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The use of Eye Tracking Technology in Maritime High-Speed Craft Navigation

Thesis for the Degree of Philosophiae Doctor

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Abstract

The change from paper charts to Electronic Navigational Charts (ENC) has been regarded as a paradigm shift in maritime navigation. The traditional navigator skills have been challenged with the introduction of integrated navigation systems, but as we have learned from the possibilities and limitations of technology, it has become clear that the craftsmanship of navigation is still needed. There have been discussions regarding the introduction of technology at the ship bridge, and it has become clear that it induces both new possibilities and challenges.

The navigator has always had an important role in conducting safe navigation, and the main job related to navigation has been to find and fix the position to keep the vessel safe. With the introduction of electronic navigation, the vessel's position is provided in more-or-less real time. The navigator's role has changed from finding and fixing the position to monitoring the position presented in the navigation system. This has been an important move for the safety at sea, but new challenges such as ECDIS-assisted grounding have emerged. This led to a discussion of the role of the navigator in integrity monitoring of the navigation system, which further demands a certain level of understanding of the sensors and systems in use (system awareness).

The introduction of technology has not only had a positive impact on the navigation task, and the literature reviews highlights that some electronic navigation aids can be inefficient. The literature review also highlights the need for Human-Centred Design (HCD) as a process to design or redesign equipment to the navigator's needs.

The Royal Norwegian Navy (RNoN) has been pursuing the state of electronic navigation, which primarily means no use of paper charts, since 2014. Along the way, several interesting observations have been made. This mainly involves the trust in the presentation of the position in the navigation system, and the level of system awareness of the navigators. The Navigation Simulators at the RNoN Navigation Competence Centre (NCC) has been increasingly used by the operational crews and in training of the new navigators, and there have been clear indications of the effectiveness of using navigation simulators. Especially the Skjold-Class Bridge Navigation Simulator has been extensively used by the Corvette service, and the feedback has been positive. There has been identified a need for a better understanding of these assertions.

Eye Tracking Technology has rapidly evolved the last ten years, and there has been an increased interest towards the technology within the domain of Human-Computer Interaction. With the introduction of Eye Tracking Glasses (ETGs), data collection of participants' eye movements has been made possible outside the laboratory. There has not been much use of ETGs in the maritime domain, but in the few studies eye tracking technology has been used; the value of such data has been highlighted. This thesis has used ETGs to better understand the work of the High-Speed Craft (HSC) navigator, by collecting eye tracking data both in field studies and in simulator studies. The aim of the data collection has been to gain a better understanding of the visual attention of the HSC navigator, and to analyse if the eye tracking data can be used in a maritime usability study.

Two different ETGs has been used in the data collection, and the pros and cons of these are presented. Three primary data collections have been completed, and a total of more than 11.5 hours of eye tracking data has been analysed and evaluated. The data analysis has resulted in a deeper knowledge of the visual attention of the HSC navigator, having gained insight into the use of eye tracking data in a design review of the Skjold-class Corvettes.

The visual attention of the HSC navigator has been compared in a field- and simulator study, and there are clear indications of the simulators providing similar training outcome as live navigation training. However, there are differences in the numerosity measurements that needs to be accounted for when designing simulator navigation exercises.

The numerosity measurements and visualizations maps have been used to conduct a maritime usability study of the Skjold-class Corvettes, and the findings and results have been implemented in a Mid-Life Update (MLU) of the navigation bridge of the Corvettes. The eye tracking data analysis shows clear indications of time-stealing displays, and the need for the HSC navigator's attention to be addressed to the surroundings of the vessel has been highlighted. This resulted in a design review of the bridge layout of the Skjold-Class Corvette, together with a new High-Speed Craft Route Monitor Window (HSCRMW) Graphical User Interface (GUI). The findings from the thesis have been implemented on board the Skjold-class Corvettes, and will be adapted in the RNoN fleet. When validating the new bridge layout and design by collecting the third eye tracking data set, the findings highlights the importance of familiarisation with new software.

Establishment of the Areas of Interest (AOIs) for the HSC Navigator has provided valuable insight into the visual attention of the navigator, and the thesis presents a suggested Scan Pattern for the Maritime Navigator based on these findings. The Navigator's Situation Awareness (SA) model is presented and discussed, and the importance of system awareness as an inherent part of SA is underlined.

