as well.

3 RESEARCH QUESTIONS AND AIM

Initially measurements were planned at four conventional airports in Sweden, two conventional airports in Estonia and at four remote tower workplaces at the RTC Sundsvall. However, due to the unforeseen outbreak of Covid-19, it was not able to keep the planned schedule. As a result, measurements in Umeå, Halmstad and Malmö as well as the RTC Sundsvall were cancelled. Especially the cancellation of measurements in the RTC led to a difficult situation, where the planned data comparison condition could not be measured. As a result, the hypotheses and research questions have been adapted. In the upcoming *HCL:Aurora* project, the remaining open aspects are planned to be answered. The research questions were revised as well.

Instead of full measurements at all planned conventional and remote airports, we were only able to conduct air traffic controller measurements at conventional tower workplaces. However, lighting measurements were performed at remote tower workplaces at the RTC Sundsvall. A restructure of the research questions was necessary, since the planned research design and research questions are were no longer possible to answer with the data collected so far. It was decided to conduct separate lighting comparisons and field study results in separate studies. In total three studies have been performed, the methods and results are presented in chapter 4, 5 and 6. Table 1 gives an overview about the aim and outline of the study triplet.

Table 1. Aim and description of the study triplet performed in the HCL:Baseline project.

STUDY	AIM
1	***Literature-Based HCL Concept Development*** *Literature-based HCL concept development for remote tower workplaces, which could be beneficial onto alertness and performance in the future.* Chapter 4
2	***Lighting Comparison*** *Lighting comparison of conventional tower and remote tower workplaces to identify differences between both workplaces and set the results of study 1 into perspective.* Chapter 5
3	***Air Traffic Controller Field Measurements*** *Conventional tower field measurements were conducted, including lighting exposition and fatigue measures at several conventional airports. This data gives an overview about influence of shift types onto fatigue and could act as a baseline for further comparisons.* Chapter 6

4 STUDY 1 – Literature-Based HCL Concept Development

This chapter presents the results of a literature review regarding best lighting conditions at a remote tower workplace. An optimal HCL design based on empirical evidence available is developed and schematically presented.

4.1 Towards a HCL Concept

The HCL for remote tower workplaces concept includes the use of biologically effective lighting that focuses on the operator, their needs and workplace characteristics. By planning of a lighting concept, it is recommended that activity and organisational features, room characteristics, workplace characteristics, lighting quality features, economic and ecological as well as biological and psychological criteria be considered (DIN EN 12464-1). The latter include the standard stipulating that daylight should be used as a priority, lighting conditions should follow a dynamic lighting pattern, lighting should be individually regulated and overall wellbeing should be conveyed by lighting (DIN EN 12464-1).

To adapt the lighting concept precisely to the remote tower workplace, its characteristics need to be considered. A special feature of the workplace in the RTC is the control room character of the workplace. A control room or control room in general is defined by properties, which also apply to the remote tower workplace: The workplace is used over 24 hours, i.e. in shifts, it may be necessary to limit illuminance and daylight is often excluded for safety as well as operational reasons (DIN SPEC 67600:2013-04). This is because daylight and its unsystematic changes, entails risks and the occurrence of glare cannot be prevented. Since air traffic controllers work in shifts, this aspect needs to be given special consideration in the lighting and illumination concept to be designed for the remote tower workplace. DIN SPEC 67600 calls for "shift work models to be developed that are less likely to interfere with people's internal clock" (DIN SPEC 67600:2013-04). Adequate lighting that helps keep employees healthy in the long term can be part of this. When planning a lighting concept for people working in shifts, i.e. also at night, a dilemma is soon faced. Bright, rather cool white light needs to be used for good visual task design and for activation and thus high concentration. However, the potential damage that bright lighting can cause at night, e.g. destabilisation of the circadian rhythm, should not be neglected. So, a compromise needs to be found between optimum task lighting on the one hand and a lighting plan that maintains and promotes employees' health on the other. Finally, it should be noted that because of the inertia of the melanopic system compared with the visual system, biologically effective lighting solutions are only suitable for rooms and workplaces where people spend long periods of time, i.e. at least several minutes (DIN SPEC 67600:2013-04). For this reason, the lighting concept is to be designed for the main workplaces in the RTC.

These aspects illustrate that the creation of a lighting concept cannot be uncompromising. In some cases, requirements overlap in such a way that no optimum solution can be shaped, but the variant that is most favourable from both an engineering and economic point of view should be preferred.

4.2 Development of a HCL Concept

The focus of this work will be on the psychological aspect, i.e. the biological effect of light in the context of the HCL. HCL promises the potential to increase both safety and the performance and alertness of air traffic controllers at the remote tower workplace.

Lighting can be dynamically designed according to the HCL model to approximate natural daylight. Daylight follows a dynamic course in terms of intensity and light colour. Applied to the interior, this dynamic can be implemented by continuously changing the illuminance, light spectra and light distribution of the room lighting. It is possible to vary their duration, the time of change and the speed and quality of change. Design recommendations such as DIN SPEC 67600 advocate a dynamic lighting system based on the progression of natural daylight. This means that in the morning, blue-enriched light should be used to create a stimulating atmosphere, and, at the end of the day, warm white light should be used for relaxation. To create a suitable environment for activities requiring a high level of concentration, bright light should always be used where concentration needs to be high. Natural daylight has a lower biological impact on humans in the morning and evening and none at night because of the low illuminance. The pineal gland hormone melatonin is less suppressed than in bright light; the circadian rhythm can run as usual. To achieve the same effect in interiors but at the same time provide the light needed to perform work tasks, it is necessary to modify the spectral properties of the light.

According to air traffic controller's job profile, controllers must observe events at the airport attentively and to make safe decisions and communicate these efficiently to the flight crew and other controllers. This results in the following basic requirements for the design of the lighting and illumination concept at the remote tower workplace: To ensure that displays are clearly identifiable, relative darkening of the room is preferable to very bright lighting. Unrestricted performance of all visual tasks needs to be ensured and glare needs to be avoided. It must be ensured that colour rendition is at least 80 on the Colour Rendering Index. The lighting concept must not jeopardise occupational safety. Short- and long-term damage to health must be prevented. HCL takes a health promotion approach through specific lighting: Both physical and mental health should be maintained and promoted by the lighting concept.

When designing a lighting and illumination concept for the remote tower workplace, the question also arises of how to regulate the individual dynamic lighting sequences. The aim of the HCL is to create an environment that supports people in their activities in the best possible way, without the individual having to permanently take care of the lighting himself, which would divert the focus away from his main activity. It can therefore be concluded that the use of automation is more appropriate in this case. Automation solutions can be designed in different ways. To fit the situation as accurately as possible, automation should be variable in design. There are two approaches: adaptive and adaptable automation (Ganßauge & Hoppe, 2016). While adaptive automation is programmed to detect environmental conditions via sensors and independently derive and make changes to the automated functions, adaptable automation offers the possibility for humans to initiate changes to the automated functions themselves. This does not have to apply to all functions, but for some functions it can be quite useful if the automation does not strictly follow their programming, but deviations are possible. The system can be set up in such a way that it automatically detects when a situation requires so much attention that it is considered critical and the lighting should be adjusted accordingly. However, it must be borne in mind that different air traffic controllers may perceive a situation as being of varying degrees of difficulty, complexity and challenge. This may depend, for example, on previous experience or the current condition of the person concerned. It can therefore be concluded that adaptive automation, which is based entirely on objectively measured values, does not have to be an exclusive solution for the lighting concept of the remote tower workstation. Rather, adaptable automation offers the possibility of making such changes adapted to the subjective assessment of the controllers themselves. A compromise solution can be found to avoid human error, i.e. misjudgements by air traffic controllers regarding their own current exposure and the associated health and safety risks. An automation concept for lighting control is to be designed for the remote tower workplace, which includes both adaptive and adaptable components. The automation system should switch on activating light as soon as response times of the controllers to requests fall below a minimum value or other potential hazards are detected. In addition, controllers should be able to deactivate or reduce the intensity of switched-on light or switch on activating light automatically when they notice the need. This argument is also supported by Ganßauge and Hoppe (2016), who point out that "maximum automation" cannot really be called "human-centred". Instead, the authors also propose an adaptable automation solution.

For the occurrence of an emergency that calls for safe decisions and rapid action, the lighting concept should be designed to permit or initiate adaptation to the circumstances. From the preceding comparison of adaptive and adaptable automation, it can be concluded that adaptable automation should be used to control the lighting system.

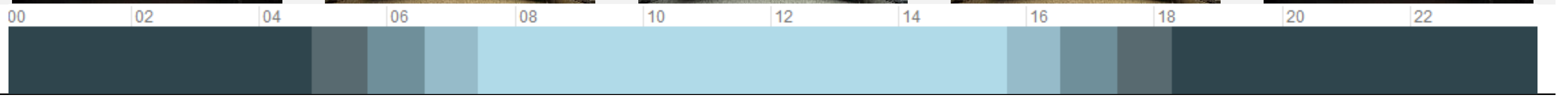
4.3 Prototypical HCL Concept

Based on results and regulations discussed, the following proposal for a dynamic HCL concept for the remote tower workplace is made:

- *To maintain the circadian rhythm and only activate in critical situations, regardless of the time of day or night, there shall be different lighting conditions during the day and night.*
- *Lighting conditions shall also change dynamically during the course of the day.*
- *Lighting changes shall be continuous so that transitions, especially towards warmer, less bright light, are unnoticed and as smooth as possible. Rapid light changes within seconds shall be avoided, as this can lead to visual perception disturbances.*
- *Lighting shall be controlled by an automated system containing adaptive and adaptable components. Lighting history and the shift schedule shall serve as an indication of how bright and in which light colour the lighting for a workplace or operator is optimal set.*

As example, a HCL concept is presented in table 2 below. The concept is then explained and justified in more detail. Changes in lighting should be understood as flowing transitions. The approximate assignment of similar colour temperatures to wavelengths was made with the help of Wien's displacement law (formula: λ_{max} = 2897.8 µm*K / T).

Table 2. Prototypical HCL concept with light intensity and light colour values. This concept was developed for a full 24-hr cycle at the 1st November 2020 at RTC Sundsvall.

	Night-Phase	*Transition-Phase to Day*	*Day-Phase*	*Transition-Phase to Night*	*Night-Phase*
RTC Local Time	00:00 – 04:00	04:00 – 08:00	08:00 – 16:00	16:00 – 18:00	18:00-00:00
Duration	4:00	4:00	8:00	2:00	6:00
Light Intensity *vertical at eye*	250-450lx *(activation in critical situations to 500-1000lx)*	>	500-750lx	>	250-450lx *(activation in critical situations to 500-1000lx)*
Light Colour *vertical at eye*	3700-5100K *(activation in critical situations to 5900-6900K)*	>	5500-6900K	>	3700-5100K *(activation in critical situations to 5900-6900K)*
Visualisation					
Night-Day Curve					

During the day, light should be applied at high illuminance to trigger activation and to imitate the natural incidence of sunlight. The illuminance values involved are averaged between 500 and 750 lx. Bright light should help to maintain concentration and attention.

It is important to ensure that displays and monitors are equipped, e.g. with matt surfaces, so that they can be optimally recognised despite bright lighting. The light colour should also mimic the natural light during every specific day. This makes it possible to create the most natural environment possible. Bright, cool light provides the human organism with information about the day, even without actual daylight openings to the outside. The light colour should shift continuously in the morning hours from warm light spectrum between 3700 and 5100 K to a cool light between 5500 and 6900 K. This can be used to activate people who start their early shift at this time of day.

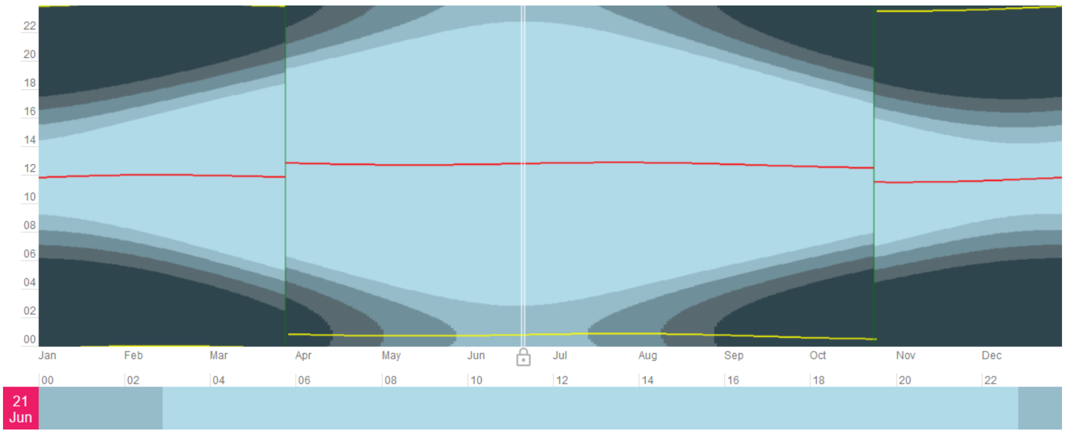
However, this type of lighting is not recommended for night-shift controllers. Here it becomes clear how important area adjusted lighting is. This enables the workplace of a night-shift controller to be automatically lighting adjusted so that the light does not shift to a cooler spectrum but tends to remain warm and in the range 3700 to 5100 K. In this way, night workers can easier fall asleep following their shift. For night workers, brighter, cooler light should only be applied for activation purposes in critical situations. Night-time lighting should be designed to ensure that natural melatonin release is largely undisturbed to maintain and promote the health of the controller in the long term. Light with lower illuminance levels than during the day should be used. However, the light still needs to be bright enough to provide adequate lighting for performing visual tasks. This means that illuminance during night-time should be between 250 and a maximum of 450 lx.