The use of ETGs to collect eye tracking data in maritime HSC navigation to better understand the navigation task of the HSC navigator has shown good potential. When utilizing eye tracking data in maritime usability studies, the importance of supporting data, such as qualitative data, for the eye tracking data is emphasised. The use of the HCD-process in maritime usability studies when utilizing eye tracking data is supported.

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List of Publications

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Paper 2: Hareide, O.S., Ostnes, R. (2017), "Maritime Usability Study by Analysing Eye Tracking Data", *The Journal of Navigation*, 70(5), 927-943. DOI: https://doi.org/10.1017/S0373463317000182

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Abbreviations

ABC	Achieving Breakthrough in research through Collaboration
AIS	Automatic Identification System
ANOVA	Analysis of Variance
AOI	Area Of Interest
AR	Augmented Reality
BRM	Bridge Resource Management
C	Contributions
CATZOC	Category of Zone of Confidence
CG	Correspondence Group
CO	Commanding Officer
COTS	Commercial Of The Shelf
CSM	Conventional Sailing Mode
CTV	Crew Transfer Vessel
DP	Dynamic Positioning
DR	Deduced Reckoning (commonly referred to as Dead Reckoning)
DSA	Distributed Situation Awareness
EBL	Electronic Bearing Line
ECDIS	Electronic Chart Display and Information System
ECS	Electronic Chart System
ENC	Electronic Navigational Chart
EP	Estimated Positioning
EPFS	Electronic Position Fixing System
ESS	Echo Sounding System
ETA	Estimated Time of Arrival
ETG	Eye Tracking Glasses
FOV	Field Of View
FPB	Fast Patrol Boat
GLONASS	GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (GNSS)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GT	Gross Tonnage
GUI	Graphical User Interface
HCD	Human-Centred Design
HCI	Human Computer Interaction
HCS	Heading Control System
HDT	Head Down Time
HNoMS	His Norwegian Majesty's Ship
HSC	High-Speed Craft
HSCRMW	High-Speed Craft Route Monitor Window
IBS	Integrated Bridge System
ICT	Information and Communication Technology
IFE	Institute for Energy Technology
IFR	Instrument Flight Rules
IMO	International Maritime Organization
INS	Integrated Navigation System
IS	Information System
ISO	International Organization for Standardisation
kn	Knots

M-AR	Maritime Augmented Reality
m/s	Meters per second
MCS	Maritime Cyber Security
MLU	Mid Life Update
ms	Milliseconds
MSA	Maritime Situation Awareness
MSC	Maritime Safety Committee (IMO)
NavSim	Navigation Simulator
NAVTEX	Navigational Telex
NCC	Navigation Competence Centre
NCSR	IMO Sub-Committee on Navigation, Communications and Search and Rescue
nm	Nautical Mile (1852 meter)
OBD	Optical Bearing Device
OEM	Original Equipment Manufacturer
OOW	Officer Of the Watch
P	Paper
PN	Portuguese Navy
PSV	Platform Support Vessel
Q	Quarterly
RADAR	Radio Detection And Ranging
RIB	Rigid Inflatable Boat
RMS	Root Mean Square
RNC	Raster Navigational Chart
RNoN	Royal Norwegian Navy
RNoNA	Royal Norwegian Naval Academy
RQ	Research Question
RV	Rescue Vessel
SA	Situation Awareness
SDME	Speed and Distance Measurement Equipment
SED	Science, Engineering and Design
SES	Surface Effect Ship
SINT	Sensor Integrator
SME	Subject Matter Expert
SMI	SensoMotoric Instruments
SOG	Speed Over Ground
SOP	Standard Operating Procedure
STCW	Standards of Training, Certification and Watch keeping for Seafarers
STW	Speed Through Water
t	Metric ton
T/P	Temporary and Preliminary Notices
TCS	Track Control System
UN	United Nations
UT	User Testing
VFR	Visual Flight Rules
VR	Virtual Reality
VSM	Visual Sailing Mode
WOP	Wheel Over Point
XO	Executive Officer
XTD	Cross Track Deviation

Terms

Navigation: The process of monitoring and controlling the movement of a craft or vessel from one place to another.

Electronic Navigation: Navigation conducted with the use of electronic aids or instruments.

High-Speed Craft (HSC): Mathematical definition in the HSC Code, generalizable to any vessel operating in speeds above 20 knots.

HSC Navigation: The process of monitoring and controlling the movement of a craft, with speeds above 20 knots, from one place to another.

Eye Tracking Technology: A sensor technology that enables a device to detect and track the features of the eyes and their movements.

Eye Tracking Glasses (ETGs): Sensor technology, mounted in a pair of glasses, which detect and track the features of the eyes and their movements.

Content

1. Introduction

“Marine navigation blends both science and art. A good navigator constantly thinks strategically, operationally, and tactically. He plans each voyage carefully. As it proceeds, he gathers navigational information from a variety of sources, evaluates this information, and determines his ship’s position. He then compares that position with his voyage plan, his operational commitments, and his predetermined “dead reckoning” position. A good navigator anticipates dangerous situations well before they arise, and always stays “ahead of the vessel.” He is ready for navigational emergencies at any time. He is increasingly a manager of a variety of resources--electronic, mechanical, and human. Navigation methods and techniques vary with the type of vessel, the conditions, and the navigator’s experience. The navigator uses the methods and techniques best suited to the vessel, its equipment, and conditions at hand.

Some important elements of successful navigation cannot be acquired from any book or instructor. The science of navigation can be taught, but the art of navigation must be developed from experience” (1, p. 12).

The craftsmanship of marine navigation is described by Nathaniel Bowditch in the book The American Practical Navigator, first published in 1802. Maritime navigation has a long history, and the use of the oceans for transportation has had great importance for mankind.

The different types of navigation has evolved with time, and are today in general divided into (1):

1. *Deduced Reckoning* (DR, commonly referred to as Dead Reckoning). The navigator deduces the position by advancing a known position for course and distances. When correcting the DR position for leeway, current and steering error it results in *Estimated Positioning* (EP).
2. *Piloting* is known to involve navigation in restricted waters, where there is a need for frequent or constant determination of position. Pilotage will be conducted in demanding littoral waters.
3. *Celestial navigation* where the navigators makes use of celestial measurements with a sextant to compute the position.
4. *Radio navigation* using radio waves to determine the position.
5. *Radar navigation* where electromagnetic waves are used to determine the distance from or bearing to object whose position is known. This process is separate from the use of radar in collision avoidance.
6. *Satellite navigation* which uses radio signals from satellites for determining the position. These systems are known as Global Navigation Satellite System (GNSS), where the Global Positioning System (GPS) is the system controlled by the United States of America Department of Defence, and most commonly used (2).

The work as a maritime navigator has evolved with the increased use of Information and Communication Technology (ICT). A modern ship bridge consists of several displays, and most modern vessels are commissioned with an Integrated Navigation System (INS). The International Maritime Organization (IMO) recommends that all governments ensure that INS is installed on vessels in accordance with the Revised Performance Standards for Integrated Navigation Systems (3).

Electronic Navigation means navigation conducted with the use of electronic aids or instruments (4), which relies on technology powered by electricity. Methods of electronic navigation include radio-, radar- and satellite navigation. Electronic navigation also implies a transformation from paper charts to digital charts and displays, adhering to the Revised Performance Standards for Electronic Chart Display and Information Systems (ECDIS) on most vessels (5). There are several reasons for moving from paper-chart to electronic charts, and the highlighted factors are (6):

1. The contribution to safer navigation
2. Vessels position is continuously updated (with the use of e.g. GPS)
3. Minimize the risk of human error (plotting of position)
4. Chart corrections carried out without risk of errors
5. Improved SA for the Officer of the Watch (OOW)
6. Fast and easy passage planning
7. New charts/cells (ENCs) available instantly (if access to internet)
8. Modern vessels and bridges facilitate for a better working environment and could thus imply a lower turnover rate on employees.

Figure 1: Integrated Navigation System on board RNoN training vessel (courtesy of RNoN)

An example of an INS is shown in Figure 1, but the complexity of such a system is first understood when looking at the schematics of the system. The schematics of the INS in Figure 1 is shown in Figure 2.