Light colour should also be adjusted during the night. Research findings show that light with a reduced blue component and a rather warm colour scheme is beneficial for maintaining the natural human circadian rhythm (Hoffmann et al., 2008). Consequently, yellow to red light of wavelengths between 570 and 770 nm should be used, which corresponds to similar colour temperatures between 3700 and 5100 K. A special feature of night-time lighting is the need for activation in critical situations. As described earlier in this chapter, sensors should be used to determine when activating light is needed. In addition, the controllers themselves should be able to detect this manually and switch on the activating light. To ensure that activation is triggered during the night without drastically increasing illuminance, it is proposed that, for an illuminance of 250 lx at the eye, a light temperature of at least 8000 K. No major increase in illuminance is necessary. This is because lighting history plays a role in determining how strongly light can have an activating effect on an individual. A person's sensitivity to light depends on the lighting conditions to which he or she was previously exposed. During the night shift, controllers are generally exposed to lower illuminance levels, so there is no need for extreme changes in illuminance. Even a slight increase can have a biological effect after a phase of dimmed lighting. The photometric change needed to activate the system in critical situations during the night shift can be achieved by a simple change of light colour in addition to a slight increase in illuminance. Thanks to lighting history, it is not necessary to use extreme values of light colour and illuminance. The values recommended by DIN SPEC 67600 are not considered necessary. Consequently, light of wavelengths in the range between 420 and 520 nm should be used, which corresponds to similar colour temperatures between 5500 and 6900 K. It should be possible to increase illuminance from the initial level of 250 to 450 lx to a maximum of 500 to 1000 lx for activation in critical situations.

To convey a sense of well-being, light should illuminate the room by a combination of direct and indirect lighting. This minimises the risk of glare and ensures that directional and diffuse light are in such a ratio that a pleasant atmosphere can be created in the room (DIN EN 12464-1, 1:2017-08). In addition, sensible modelling can help prevent the formation of excessive shadows that can restrict visibility. This type of lighting can be created by using individually adjustable luminaires at the workplace for directional lighting and luminous surfaces installed over a large area on the ceiling. The large surfaces use a solid angle of more than 0.5 sr and create the impression of natural daylight incidence. Due to solid angles from a size of 0.5 sr upwards, lower illuminance levels are required to achieve a biological effect of light on people. Planar lighting does not cause excessive luminance levels to reach the eye of the observer either directly or indirectly, i.e. via glare. Visual comfort is enhanced.

Finally, it needs to be noted, that the lighting should be adapted on a daily basis to the RTC location and day as well as night length. The example Sundsvall demonstrates that the night varies over the year between 12:47hrs on the 21st of December and no astronomical night on the 21st of June (figure 4).

Figure 4. Daylight available in Sundsvall.



4.4 Benefit Analysis HCL Concept

After development of a prototypical HCL design, the potential of the concept will now be theoretical assessed. For this purpose, it makes sense to detach the focus from the remote tower workplace and to take a holistic perspective on HCL. Further, input on follow-up steps when HCL is installed are given.

HCL promises to increase human performance, well-being and health by optimising light and lighting. In the work context as well as in all other situations to which people are exposed, simply designing HCL-compliant lighting could bring about a significant improvement in productivity, satisfaction, and health.

Based on the HCL concept developed, the concept offers opportunities to use simple means to improve both the safety of the air traffic under surveillance and the health of controllers in their work. However, the fact that HCL does not provide a solution to all the problems related to fatigue, especially during night work, is an important fact that must be kept in mind. In combination with other safety and health means, such as adapted rostering, sufficient breaks, and a lighting-exposition score, HCL can contribute to an increase in safety, performance and health. HCL directly targets health variables by stabilising the biorhythms of workers, which helps to prevent sleep disturbances caused by shift work.

A lighting concept according to HCL can be applied not only to the application case of the controllers in the RTC described here. Other conceivable areas of application are, for example, other workplaces where shift work is carried out and where tasks of high vigilance are performed. HCL could also be useful in an educational context, e.g. for lighting classrooms Karlsson (2015), lecture halls or libraries. At this point, it is important to stress that lighting concepts according to HCL can or must be designed completely differently depending on the scope of application. Depending on what a particular activity or other circumstances require, HCL should serve to optimally adapt light to the requirements to the operator.

To ensure a proper mechanism constant feedback and adjustments are crucial. An evaluation study on psychological (situational awareness, fatigue), biological (melatonin, cortisol) and emotional aspects (well-being, comfort) should be conducted when HCL is in place. Further, an assessment that traces the effects of lighting on the long run should be striven for.

5 STUDY 2 – LIGHTING COMPARISON

In order to compare different existing lightings at conventional and remote tower workplaces, various light measurements have been conducted. This chapter describes method, setup and results of the measurements.

5.1 Method and Setup

To gain lighting data during the wintertime, lighting measurements at airports in Sweden and Estonia have been conducted at several times during the winter season 2019/2020. A measurement plan, including historical METAR is presented in the table 3 below. The METAR is presented since cloud situation can influence lighting measurements significantly.

Table 3. Locations and measurement times as well as local METAR.

WORK	UNIT	DATE / LOCAL TIME	METAR
Convent.	*Kiruna (ESNQ)*	2020-01-21 / 12:50	`ESNQ, 2020-01-21 11:50, ESNQ 211150Z 26010KT CAVOK M03/M07 Q0987`
	Malmö[a] (ESMS)	2019-11-26 / afternoon	`ESMS, 2019-11-26 12:20, ESMS 261220Z 15008KT 110V170 3200 BR BKN007 BKN009 OVC015 06/05 Q1005`
	Tartu (EETU)	2020-02-18 / 13:10	`EETU, 2020-02-18 11:50, EETU 181150Z 23017KT 9999 -RA BKN024 OVC036 06/03 Q0999`
	Tallinn (EETN)	2020-02-21 / 13:00	`EETN, 2020-02-21 10:50, EETN 211050Z 19016G26KT 8000 -RASN OVC008 02/01 Q1003 R08/290195 NOSIG`
Remote	*Sundsvall (ESNN)*	2019-11-05 / 13:10	`ESNN, 2019-11-05 12:20, ESNN 051220Z 30003KT CAVOK M03/M07 Q1008 R16/09//95`
	Linköping (ESSL)	2019-11-05 / 13:20	`ESSL, 2019-11-05 12:20, ESSL 051220Z 03010KT 340V050 CAVOK 02/M03 Q1000`

[a]measurement took place independent of the *HCL:Baseline* project by other researchers. The measurement took place in the afternoon, no information about measurement time are given.

For achieving standardized and comparable data, the lighting was measured with the same device, a *Konica Minolta CL-70F CRI illuminance meter*, at all sides. The CL-70F is a compact and handheld instrument for measuring the dominant colour and illuminance. Recorded data was illuminance, dominant wavelength, and correlated colour temperature.

A measurement was conducted at the position of the head of the air traffic controller sitting in position. Alternatively, a measurement was done at a fixed height of 120cm above the floor, which simulates roughly the position of the head in the room. The area of interest was always at the primary working position at the workplace. That means, that all measurements were done at the primary working position. All measurements were performed using two cardinal directions: sensor directed horizontal to ceiling (*horizontal*) and sensor directed vertical towards the screens or windows (*vertical*). A vertical measurement is relevant, since the direction of light at the retina plays an important role in non-visual effects of lighting (Aarts et al., 2007).

5.2 Results

5.2.1 Conventional Tower Workplaces

Lighting figures and data acquired among the conventional tower workplaces ESNQ, EETU and EETN are presented in table 4 and figure 5-10 below.

Table 4. Lighting measurement figures of three conventional workplaces.

UNIT	HORIZONTAL		VERTICAL	
	Illuminance[a]	T_{cp}[b]	Illuminance[a]	T_{cp}[b]
ESNQ	333	6032	1190	4323
EETU	269	6608	388	7004
EETN	72.6	7541	290	6513

[a]in lux; [b]in Kelvin

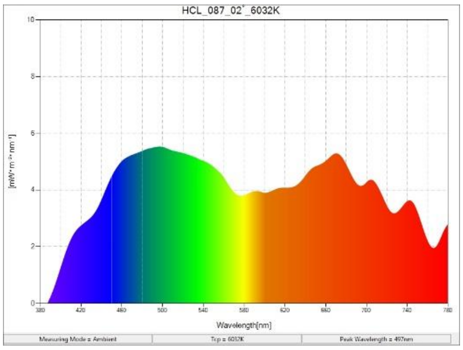


Figure 5. Horizontal, ESNQ

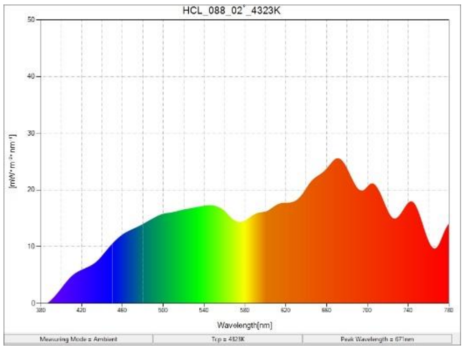


Figure 5. Vertical, ESNQ

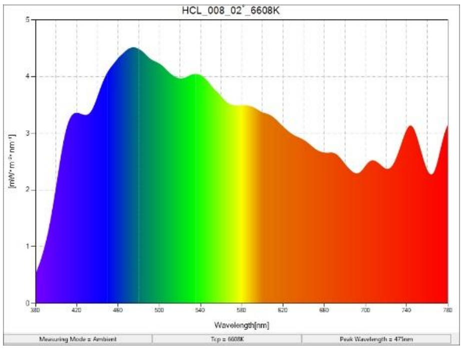


Figure 7. Horizontal, EETU

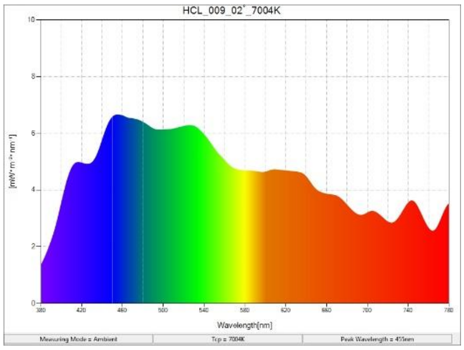
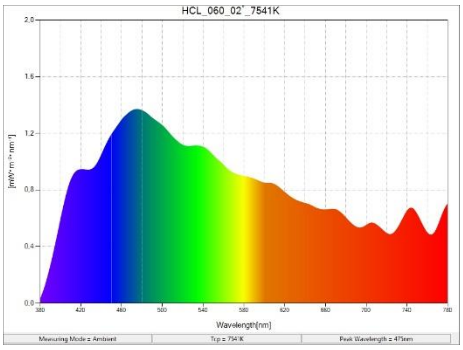


Figure 8. Vertical, EETU



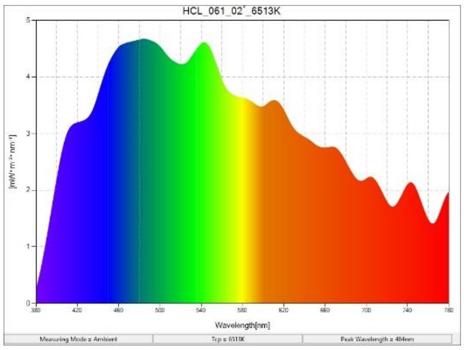


Figure 9. Horizontal, EETN

Figure 10. Vertical, EETN

Lighting measurements in ESMS were conducted independently of the present study, but also under realistic conditions. The data is presented, however not all figures were available for this report.

Table 5. Illuminance values measurement in Malmö-Sturup (ESMS).

SENSOR DIRECTED TO	ILLUMINANCE[a]
Worktable	60-190
Screens	60-90
General lighting through windows	120-150

[a]in lux

5.2.2 Remote Tower Workplace

In order to understand and study the lighting context given under operational work, lighting measurements were performed under a randomly setting. The lighting was not changed or adapted due to the measurement, but rather shows a snapshot under which lighting conditions air traffic controller were working. Figures and data acquired among the remote tower workplaces are presented below.

Table 6. Lighting measurement figures of two remote workplaces.

UNIT	HORIZONTAL		VERTICAL	
	Illuminance[a]	T_{cp}[b]	Illuminance[a]	T_{cp}[b]
ESNN	147	6459	199	7613
ESSL	201	4808	161	5985

[a]in lux; [b]in Kelvin

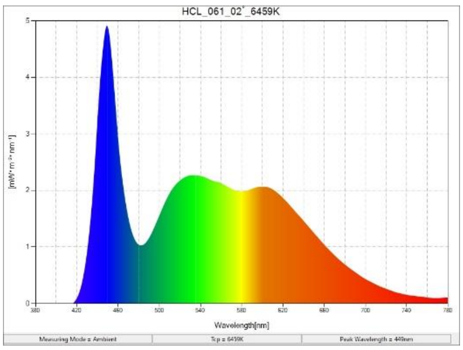


Figure 11. Horizontal, ESNN

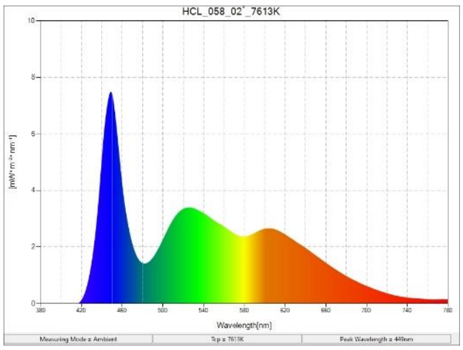


Figure 12. Vertical, ESNN

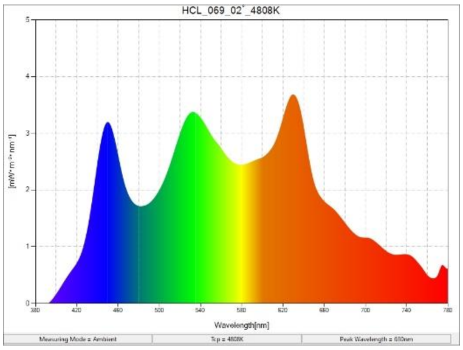


Figure 13. Horizontal, ESSL

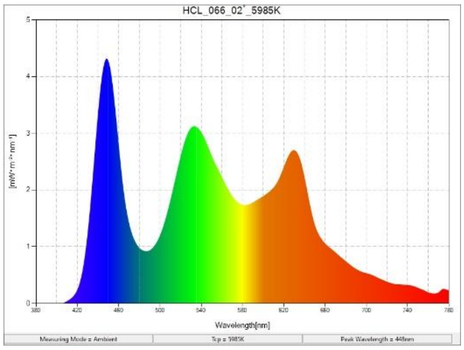


Figure 14. Vertical, ESSL

5.2.3 Merged Lighting Data of Remote and Conventional Workplace

The figures 15 and 16 depict illuminances and Tcp at the measured workplaces.

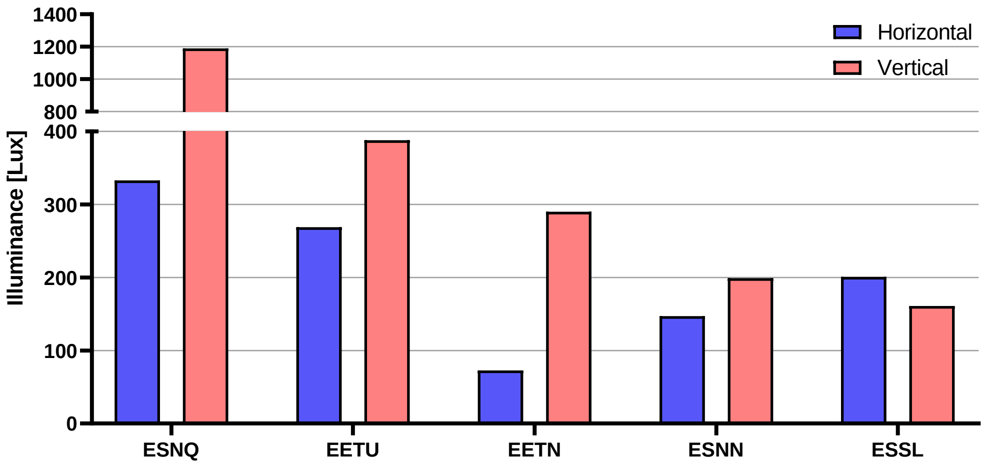


Figure 15. Illuminance measures at conventional and remote workplace.

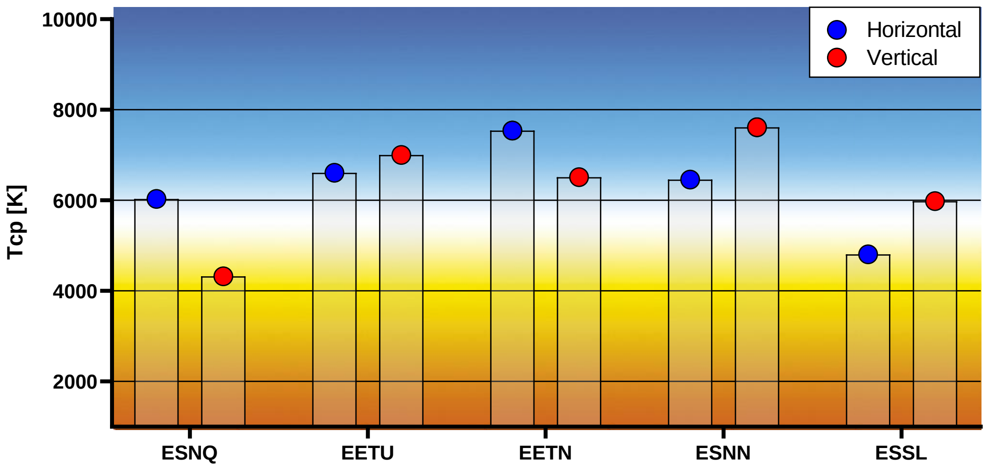


Figure 16. Colour measures at conventional and remote workplace.

5.2.4 Lighting Possibilities in Remote Tower

Illuminance and correlated colour temperature (T_{cp}) measurements were conducted at six different positions (figure 17 and 18) using the CRI illuminance meter Konica Minolta CL-70F. Measurements where conducted under two different lighting configurations (Config A = dimmed, Config B = maxed). Dimmed means, that all lighting modules where disabled. Maxed means, that lighting brightness was set to maximum.

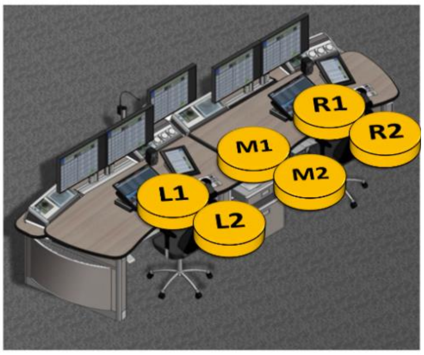


Figure 17. Measurement locations.

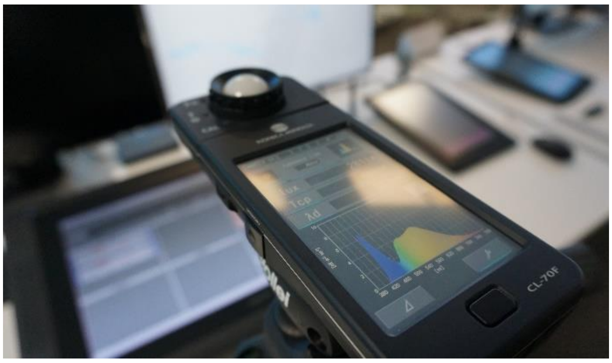


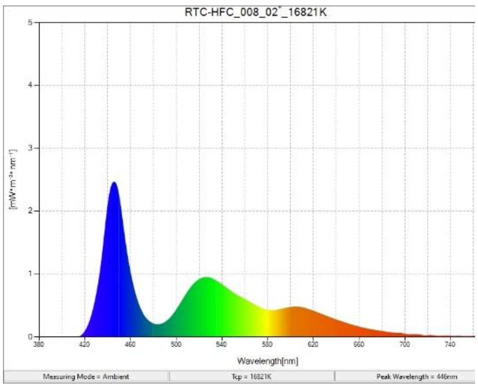
Figure 18. CL-70F measurement at L1.

The results of the measurements on illuminance and correlated colour temperature (T_{cp}) are shown below. The first table 7 presents results based on sensor directed horizontal ceiling, while second table 8 presents data with sensor directed vertical towards the screens. Figures 19-22 present the spectral distribution in both configurations in vertical and horizontal measurements.

Table 7. Horizontal lighting measurement.

SPOT	CONFIG A		CONFIG B	
	Illuminance[1]	T_{cp}[2]	Illuminance[1]	T_{cp}[2]
L1	44.0	16821	368	4261
L2	25.8	14625	248	4333
M1	43.0	16386	290	3959
M2	28.3	15028	174	4295
R1	44.4	14965	345	3753
R2	26.5	14204	179	4160

[1]in lux; [2]in Kelvin



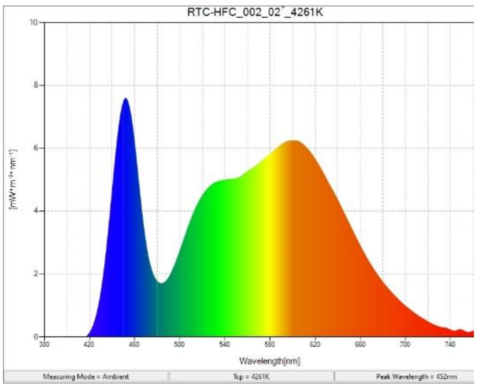


Figure 19. Horizontal, Config A.

Figure 20. Horizontal, Config B.

Table 8. Vertical lighting measurement.

SPOT	CONFIG A		CONFIG B	
	Illuminance[1]	T_{cp}[2]	Illuminance[1]	T_{cp}[2]
L1	95.6	12931	243	4922
L2	60.9	12905	224	4771
M1	98.4	15304	352	4241
M2	72.4	13962	224	4740
R1	102	12552	370	4197
R2	68.0	13048	242	4415

[1]in lux; [2]in Kelvin

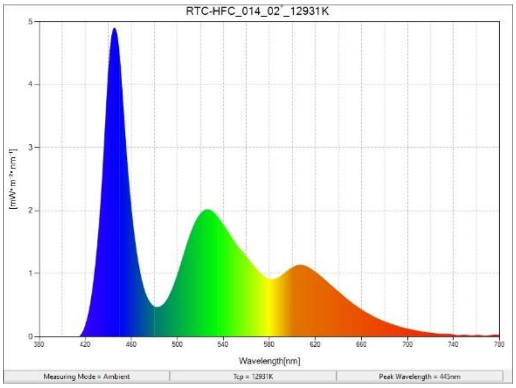


Figure 21. Horizontal, Config A.

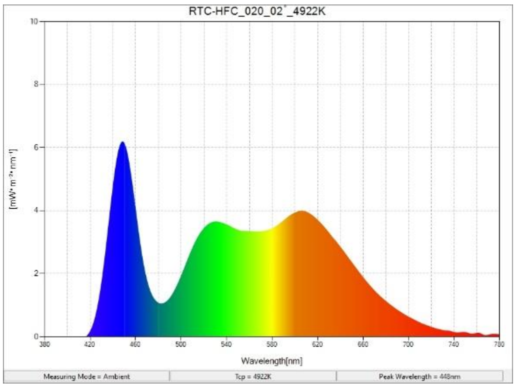


Figure 22. Horizontal, Config B.

5.3 Discussion

In study 2 we investigated lighting characteristics at various conventional and remote tower workplaces in Sweden and Estonia. Light measurements took place at a standardized time enabling the possibility to do comparison between the workplaces. As key values were illuminance and dominant colour presented, measurements took place using two directions: sensor directed horizontal to ceiling (*horizontal*) and sensor directed vertical towards the screens or windows (*vertical*). While *horizontal* gives an estimation about the overall room lighting characteristics, *vertical* is the operationalisation of how huge the cognitive effect of the lighting is. Light can only effect when received by the human retina, a vertical measurement simulates the eye position in the room.

Illuminance. The overall lighting conditions were at conventional and remote workplaces at a maximum intensity of 400 lux (vertical and horizontal). An exception was found for ESNQ, where 1200 lux were measured, probably due to the influence of the low standing sun and measurements to the south. Both measurements could indicate fatigue problems, as lighting conditions below 500 lux during daytime are rated as to less for supporting alertness. For comparison, the recommended illuminance in office environments with computer work is around 500 lux (ANSI / IESNA, 2004). On the other hand, too bright conditions can lead to eye strain and glare, impairing visual capabilities. It was noticed that some air traffic controllers wear sunglasses in low standing sun conditions at ESNQ which indicates the negative effect of too much light as well. A risk of eye strain and glare could be existing.

Measurements at the remote tower workplace indicated lower (vertical) illuminances less than 200 lux than at the conventional workplace. The screens emitting less bright light resulting in overall lower lighting conditions than in conventional. Horizontal lighting was lower in relation to vertical. These figures represent the lowered overhead lighting and room lighting characteristics. However, it is more relevant if and which light hits the human retina as this is needed for a biological effect to act. Our measures indicate reduced vertical illuminance in comparison to conventional, which can lead to reduced biological and cognitive alerting effect. Here can an improvement potential be given. Measurements at the remote tower workplace ESSL show even slightly brighter horizontal illuminance which was likely caused by big windows behind the remote tower workplace. In other words, even with windows at the remote tower workplace lighting characteristics are lacking behind the higher values detected at the conventional tower.

Colour. The result indicated in the conventional workplace dominant values in lower wavelengths (peaking in the blueish part), however, lighting had a bigger distribution. The higher spread is due to the daylight characteristics as natural sunlight features all wavelengths. The remote tower workplace also featured a dominant peak in lower wavelength, however, the peak was way stronger. This is due to technological characteristics of the LCD-screens that emit a big amount of blue light. From a biological perspective can that be positively seen, as blue-enriched light influences directly the suppression of melatonin (refers to 2.2). On the other hand, the melatonin release is as well influence while working in night-time which could lead to a risk for circadian disruption. A potential blue-light filter as night-mode could be a solution but this needs to be evaluated quite carefully, since any visual impairments need to be avoided. Additionally, the blue light hazard risk could be given in long-time working with screens that feature a high amount of blue light. The blue light hazard describes the relative spectral sensitivity of the human eye to the blue light. This theory bases on the relative spectral effectiveness of optical radiation to induce retinal photochemical injury (photic maculopathy) (Jaadane et al., 2020; Norren & Gorgels, 2011). However, the effect in humans in daily work with screen has not been evaluated so far and it remains unclear if and how blue light could negatively affect cells on the human retina.

It needs to be noted, that the present data collection does not take weather and seasonal effects into account. In CAVOK conditions, illuminance conditions in the tower can reach or even outperform 500 lux, as seen in ESNQ. Hence, we recommend further studies to evaluate lighting conditions during day and night-time, as well as during different seasons. Further, a deeper analysis of the data could be performed to calculate the “melanopic” effect of the lighting.

Taken together, we found clear differences in the lighting conditions between remote and conventional workplaces. In both workplaces did we find negative aspects that are potentially linked to fatigue and health. With the given evidence in mind, a clear optimisation potential is given for the remote tower workplace. Systematic and consistent usage of lighting, for example by means of an HCL concept, could help for maintaining cognitive capabilities and health.

6 STUDY 3 – AIR TRAFFIC CONTROLLER FIELD MEASUREMENTS

To understand the interplay between fatigue, vigilance and lighting, field measurements with air traffic controllers working operational have been carried out. Measurements took place at small to medium-sized airports with low to medium-traffic density. The following sections cover method, study setup and results of the study.

6.1 Method and Study Setup

Various methods were applied, that were either requiring active participation by the participant or were done passive, requiring no certain action.

6.1.1 Active Methods

As active method we used questionnaires, workload queries and the Psychomotor Vigilance Task (PVT). These methods are described in the following.

6.1.1.1 Questionnaires

Over the course of a shift filled the participants various questionnaires in. Basically, three different types of questionnaire were used: a questionnaire before beginning the shift (*Q1*), a questionnaire filled in every second hour (*Q2*) and finally a questionnaire after the shift (*Q3*). A table providing an overview about questionnaires and when applied is given below (table 8).