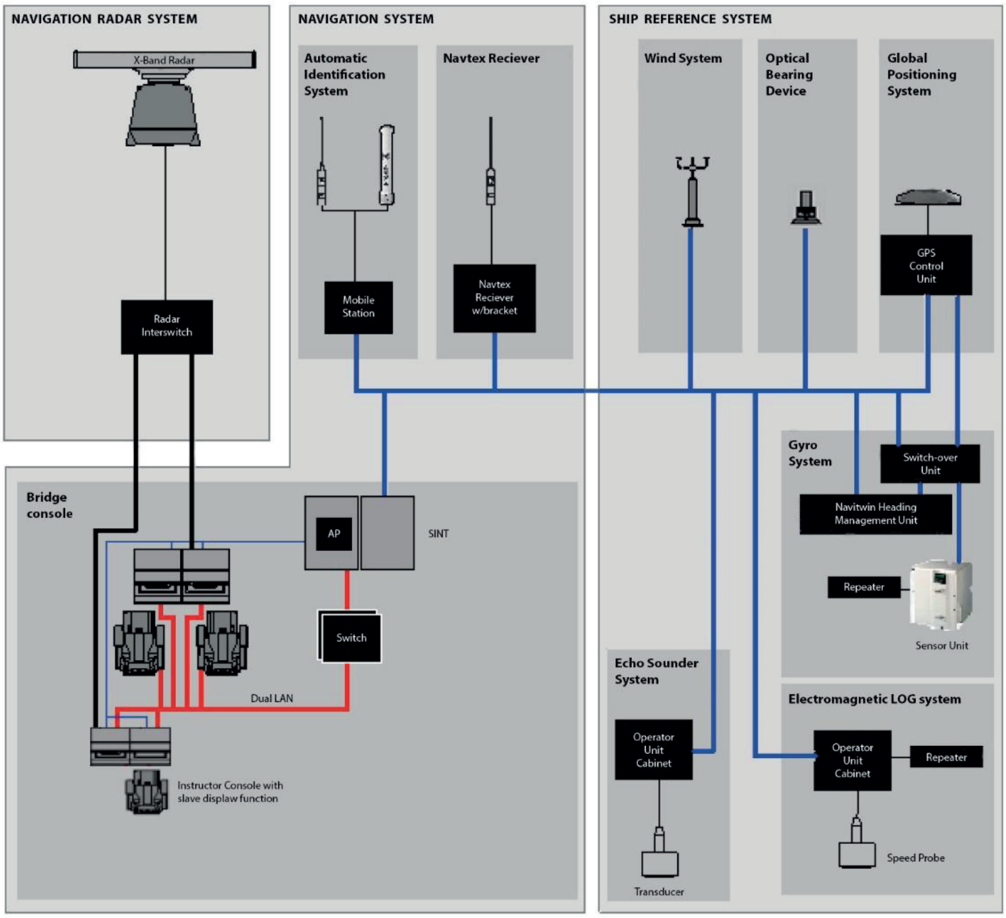

Figure 2: Schematic of INS on board RNoN training vessel (courtesy of RNoN)

As shown in Figure 2, there are several navigation sensors and systems networked for the integration of the information presented to the navigator on a display. The most commonly used sensors and systems are (3):

- Electronic Position Fixing System (EPFS) (e.g. GNSS as GPS or Galileo)
- Heading Control System (HCS) (e.g. Gyro)
- Depth sensor (Echo Sounding System, ESS)
- Speed and Distance Measurement Equipment (SDME) (e.g. Electromagnetic Log)
- Collision avoidance systems (e.g. Radar and AIS)
- Route planning and monitoring systems (e.g. ECDIS or Electronic Chart System (ECS))
- Track Control System (TCS) (e.g. Autopilot)
- Navigation information and weather messages (e.g. Navigational Telex (Navtex))
- Support systems, such as wind sensors and Optical Bearing Devices (OBD).

The modern navigation systems is arguably a complex system as information overload is endemic (7). Sensors are interconnected in systems, and information is integrated and presented to the navigator (8). Each of the sensors have possibilities and limitations, and when integrating the information through a sensor integrator (SINT), filtering is used for the presentation of the best information for the navigator (9). It is therefore imperative that the navigator has knowledge of each of the sensors and systems which are interconnected in the navigation system in use, in order to obtain a high degree of system awareness to facilitate proper integrity monitoring (8).