Table 8. Questionnaire methods and timely application.

When Applied			Method	Variables/Description
Q1	Q2	Q3		
x			*Demographic Questionnaire*	*Age, Gender, Working Position, Workplace, Experience, Other Positions*
x	x	x	*ISA*	*Please refer to section 6.1.1.2. Explanation for air traffic controller, without further task necessary. Guided and explained by present experimenter.*
x	x	x	*Test Battery*	*Please refer to section 6.1.1.3. Explanation for air traffic controller, without further task necessary. Guided and explained by present experimenter.*
x	x	x	*H&ES Questionnaire*	*Headache and eye strain questionnaire developed by and used in (Viola et al., 2008) Items onto current perception of irritability, headache, eye strain, eye discomfort, eye fatigue, difficulty focusing, difficulty concentrating and blurred vision. Participant was asked to rate every item onto a Likert scale ranging between none, light, moderate and severe.*
x	x	x	*PANAS*	*Positive and Negative Affect Schedule (Watson et al., 1988) is a self-report consisting of two 10-item scales to measure both positive and negative emotions.*

x			*PSQI*	*Pittsburgh Sleep Quality Index (Buysse et al., 1989) is a questionnaire for measuring sleep quality. The PSQI asks retrospectively for a period of four weeks about the frequency of sleep disturbing events, sleep quality, usual sleeping times, sleep latency and duration, intake of sleep medication and daytime sleepiness. A total of 18 items are used for quantitative evaluation and 7 components are assigned, each of which can assume a value range from 0 to 3.*
		x	*MSQ*	*The Minnesota Satisfaction Questionnaire (MSQ) is a paper-and-pencil inventory of the degree to which vocational needs and values are satisfied on a job. The short-version, consisting 20 item was used.*

The air traffic controller name, date, current local time, and position was noted on every questionnaire by the experimenter.

6.1.1.2 *Workload Queries*

Workload was rated using the Instantaneous self-assessment of workload technique (ISA; Jordan & Brennen, 1992). The technique provides immediate subjective ratings during live operations. Participants were asked to rate their current workload every 15 minutes on a scale of 1 (low) to 5 (high). A description of every number was delivered to the participants, adapted to (Kirwan et al., n.d.). The table is presented below (*Table 10.* ISA scale, adapted according to Kirwan at al. (1997)

Table 10. ISA scale, adapted according to Kirwan at al. (1997).

LEVEL	WORKLOAD HEADING	SPARE CAPACITY	DESCRIPTION
1	Under-Utilised	Very Much	*Nothing to do. Rather boring.*
2	Relaxed	Ample	*More than enough time for all tasks.*
3	Comfortable Busy Place	Some	*All tasks well in hand. Busy but stimulating pace. Could keep going continuously at this level.*
4	High	Very Little	*Non-essential tasks suffering. Could not work at this level very long.*
5	Excessive	None	*Behind on tasks, losing track of the full picture.*

6.1.1.3 *Test Battery*

The test battery is a computerized software, that was used in Najjar et al. (2014). The software consists a reaction time task (Psychomotor Vigilance Task, PVT) and KSS. It was applied according to the table onto questionnaires above. A further explanation on PVT and KSS is delivered in the table below (*Table 11.* Explanation of PVT and KSS.).

Table 11. Explanation of PVT and KSS.

METHOD	VARIABLES/DESCRIPTION
PVT	*The psychomotor vigilance task (PVT; Dinges & Powell, 1985) is a sustained-attention, reaction-timed task that measures the speed and error rate with which participants respond to a visual stimulus. The PVT was running over a time of 3 minutes and participants were asked to respond as quickly as possible when a cue appeared on the screen. The inter trial interval (ITI) was set between 3000ms and 8000ms. The cue was faded out after 1000ms in case of no reaction and was rated as lapse.*
KSS	*The Karolinska Sleepiness Scale (KSS, Åkerstedt & Gillberg, 1990) is a single item scale, that measures the subjective level of sleepiness right now. The KSS features a 9-point scale (1 = extremely alert, 3 = alert, 5 = neither alert nor sleepy, 7 = sleepy – but no difficulty remaining awake, and 9 = extremely sleepy – fighting sleep).*

6.1.2 Passive Methods

As passive methods were a heartrate chest belt, a lighting sensor wrist band, a illuminance meter, video recordings as well as a LiDAR sensor used. These methods are described in the following.

6.1.2.1 Heartrate Chest Belt

For measuring heartrate data, a EcgMove 4 (movisens GmbH, Karlsruhe), attached on an electrode chest belt, was applied. The sensor acquired a single channel ECG signal (1024Hz). In addition, the sensor recorded the physical activity through the acquisition of acceleration in three dimensions, the angular rate (gyroscope) and atmospheric air pressure. Moreover, the ambient temperature is acquired. Data was recorded but not covered in present report.

6.1.2.2 Lighting Sensor Wrist Band

For measuring total lighting exposition, a LightMove 4 (movisens GmbH, Karlsruhe), attached on the participants non-dominant hand, was applied. The ambient light was detected via a colour light sensor. This sensor allowed the measurement of Lux, the brightness measurement over a wide range (darkness to sunlight), colour temperature measurement and light source type detection (enabled by an integrated additional IR channel). Moreover, the sensor recorded the rotation rate and the ambient temperature as well as physical activity of a person based on the acquisition of acceleration in three dimensions and atmospheric air pressure.

6.1.2.3 Illuminance Meter

For achieving more standardized data, the lighting was measured with a Konica Minolta CL-70F CRI illuminance meter. The CL-70F is a compact and handheld instrument for measuring the colour and illuminance. Recorded (relevant) measurement data was illuminance, dominant wavelength, and correlated colour temperature. A measurement took place every hour, at the position of the head of every air traffic controller. Both vertical and horizontal measurements were conducted. Data and a further description is given in chapter 6.

6.1.2.4 Video Recordings

Recording of facial- and eye-parameters to estimate a fatigue value through facial expression, eye-openness and blinking rate are aimed to be done in a further activity.

Data was recorded but not covered in present report. The reader is referred *to Safe Tower* study final report (Meyer, 2020).

6.1.2.5 LiDAR Pointclouds Bodytracking

The LiDAR pointcloud bodytracking for estimating fatigue parameters by body pose and movements behaviour are aimed to be done in a further activity. Data was recorded but is not covered in present report. The reader is referred to *Safe Tower* study final report (Meyer, 2020).

6.1.3 Study Procedure

In this field study setup, all participating air traffic controller have been measured in the same pattern under operational-active shifts. After salutation of participants, a short briefing on the methods and the study day was conducted. Heartrate chest belt as well as wrist band were put on. Devices were started by the research staff, while the participants filled in the before shift questionnaire (*Q1*). Every hour a workload queries was verbally asked, and a lighting measurement performed. Every second hour conducted the participant a PVT as well as the KSS. Additionally, the during questionnaire was filled in (*Q2*). At the end of the shift, the participants filled in the after-shift questionnaire (*Q3*). Measurements were stopped and data was saved.

Philosophy by conducting a research study in the field was always that safety as well as operational tasks were from the highest importance. Additionally, the research project adapted to operational environment as much as possible to not influence the air traffic controller and invalid the data consequently.

6.1.4 Measurement Locations

Initially measurements where planned in four conventional airports in Sweden, two conventional airports in Estonia and in the RTC Sundsvall (figure 23). However, due to the outbreak of Covid-19, we were not able to follow the schedule. As a result, measurements in Umeå, Halmstad and Malmö as well as the RTC Sundsvall had to be postponed until further notice.

Figure 23. Locations of the measured conventional towers. The locations in grey were scheduled but had to be excluded due to the travel restrictions starting in February following Covid-19.

6.1.5 Sample Characteristics

The sample characteristics show an average age of *M* = 35.0 years (*SD* = 11.9) with 5 female and 7 male participants (all licensed air traffic controller). The sample had an average work experience of *M* = 12.4 years (*SD* = 10.7). The PSQI showed an average score of *M* = 2.00 (*SD* = 1.97). Since the PSQI maximum score is 21, indicating reduced sleep quality, a good sleep quality over all participants is given. The demographic data of the sample based on the workplace unit is presented in the table 12 below.

Table 12. Locations and sample characteristics.

UNIT	*N*	AGE (SD)	GENDER	EXPERIENCE (SD)	SHIFTS	COMMENT
EETU (2019)	*2*	*30.0 (4.24)*	*2m*	*6.5y (6.37)*	*2*	
EETN (2019)	*3*	*26.7 (3.21)*	*2m, 1f*	*3.0y (1.73)*	*6*	*3 participants measured twice*
ESNQ (2020)	*5*	*46.3 (13.73)*	*1m, 4f*	*24.8y (13.13)*	*7*	*2 participants measured twice*
EETU (2020)	*3*	*32.0 (4.36)*	*3m*	*7.66y (5.51)*	*3*	
EETN (2020)	*4*	*31.0 (9.05)*	*3m, 1f*	*9.66y (5.50)*	*4*	

Note. Figures are calculated per sample at every measured unit. A total of 22 shifts were measured, while a total of n = 12 different participants was measured over the entire course of the study.

The following table 13 gives an overview about all shifts measured, how long and at which location. A rating of the shift type due to the working times was done beforehand. When a shift begun from 04:00 it was rated as morning shift. A begin from 08:00 was rated as day shift, from 14:00 as evening shift and from 22:00 as night shift.

Table 13. Shifts per workplace.

UNIT	CODE	DATE	START	END	SHIFT TYPE	COMMENT
EETU (2019)	*H001*	12/12/2019	11:40	18:00	Day	*Data excluded*[a]
	H002	13/12/2019	08:50	18:00	Day	
EETN (2019)	*H003*	16/12/2019	06:30	13:30	Morning	
	H004	16/12/2019	07:30	12:40	Morning	
	H005	16/12/2019	10:10	11:30	Day	*Data excluded*[a]
	H006	17/12/2019	06:50	12:30	Morning	
	H007	17/12/2019	07:30	13:30	Morning	
	H008	17/12/2019	10:00	11:30	Day	*Data excluded*[a]
ESNQ (2020)	*H009*	21/01/2020	05:20	15:00	Morning	
	H010	21/01/2020	10:00	16:30	Day	*Data excluded*[b]
	H011	21/01/2020	15:00	23:00	Evening	
	H012	22/01/2020	05:20	14:40	Morning	
	H013	22/01/2020	14:30	23:10	Evening	
	H014	23/01/2020	05:30	15:00	Morning	
	H015	23/01/2020	14:40	23:20	Evening	
EETU	*H016*	18/02/2020	08:50	17:30	Day	

(2020)	*H017*	19/02/2020	23:30	05:30	Night
	H018	20/02/2020	09:00	16:00	Day
EETN (2020)	*H019*	21/02/2020	07:00	13:30	Morning
	H020	21/02/2020	07:30	13:30	Morning
	H021	21/02/2020	10:10	17:30	Day
	H022	21/02/2020	13:00	16:20	Day

Note.
[a]Data excluded from further analysis since shift was only partially measured.
[b]Data excluded from further analysis due to invalid measurement.

A total of 22 shifts were measured, while 4 were excluded from further data analysis due to invalid measurements. Among the remaining 18 shifts were 9 dedicated morning shifts, 5 dedicated day shifts, 3 dedicated evening shifts and a single dedicated night shift.

6.1.6 Statistical Analysis

Statistical analysis of the data was performed using SPSS, version 26 (IBM Corp). Specific calculations are noted in the results chapter under each section.

6.2 Results

6.2.1 Sleep Behavioural Data

Data regarding sleep behaviour, including sleep quantity and sleep time prior each shift is presented in the table 14 below.

Table 14. Sleep quantity data.

	OVERALL		PER SHIFT							
			Morning		Day		Evening		Night	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Sleep in bed[a]	6.93	1.22	6.61	1.08	6.87	1.43	8.17	0.76	6.0	- [c]
Hours in bed[a]	7.80	1.40	7.16	1.08	7.75	1.19	9.00	1.00	6.0	- [c]
Time get up[b]	07:04	02:33	05:13	00:43	07:35	00:49	08:05	01:36	16:00	- [c]

Note.
[a]in hours.
[b]local times.
[c]data only from one participant due to a single shift measured.

For investigating differences was one-way ANOVA carried out. Levene test for variance homogeneity showed no significance, meaning that the variances are equal. There was no significant effect of the shift types at the $p < .05$ level on the sleep in bed, $F(3,13) = 1.65$, $p = .226$, and hours in bed, $F(3,13) = 2.847$, $p = .079$. A significant effect of the shift type on time to get up could be found, $F(3,13) = 43.41$, $p < .001$.

6.2.2 PANAS

Data regarding positive (PA) and negative affect (NA) is presented in the figures 24 and 25 below.

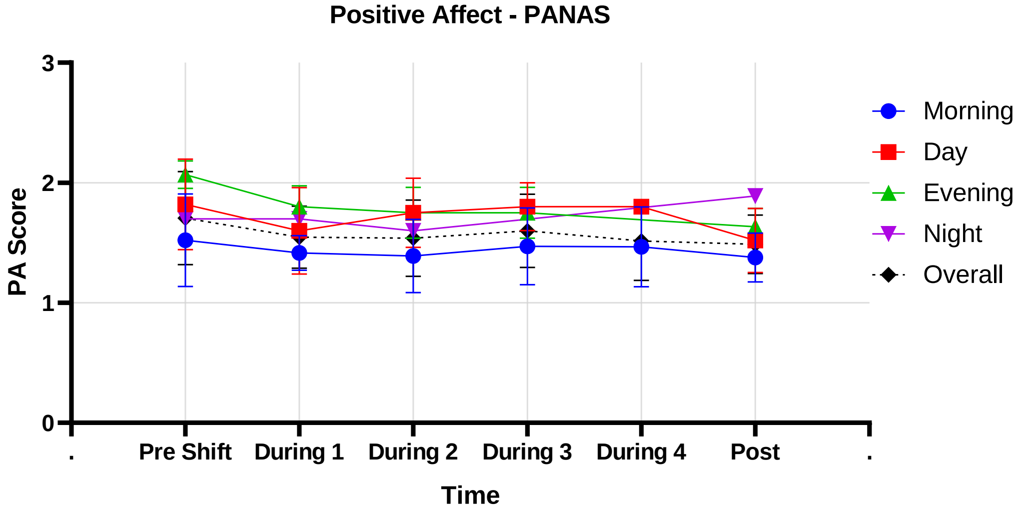


Figure 24. PANAS positive affect values.