In parts of the maritime community there has been a concern about the amount of displays on a vessel's bridge, especially when it comes to enhancing the SA of the navigator (10-12). The concern is related to the craftsmanship of navigation, and the possible decay of this when introducing electronic navigation. Traditionally, the work of the navigator consisted of finding and fixing the position of the vessel on a paper chart. With the introduction of electronic aids which provides an automatic and continuous track of the vessel's position, the navigator is monitoring the position presented. GNSS such as the GPS, Glonass, Beidou and Galileo provides the navigator with almost real-time positioning of the vessel (2), but the system is also vulnerable towards signal interference (13). There are several known examples where signal interference on GNSS frequencies hampers the navigator's SA (14, 15), which highlights the importance of traditional navigation craftsmanship.

The performance demands for the High-Speed Craft (HSC) navigator are high, due to the complexity of the operations and systems in use. The purpose of the INS is to support the navigators SA, enhancing the safety of navigation by providing integrated and augmented functions to avoid hazards (3). The HSC navigator has less time to conduct the navigation task, due to the increase in speed. Thus the demands for quality in performance solving the navigation task, regarding speed, accuracy and attention demands are high. The navigator's vision is the primary sensor for information collection for the navigation task, and the visual search of the navigator is essential (16). Research into the visual search pattern of the navigator has primarily been done within the aviation domain, and the maritime domain could learn from the lessons learned in aviation (17, 18).

Eye Tracking Technology (ETT) is a sensor technology that enables a device to know exactly where the eyes are focusing. This information can be used to gain insight into behaviour or to design new user interfaces across various devices. The device most often used for measuring eye movements is commonly known as an eye tracker (19). Eye tracking technology, such as Eye Tracking Glasses (ETGs), detect and track the features of the eyes and their movements. Presuming that we can track someone's eye movements, we can analyse and follow along the path of attention deployed by the observer, which will provide insight into what the user's attention was drawn to and how the user perceived and interpreted whatever he or she saw.

1.1 Background

The Norwegian littoral waters are known to be a beautiful and scenic sea areas. They consist of a large amount of islands, skerries and underwater rocks, and is known to be challenging when it comes to maritime navigation. The land of the midnight sun is also dark during most of the winter season, and the weather is known to be harsh and challenging when travelling the seas. This makes the Norwegian coastline a challenging working environment for the maritime navigators, and especially when travelling at high-speeds. Demanding littoral waters are not only found in Norway, and the challenges within safe navigation for a navigator are a universal challenge.

Norway is dependent on the resources found in and below the large economic and territorial waters, and it is the strategy of the Norwegian government to make good and sustainable use of these resources (20). This also includes sovereignty and exercise of authority in Norwegian waters by the Royal Norwegian Navy (RNoN). Using the Norwegian littoral waters to its advance is one of the tactics of the RNoN. It is important for the RNoN to have good mobility within its fleet, and one of the tools for mobility is the Skjold-class Corvette (21) as shown in Figure 3.

Figure 3: RNoN Skjold-class Corvette (courtesy of RNoN)

The RNoN has aimed for Electronic Navigation in the fleet within 2014. The journey to this PhD study started in 2007, when the Skjold-class was inaugurated in the RNoN. This was a turning point for the RNoN in HSC navigation and the use of complex integrated and networked navigation systems, which introduced new challenges for the HSC navigator. There was a growing concern that the navigator would fall into "PlayStation-mode", addressing the displays more than the actual surroundings of the vessel (22), and the system awareness of the navigator was also challenged due to the introduction of new and integrated technologies (23). Challenges with layout, design and interface are reinforced when speed is increased (24). With increasing speed, the time available to conduct the task necessary for safe navigation decreases, and the limited amount of time challenges the navigator SA (25). Thus, the discussions concerning integrity monitoring of the navigation system, and discussions regarding the understanding and degree of system awareness of the navigator arise. The navigator holds an important task in conducting integrity monitoring of the navigation systems in use, which is done by e.g. comparing the position presented in the ECDIS with the surroundings of the ship. In order to better understand the possibilities and limitations within the navigation system, the navigator needs extensive knowledge of the systems in use, in order to obtain a high degree of system awareness. The need for a thorough understanding of this issue in the RNoN was evident (22, 23), especially with the RNoN tactics of utilizing the littoral waters to one's advantage.