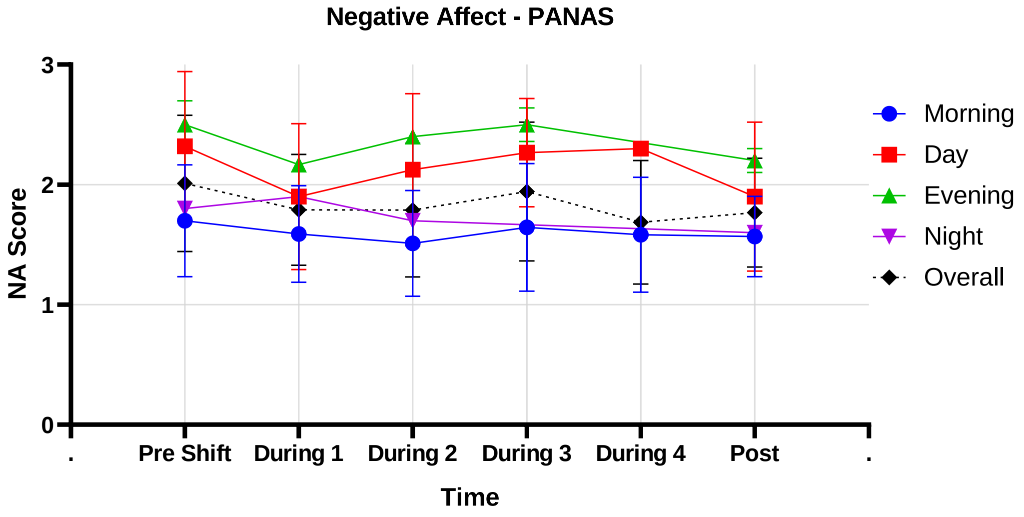


Figure 25. PANAS negative affect values.

For investigating differences PA and NA depending on shift type, a one-way ANOVA was carried out. Levene test for variance homogeneity showed no significance, meaning that the variances are equal. Results are presented in the tables 15 and 16 below.

Table 15. PA values for every time measured.

		Sum of Squares	*df*[A]	Mean Square	*F*	Sig. (*p*)
Pre	Between Groups	.759	3	.253	1.979	.163
	Within Groups	1.790	14	.128		
	Total	2.549	17			
During 1	Between Groups	.384	3	.128	2.389	.113
	Within Groups	.750	14	.054		
	Total	1.133	17			
During 2	Between Groups	.474	3	.158	1.815	.198
	Within Groups	1.044	12	.087		
	Total	1.518	15			
During 3	Between Groups	.281	2	.140	1.709	.235

	Within Groups	.739	9	.082		
	Total	1.020	11			
During 4	Between Groups	.095	1	.095	.861	.396
	Within Groups	.553	5	.111		
	Total	.649	6			
Post	Between Groups	.339	3	.113	2.357	.116
	Within Groups	.670	14	.048		
	Total	1.009	17			

Note.
[a]Degree of freedom

Table 16. NA values for every time measured.

		Sum of Squares	*df*[A]	Mean Square	*F*	Sig. (*p*)
Pre	Between Groups	2.110	3	.703	2.923	.071
	Within Groups	3.368	14	.241		
	Total	5.478	17			
During 1	Between Groups	.862	3	.287	1.450	.271
	Within Groups	2.776	14	.198		
	Total	3.638	17			
During 2	Between Groups	1.901	3	.634	2.759	.088
	Within Groups	2.756	12	.230		
	Total	4.658	15			
During 3	Between Groups	1.565	2	.783	3.317	.083
	Within Groups	2.124	9	.236		
	Total	3.689	11			
During 4	Between Groups	.440	1	.440	1.917	.225
	Within Groups	1.148	5	.230		
	Total	1.589	6			
Post	Between Groups	1.040	3	.347	1.973	.164
	Within Groups	2.460	14	.176		
	Total	3.500	17			

Note.
[a]Degrees of freedom

6.2.3 H&ES Questionnaire

A score for the H&ES questionnaire was calculated by summarizing each number given in the questionnaire. The data is presented in the following figure 26.

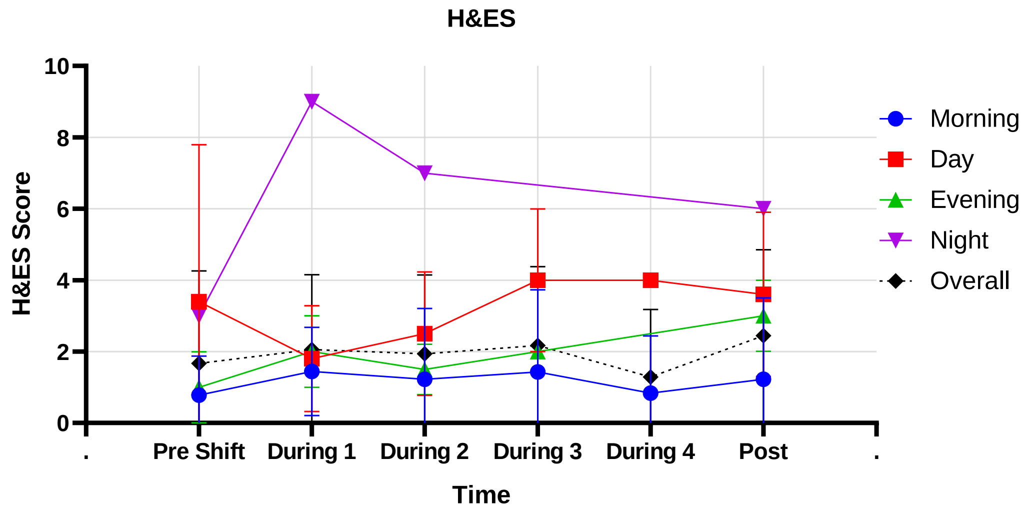


Figure 26. H&ES over time.

For investigating differences of the H&ES score depending on shift type, a one-way ANOVA was carried out. Levene test for variance homogeneity showed no significance, meaning that the variances are equal. Results are presented in the table 17 below.

Table 17. H&ES score differences between the shifts for every measurement.

		Sum of Squares	*df*[A]	Mean Square	*F*	Sig. (*p*)
Pre	Between Groups	25.244	3	8.415	1.327	.305
	Within Groups	88.756	14	6.340		
	Total	114.000	17			
During 1	Between Groups	51.922	3	17.307	**10.525****	.001
	Within Groups	23.022	14	1.644		
	Total	74.944	17			
During 2	Between Groups	31.882	3	10.627	3.106	.067
	Within Groups	41.056	12	3.421		
	Total	72.938	15			
During 3	Between Groups	13.952	2	6.976	1.581	.258
	Within Groups	39.714	9	4.413		
	Total	53.667	11			
During 4	Between Groups	8.595	1	8.595	3.349	.127
	Within Groups	12.833	5	2.567		
	Total	21.429	6			
Post	Between Groups	33.689	3	11.230	2.428	.109
	Within Groups	64.756	14	4.625		
	Total	98.444	17			

Note.
[a]Degrees of freedom
** *p* < .001

6.2.4 MSQ

The MSQ global data for every shift is presented in the table below. Furthermore, it was analysed for any significant differences between the shifts. The Levene test for variance homogeneity showed no significance, meaning that the variances are equal. A one-way ANOVA was carried out. No significant differences were found, $F(3,14) = 1.39$, $p = .286$ (Table 18).

Table 18. MSQ values.

	OVERALL		PER SHIFT							
			Morning		Day		Evening		Night	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
MSQ	71.33	18.88	76.56	6.81	73.60	7.60	52.00	45.01	71.00	- [a]

Note.
[a]data only from one participant due to a single shift measured.

Furthermore, a correlation analysis was conducted in order to detect correlative variables. The data is presented in the correlation matrix below (table 19).

Table 19. Correlation of selected variables with MSQ.

		AGE	MSQ SCORE	TIME GET UP	POST PA	POST NA	SHIFTTYPE
Age	Pearson Correlation		-.267	.236	.459	.440	**.524***
	Sig. (2-tailed)		.283	.361	.055	.068	.026
	N		18	17	18	18	18
MSQ	Pearson Correlation			-.038	-.026	-.177	-.349
	Sig. (2-tailed)			.885	.919	.482	.156
	N			17	18	18	18
Time Get Up	Pearson Correlation				**.551***	.126	**.848****
	Sig. (2-tailed)				.022	.631	.000
	N				17	17	17
Post PA	Pearson Correlation					**.774****	**.571***
	Sig. (2-tailed)					.000	.013
	N					18	18
Post NA	Pearson Correlation						.380
	Sig. (2-tailed)						.119
	N						18
Shifttype	Pearson Correlation						
	Sig. (2-tailed)						
	N						

Note.
* $p < .05$
** $p < .001$

6.2.5 ISA Workload

Due to significant differences between the workplaces, the ISA workload results over the entire course of the shifts are presented separately for every unit. Note, that no statistical calculations have been performed due to lack of variance within the data. Hence, all data is only presented for describing reasons.

6.2.5.1 EETU and EETN (2019)

The first figure 27 below indicates ISA values for both day shifts measured in EETU in 2019, while the second figure 28 below indicates ISA values for all six shifts measured in EETN on both days 2019.

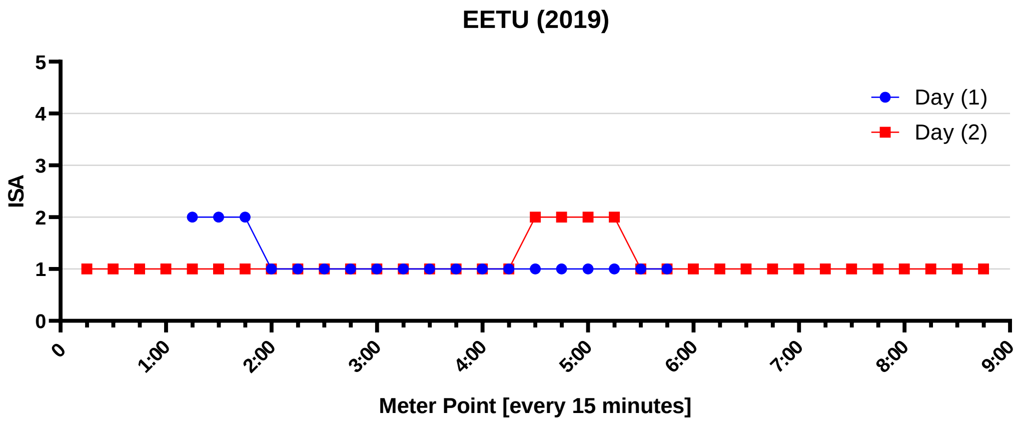


Figure 27. ISA EETU.

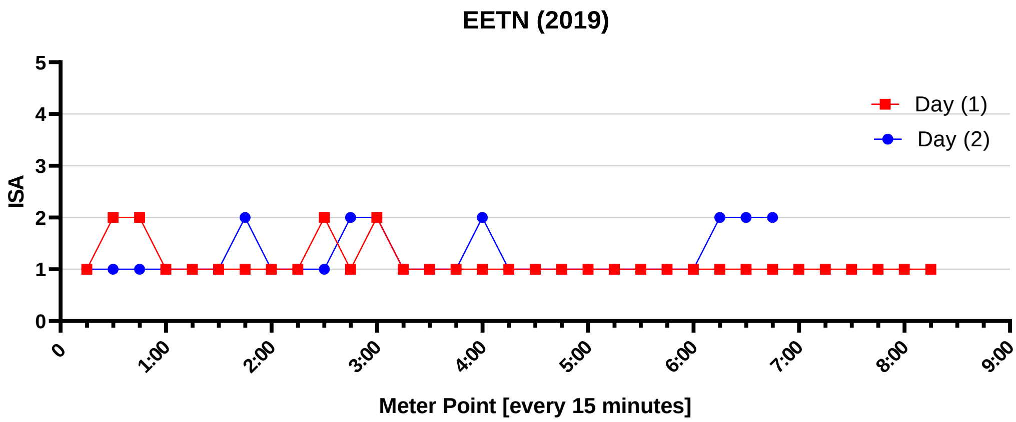


Figure 28. ISA EETN.

6.2.5.2 ESNQ (2020)

Due to technical issues in the ESNQ, only ISA measurements for the first day are available. The table 20 and figures 29-31 show ISA data in ESNQ.

Table 20. ISA values in ESNQ.

	PER SHIFT					
	Morning			Evening		
	M	*Median*	*Rel. Amount*	*M*	*Median*	*Rel. Amount*
ISA						
0	5.00	5.00	55.6%	4.83	4.50	60%
1	7.25	7.50	44.4%	3.75	3.00	40%
2	-	-	-	-	-	-
3	-	-	-	-	-	-
4	-	-	-	-	-	-
5	-	-	-	-	-	-

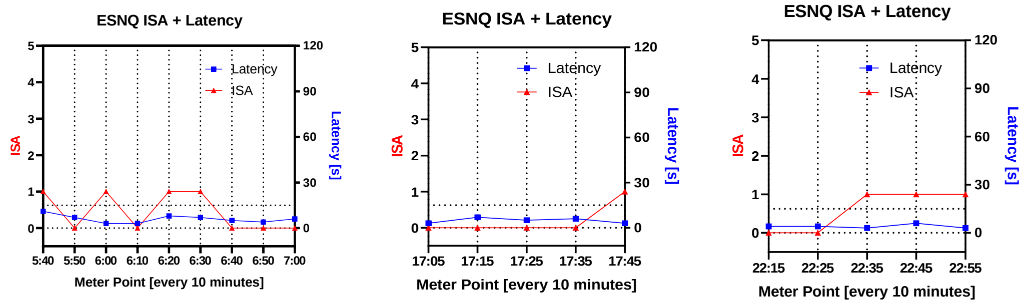


Figure 29-31. ISA ESNQ for the early morning (left), early evening (mid) and evening (right).

6.2.5.3 EETU and EETN (2020)

ISA data is not available.

6.2.6 PVT

The PVT requires a reaction as quick as possible whenever a cue is presented on the screen. To avoid prediction of the next cue by the participant, the inter trial intervals (ITI) were randomized between 3000ms and 8000ms.
A first visualisation of the data gathered revealed outliers (reaction time (RT) less than 200ms) and a software data saving problem, since ITI with more than 8000ms were saved. This was due to a missing indication in cases of a previous lapse which did not stop the ITI time. However, since the RT data is still valid is this data considered as well. Outliers with an RT <200ms were filtered out. From originally 2893 data points, 6 points were excluded. Hence, 2887 data points were taken for further analysis (Figure 32).

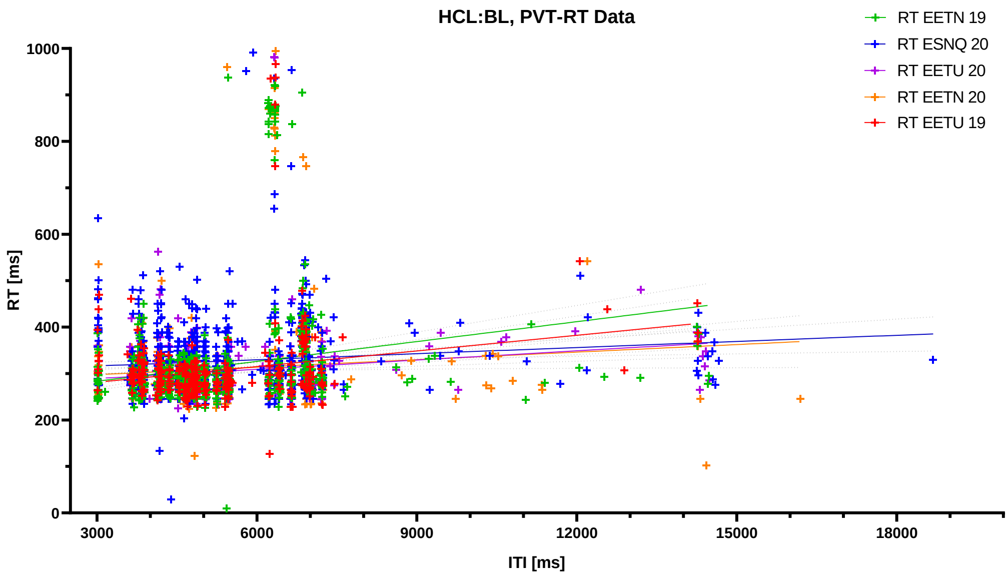


Figure 32. All gathered data points, including the outliers.

Note, that in both figures regressions grades indicate a positive correlation between RT and ITI. The data is presented in the table 21 below.

Table 21. PVT and ISI correlations.

Unit	*F*	*df*	Sig. (*p*)
EETU 2019	14.07	1, 309	.000
EETN 2019	30.49	1, 746	.000
ESNQ 2020	9.33	1, 910	.002
EETU 2020	15.73	1, 424	.000
EETU 2020	7.03	1, 488	.007
All	66.93	1, 2885	.000

The distribution of the data gathered is not following a normal distribution.

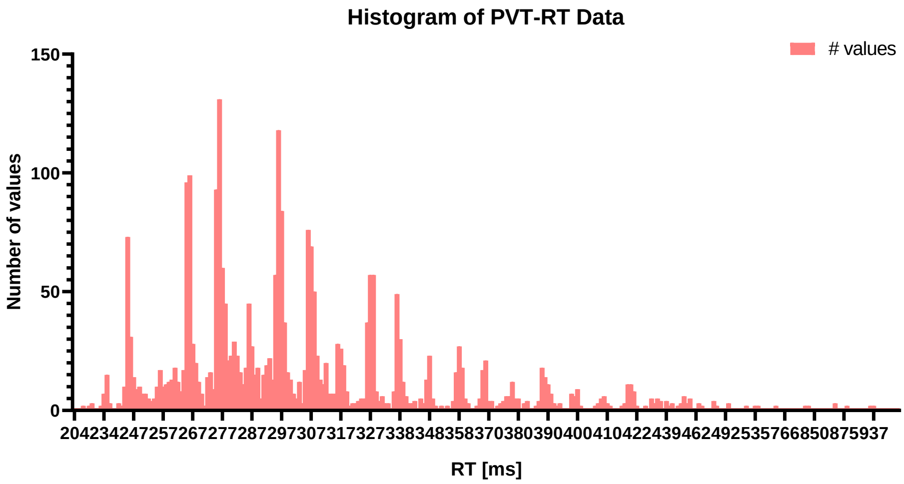


Figure 33. Histogram of PVT reaction time (RT) data.

The following PVT output variables were selected and calculated for all trials in a separate run: Mean RT, Mean 1/RT, Median 1/RT, Percentile 10%, Percentile 90%, Lapses and False Starts.

A correlation analysis showed significant correlations between shift length and mean rt ($r(16) = .515$, $p = .029$), mean 1/rt ($r(16) = -.592$, $p = .010$), median 1/rt ($r(16) = -.529$, $p = .024$), 10% percentile ($r(16) = -.604$, $p = .008$) and 90% percentile ($r(16) = -.504$, $p = .033$). No significant correlation between shift length and lapses ($r(16) = .005$, $p = .985$) as well as false starts ($r(16) = .039$, $p = .879$) could be found.

6.2.6.1 *Mixed ANOVA with repeated measures*

To investigate the effect of the test time and shift on PVT variables a series of mixed ANOVA with repeated measures for every output variable was conducted. As between-subjects factor the shift type was selected. Mauchly's test of sphericity revealed significance for mean RT (p = .007) and percentile 10 (p = .001).

Mean RT. A mixed ANOVA revealed no significant differences between the shifts and measurement times ($F(3.924, 18.310) = .313$, $p = .063$), Greenhouse-Geisser corrected. Post hoc tests using the Bonferroni correction revealed no significant differences between separate shifts and measurement times. Figure 34 depicts the data.

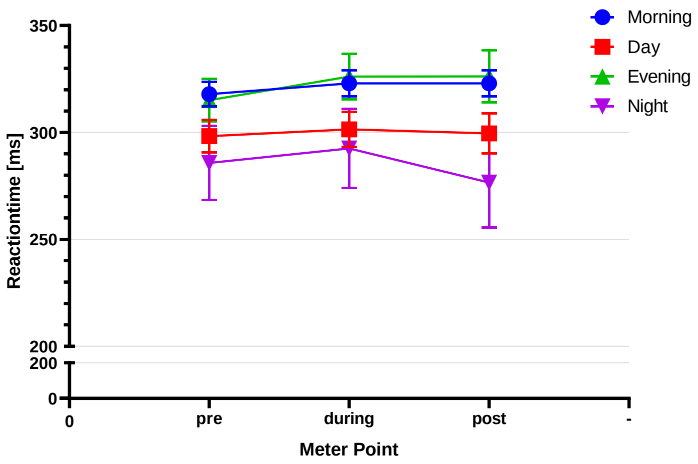


Figure 34. PVT reaction time data for all three meter points per shift.

Mean 1/RT. A mixed ANOVA revealed no significant differences between the shifts and measurement times ($F(5.181, 24.180) = .011$, $p = .201$), Greenhouse-Geisser corrected. Post hoc tests using the Bonferroni correction revealed no significant differences between separate shifts and measurement times.

Median 1/RT. A mixed ANOVA revealed no significant differences between the shifts and measurement times ($F(4.856, 22.664) = .031$, $p = .344$), Greenhouse-Geisser corrected. Post hoc tests using the Bonferroni correction revealed no significant differences between separate shifts and measurement times.

Percentile 10. A mixed ANOVA revealed no significant differences between the shifts and measurement times ($F(3.658, 17.070) = .128$, $p = .330$), Greenhouse-Geisser corrected. Post hoc tests using the Bonferroni correction revealed no significant differences between separate shifts and measurement times.

Percentile 90. A mixed ANOVA revealed no significant differences between the shifts and measurement times ($F(4.972, 23.201) = .021$, $p = .124$), Greenhouse-Geisser corrected.

Post hoc tests using the Bonferroni correction revealed no significant differences between separate shifts and measurement times.

Lapses. A mixed ANOVA revealed no significant differences between the shifts and measurement times (F(5.501, 25.673) = .152, p = .073), Greenhouse-Geisser corrected. Post hoc tests using the Bonferroni correction revealed no significant differences between separate shifts and measurement times.

False Starts. A mixed ANOVA revealed no significant differences between the shifts and measurement times (F(4.911, 22.917) = .265, p = .069), Greenhouse-Geisser corrected. Post hoc tests using the Bonferroni correction revealed no significant differences between separate shifts and measurement times.

6.2.6.2 *Regression Analysis*

Mean RT. A linear regression analysis was used to test if the shift length significantly predicted PVT outcome measures. The results of the regression indicate that shift length explained 35% of the variance (R^2 = .265, F(1,16)=5.772, p = .029). It was predicted, that shift length predicted the mean RT (β = .515, p = .029) (figure 35).

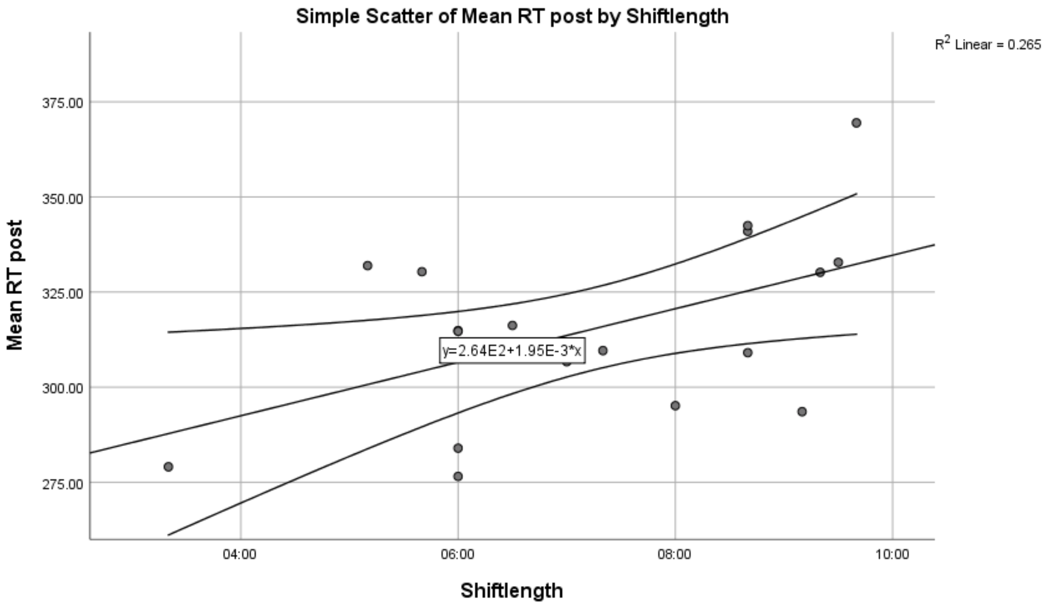


Figure 35. Regression analysis shows with longer shift length higher mean reaction times (mean).

Mean 1/RT. A linear regression analysis was used to test if the shift length significantly predicted PVT outcome measures. The results of the regression indicate that shift length explained 35% of the variance (R^2 = .350, F(1,16)=8.613, p = .010). It was predicted, that shift length predicted the mean 1/RT (β = -.592, p = .010) (figure 36).

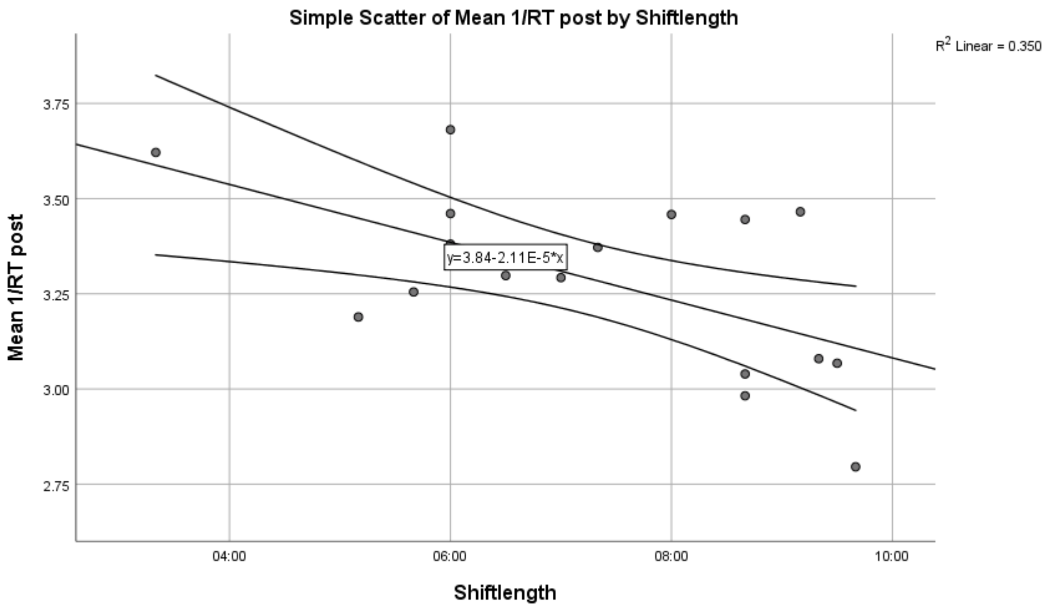


Figure 36. Regression analysis shows with longer shift length higher mean reaction times (1/RT).

6.2.6.3 Case Analysis – Nightshift

Since it was only possible to measure a single night shift, the data was calculated for presentation reasons only (figure 37-39).

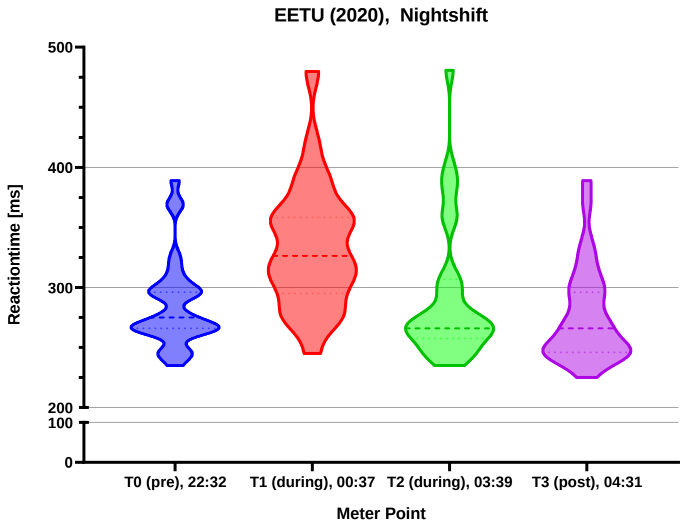


Figure 37. Reaction times in violin plot for night shift at EETU.

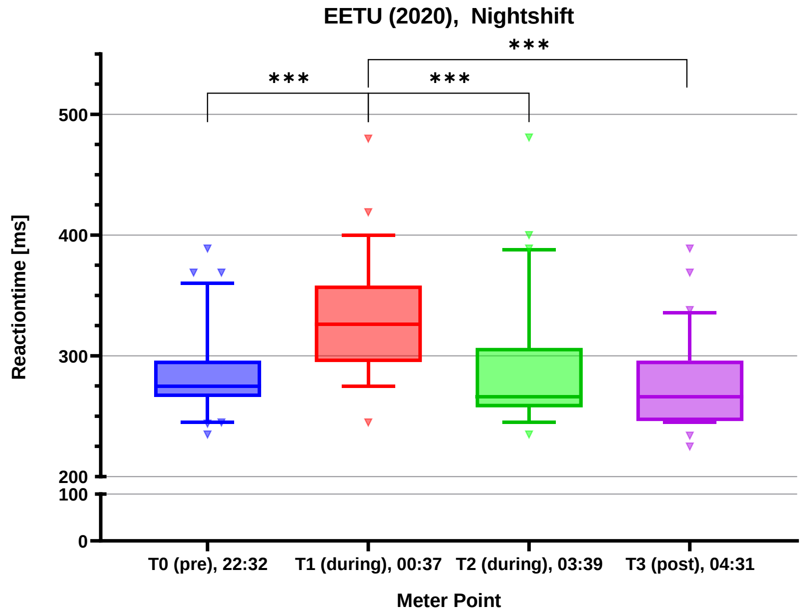


Figure 38. Reaction times show significant slower reaction times at T1 (Mann-Whitney-U-Test).

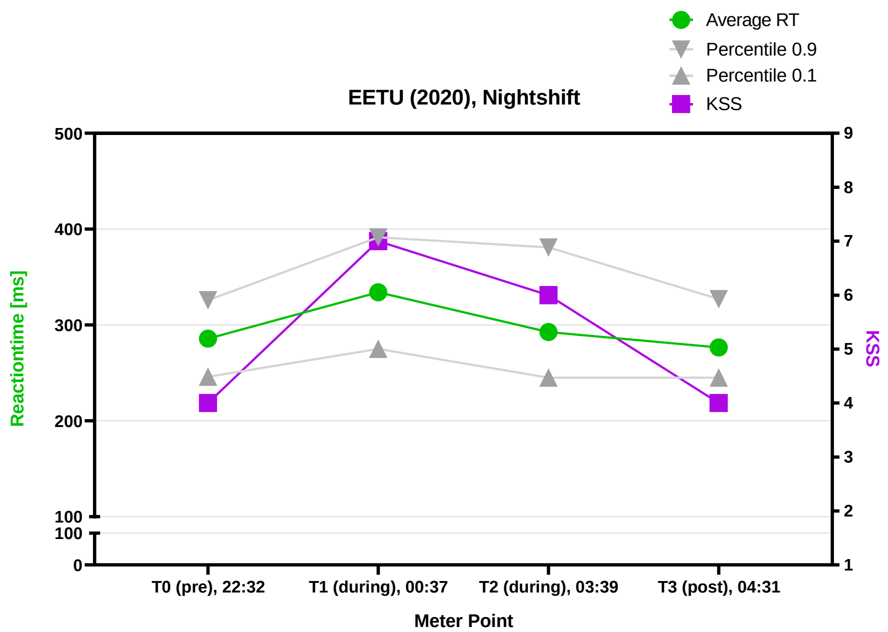


Figure 39. Mean reaction times for night shift at EETU.

6.2.7 KSS

To investigate the effect of the test time and shift on KSS s series of mixed ANOVA with repeated measures for every output variable was conducted. As between-subjects factor the shift type was selected. Mauchly's test of sphericity revealed no significance for KSS values. The mixed ANOVA revealed no significant differences between the shifts and measurement times (F(4.380, 18.980) = 1.180, p = .214), Greenhouse-Geisser corrected. Post hoc tests using the Bonferroni correction revealed no significant differences between separate shifts and measurement times (figure 40).

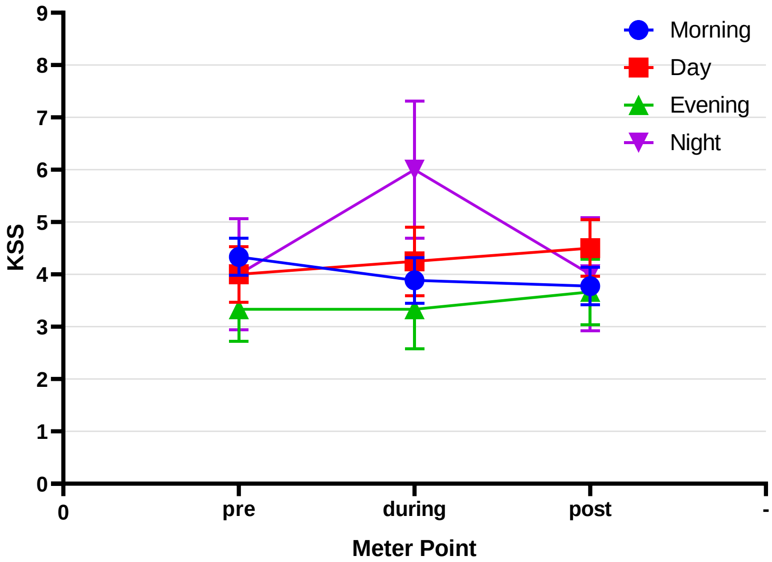


Figure 40. Mean KSS values per shift and over time.

6.2.8 Lighting Sensor Wrist Band

6.2.8.1 EETU 2019

The results of the shift measurements at EETU in 2019 are depicted in figure below.

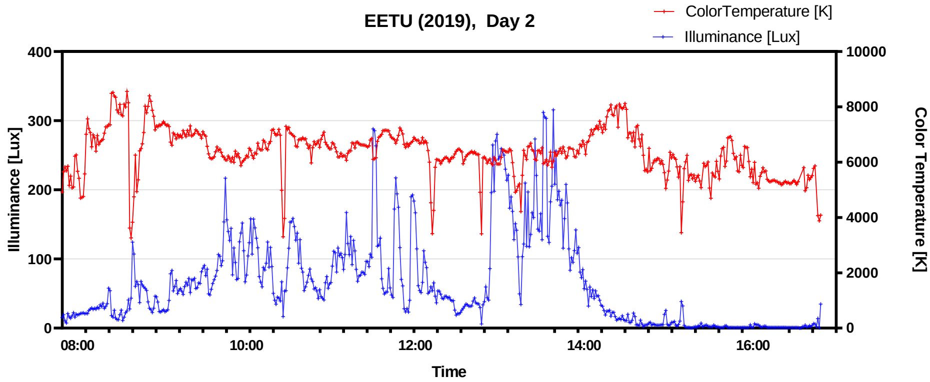


Figure 41. Illuminance and colour temperature in EETU (2019).

6.2.8.2 EETN 2019

The results of the shift measurements at EETN in 2020, day 1 and day 2, are depicted in figures below.

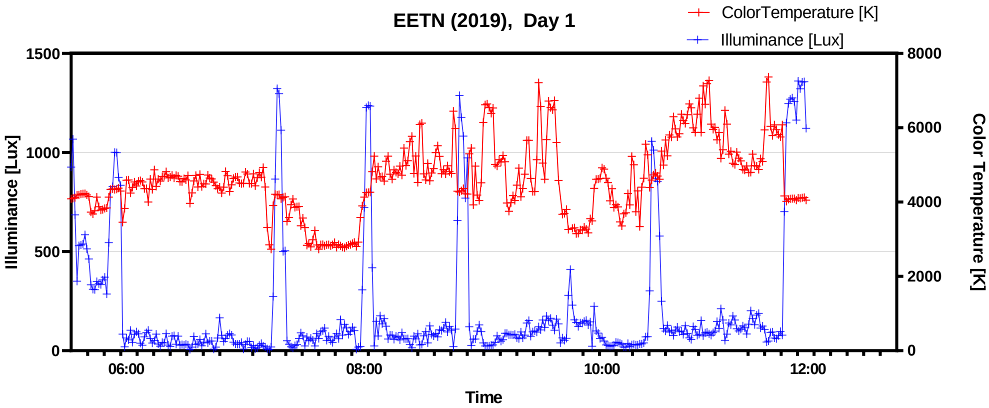


Figure 42. Illuminance and colour temperature in EETN, day 1 (2019).

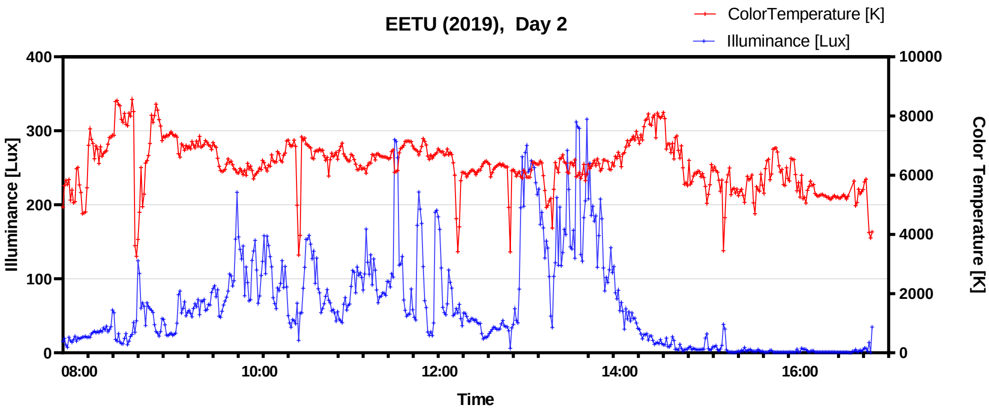


Figure 42. Illuminance and colour temperature in EETN, day 2 (2019).

6.2.8.3 ESNQ 2020

The results of the shift measurements at ESNQ in 2020, morning and evening shift, are depicted in figures below.

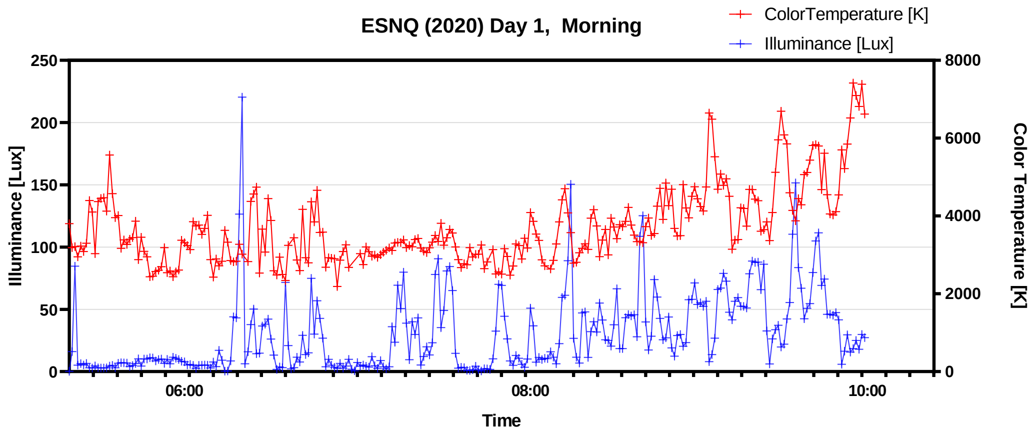


Figure 43. Illuminance and colour temperature in ESNQ, morning (2020).

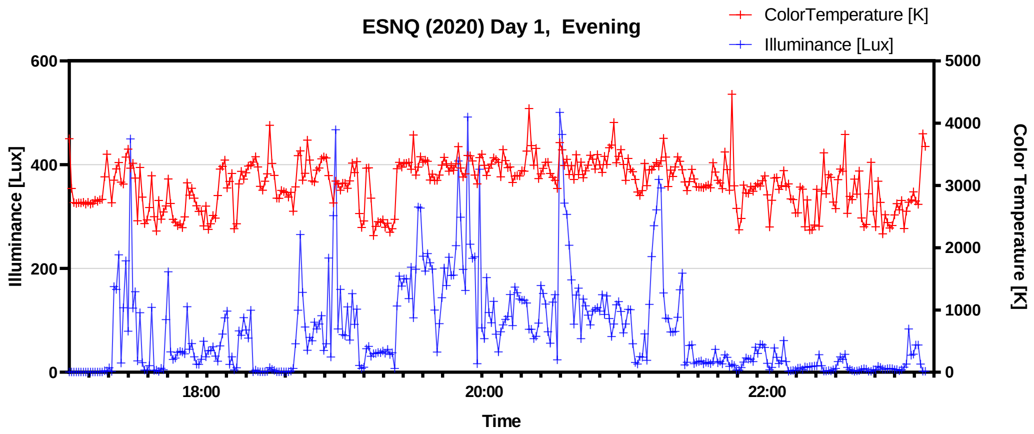


Figure 44. Illuminance and colour temperature in ESNQ, evening (2020).

6.2.8.4 EETU 2020

The results of the shift measurements at EETU in 2020, day 1, day 2 and nightshift, are depicted in figure below.

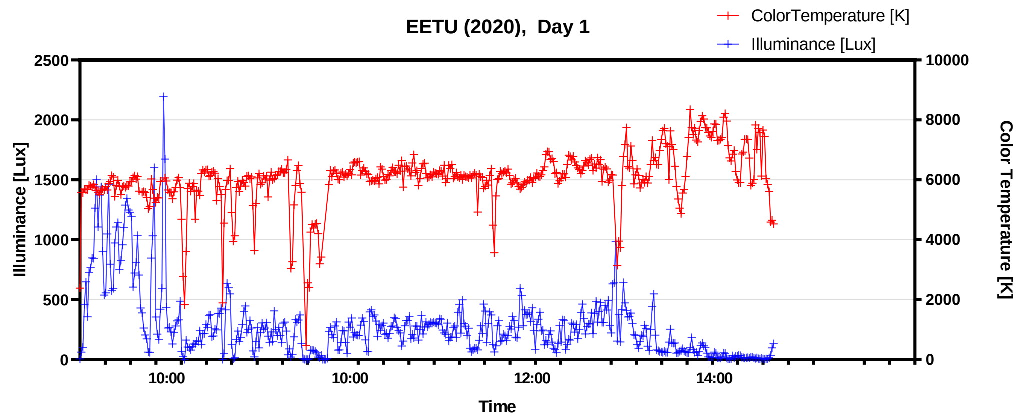


Figure 45. Illuminance and colour temperature in EETU, day 1 (2020).

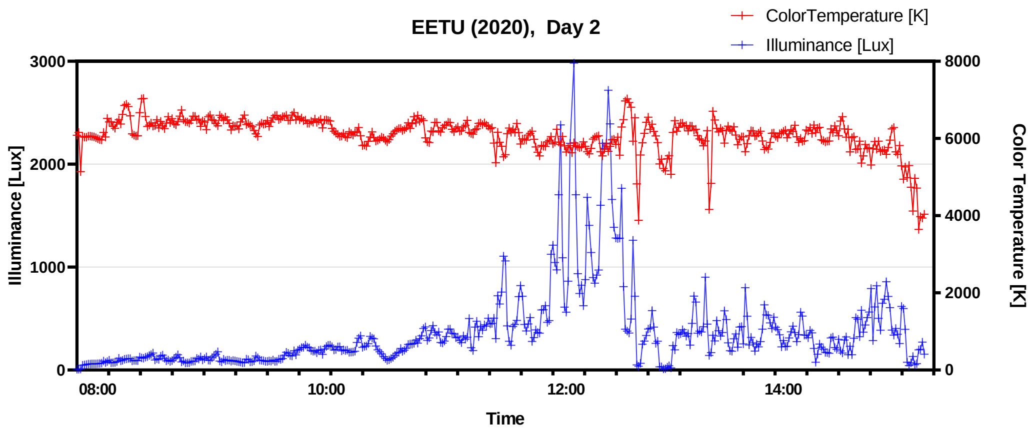


Figure 46. Illuminance and colour temperature in EETU, day 2 (2020).

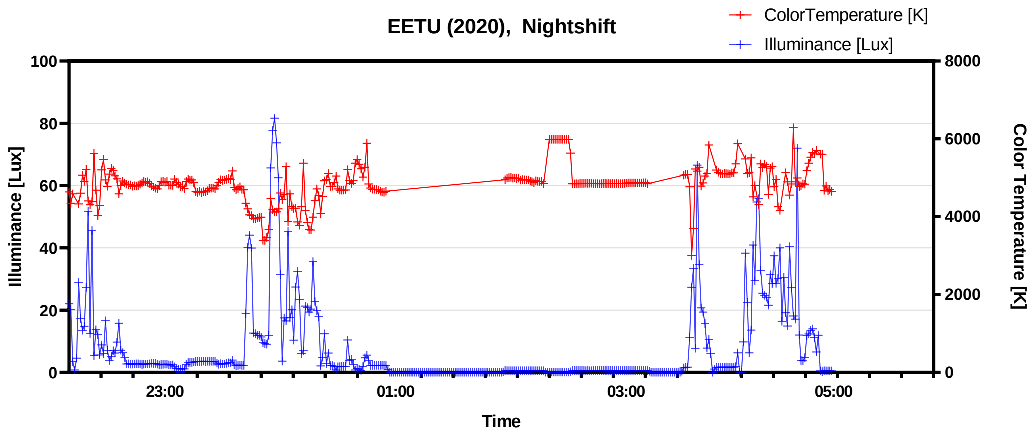


Figure 47. Illuminance and colour temperature in EETU, night shift (2020).

6.2.8.5 EETN 2020

The results of the shift measurements at EETN in 2020 are depicted in figure below.

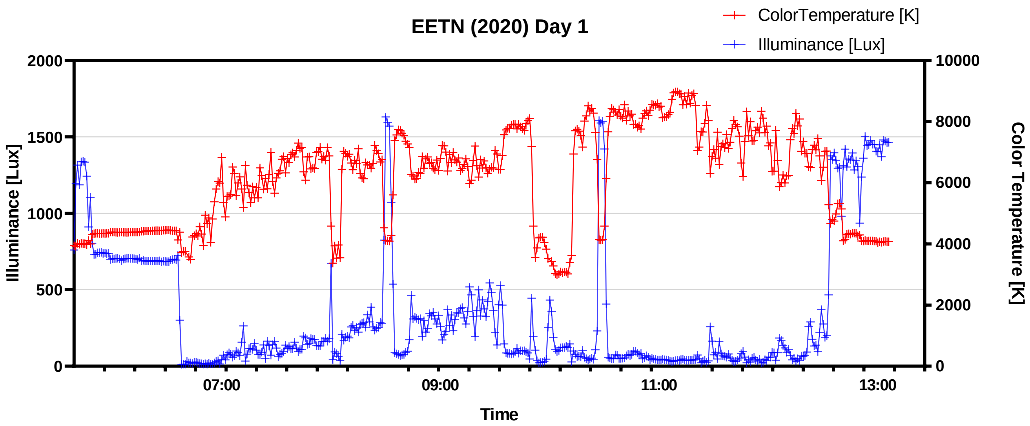


Figure 48. Illuminance and colour temperature in EETN, day 1 (2020).

6.3 Discussion

Study 3 measured fatigue and performance related variables in a field study setting in air traffic controllers in Estonia and Sweden. For that purpose, measurements took place at three different airports in conventional tower workplaces. A total of 18 shifts were taken into analysis. Morning, day, evening and a single night shift were observed.

The analysis of sleep behavioural data revealed least prior shift sleep for night shifts, however, the result bases only on one participant since only a single night shift was measured. The average of sleep prior a shift was at around 7 hours, which can be rated as a good and sufficient sleep duration. Sleep duration is depending on individual variables, but a minimum of 6 hours is rated as sufficient for the most humans. Even for morning shifts did we see 6.5 hours of sleep, which reflects a good adaptation by the controllers to a morning shift. Usually workers get less sleep prior a morning shift due to the need to fall asleep earlier, which is often seen as complicated to achieve.

The PANAS affect scale showed no significant differences between all shift types and times measured. However, on a descriptive level did we find higher negative affect values for evening shifts than on morning shifts. This could be due to fatigue that was emerging later at the evening or simply that in our sample morning shifts are preferred by the participating air traffic controller. Contrastingly, we found a positive correlation between get up time and positive affect. This means, that the earlier participants had to get up the less positive emotions were present. Work motivation was reduced for evening shifts as well, otherwise identified we no differences between shift types.

Regarding eye strain did we found no differences over the time in the morning shift. Between the shifts we could identify a spreading starting at the second half of the shifts. While morning shift H&ES score was rather low, day and evening shift scores showed increasing values over time. A significant higher eye strain could be detected for night shift, especially shortly before sleep rest. This can be due to increasing sleepiness which manifest by physiological eye strain.

Workload was measured by means of the ISA every 15 minutes. At the tower in Tartu measured we the ISA verbally and gathered values ranging between 1 and 2, indicating less or little work to do. Interestingly, at the more task load featuring tower in Tallinn did we received the same data range. This indicates the habituation effect of the controllers to the traffic amount given at a workplace. While on aircraft at a time can be rated as 2 in Tartu, it would be rated as 1 in Tallinn. This result demonstrates that a comparison of ISA values between different units is not possible as the baseline is different. In Kiruna did we apply a computerized form of the ISA. The controller was asked to answer the ISA value on buttons after an auditive tone. This enabled us to gather also answer latency values which can act as indicator for workload as well (higher latency means higher workload). We found variance in the data but not following a system. Hence, we conclude that potentially more influencing factors were present. For instance, when low traffic volume was present did the controllers move away from the primary working position to a secondary computer to perform other tasks. When then an ISA prompt was present, it took time for the controller to come back to the work position to press the button. A potential solution could be a software running on a smartwatch that is attached to the wrist of the participating controller. The influence on the latency values due to movement at the workplace could so be reduced.

The reaction time task PVT was conducted every two hours under all measured shifts. However, for making comparisons between all shifts with variable shift lengths possible, only pre, mid and post PVT runs were analysed. We identified that shift length was correlated with lowered reaction times, indicating the fatigue effect at a later stage in the shift. Overall, could we find an increase of the reaction time over time, even marginal differences indicate increase in fatigue. Usually quicker reaction times would be expected due to training effects, which we did not observe in the data available. The night shift case study revealed faster reaction times at the end of the shift. This is counter intuitive, since after working through the night and receiving less sleep higher fatigue values would be expected. This could be due to the sleep break, which was sufficient for the controller to recover alertness. The other observation did not reveal variance differences between the shifts, which was against our hypotheses. A reason could be the lack of samples and shifts that were measured.

The gathered KSS values follow roughly the PVT figures, however, the morning shift was rated better even though that reaction time was increased. This fact shows that the self-assessment of fatigue is not quality sufficient rated by the controllers. The separate case analysis performed on the night shift did we found significant slower reaction times (measured at 1:30am local). That was shortly before a sleep brake under the night shift. Interestingly did the KSS values follow accurately the PVT reaction time figures. This can be due to the fact, that human can rate sleepiness accurate again when they are at high sleepiness levels.

Overall, did we perceive highly motivated participants in our study. We assume, that motivation for participation influences the data, since we measured only volunteering participants. We were not able to establish a lab setting at every tower workplace, hence, we expect more confounding variables that might impacted on the results. Distraction due to operational tasks or colleagues around was minimised but could not be excluded. A standardized measurement protocol was applied to support quality data gathering.

7 INTEGRATION AND OUTLOOK

This research project focused on drawing connections between lighting characteristics at tower workplace and performance as well as alertness management. Latest research suggests significant connections between lighting and performance, fatigue and health (Cajochen, 2007; Najjar et al., 2014). Safety critical domains like nuclear, railroad or air traffic control require consistent and persistent performance by the human in the system. In air traffic control, the change process from conventional to remote tower is in progress. While safety and economic benefits are expected, overall lighting exposition of the controller will likely change. A careful and slow development is necessary, as latest evidence suggests a significant influence on performance, fatigue, and health due to lighting. The future remote tower workplace features the chance to install systematic influencing lighting – for instance, an HCL concept.

It was very unfortunate, that a change of the planned and scheduled measurements was necessary. The impact of Covid-19 limited the overall results of this research work, however, given the complicated circumstances interesting data as well as future docking points for research questions were identified.

In study 1 we developed an HCL concept, based on literature and theoretical evidence. We identified separate scenes with dynamic changing light colours and illuminances. Main driver should be the actual local time, however, light impulses to improve alertness on the spot should be available when sleepiness is self-detected or work-related tasks require increased alertness. Moreover, not only the workplace but also the break room and halls should feature a lighting concept. Additionally, individual designed HCL based on chronotype and rooster should be developed in future research works. The challenge could be here, to select only relevant factors as many aspects influence human fatigue.

A demand for enhanced lighting at the tower workplace was demonstrated in study 2. Here we investigated lighting situations at conventional but also remote tower workplaces. As the conventional tower workplaces lighting is strongly impacted by daylength, location and weather, we measured rather different values of lighting. With more measurements a higher variability of lighting values would be expected. However, the remote tower workplaces lightings were rather similar. We identified overall reduced illuminances and a blueish-colour peak colour temperature, most probably emitted by the visual presentation screens. While blue-enriched light can act supportive for alertness, the bluish part of the lighting should be avoided during night-time as circadian rhythm could be desynchronized. In order to quantify the effect a measurement also during evening hours should be conducted, which includes also melatonin samples and performance ratings.

The results could then be linked to the baseline results gathered in study 3. In this field measurement did we study fatigue and performance ratings in various shifts across conventional towers in Estonia and Sweden. Overall, did we see less fatigue effects than expected. However, especially work in the evening and night-time was linked to increased fatigue ratings as well. Taken together, we see a demand of HCL especially during evenings and night work. Additionally, must be noted, that the project misses human performance and fatigue data gathered in the remote tower workplace. This is a necessary supplement for putting conventional results into perspective.

Finally, it must be stated, that before installing a HCL concept in the remote tower a separate study should be carried out. That study should aim on delivering actual evidence and data if and how big the alertness benefit is. Moreover, other fatigue related aspects like break time, break behaviour, workload management, shift styles and rostering should be taken care of as well. Lighting and HCL is beneficial, however only when embedded in a systematic and well thoughtful holistic fatigue concept.

A holistic fatigue concept for air traffic control will be developed and tested by the upcoming *HCL:Aurora* study, which is planned to start in 2021.

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APPENDIX

The study material and questionnaires are available upon request.