The practical problem is also known in merchant shipping, being more evident in HSC passenger shipping (12). In all merchant shipping there has been an increasing demand for Human-Centred Design (HCD) (26), and there are several initiatives on research driven development of future navigation systems (27). Maritime accident reports highlights the consequences of lack of standardisation and HCD in navigation systems (28). It is argued that technology underpin the navigator's SA, but at the same time the technology can make it difficult for mariners to navigate safely (29). There are few differences between military and civilian HSC navigation. The most profound difference is their area of operations; Civilian HSC normally operates a route, which makes the navigator's highly familiar with the area. Military HSC navigator's has a larger area of operation, and the same familiarisation with the route is difficult to achieve. However, this does not imply that there should be any differences in the design of systems to support safe navigation.

With an increasing amount of computers and displays being introduced to the navigator, the need for new skills and competencies has arisen (30). The need for new competencies for the HSC navigators have gradually matured, and a regulation framework for the conduct of electronic navigation in the RNoN was established in 2013 as well as a need for continuous revision and updating (4). The integrity monitoring and the system awareness are important components in the understanding of the competence requirements for the navigator. The curriculum at the Royal Norwegian Naval Academy (RNoNA) is being updated with an educational reform in the Armed Forces (31), and there is a general trend towards a more thorough understanding of the technology in use (32, 33).

The further existence of the Corvettes has been debated, and in the long term defence plan it is decided to keep the Skjold-class until 2025 (31). This led to an Mid-Life Update (MLU) of the Skjold-class navigation system in 2017, with the aim of providing the vessel with upgraded hardware and software to comply with international standards and to improve the SA of the navigator. Work done in this thesis has been aimed to provide a better understanding of the work conducted by the HSC navigator, and contribute to improving the design of the Skjold-class bridge and navigation system. The data collection in this PhD has had direct impact on the MLU process, and the work is still an ongoing iterative HCD-process (34, 35).

I started my career in the RNoN in 2003, and I have primarily been working with HSC navigation. Being a part of the paradigm shift when the Skjold-class was put into service, provided an insider perspective to the challenges which are presented in this thesis. On the first voyage from Bergen to Hammerfest with HNoMS *Skjold* in 2009, challenges regarding the state-of-the art navigation system was experienced first-hand. When leaving operational service in 2012, I gained insight into the challenges in educating new navigators at the RNoNA while working as a Technical Manager in Electronic Navigation at the Navigation Competence Centre (NCC). Possessing the insider perspective and being a part of the education system in the RNoN, are important contexts when highlighting and evolving this thesis.

1.2 High-Speed Craft Navigation

HSCs have been evolving since the first Hydrofoils in the 20th century, and different types of hull materials and types are in use. Most commonly an HSC of today is a catamaran, built in composite material (36). A Surface Effect Ship (SES) is a ship which combines the hull of a catamaran and the use of an air cushion, like the hovercraft. When the air cushion is in use, a small portion of the hull remains in the water. With no use of the air cushion, the full weight of the vessel is supported by the buoyancy of the twin hulls. This makes the SES capable of higher speeds, and the original historical thrust was to obtain speeds of 80-100 knots (37). One example of a SES is the RNoN Corvettes, known as the Skjold-class, as shown in Figure 3 (38). Yards are offering SES for passenger transportation, logistic operations, military operations and maintenance for wind farms (39).

The working environment for the navigator and the navigation team, which conducts the passage of the HSC, is imperative to support safe navigation. In order to design usable navigation equipment for HSCs, one has to have knowledge about the task of the HSC, the crew that carry out the navigation, and the contexts in which navigation takes place (24).

Røed (24) describes navigation as consisting of five activities:

1. Passage (route) planning
2. Start of voyage/navigation
3. Monitoring the navigation plan (integrity monitoring)
4. Changing course
5. Arrival at port

The methodology when conducting navigation is crucial for conducting a safe passage, and can be seen as a decision-making process (40). The evolution and understanding of this dynamic navigation methodology is imperative for the maritime navigator (41), and is further underlined with the increase of speed (42).

1.2.1 Integrity Monitoring

Most HSCs have modern navigational equipment, which consists of several navigation sensors and systems which are integrated. In an INS, integrity monitoring is an intrinsic function. The INS supports safe navigation by evaluating inputs from several sensors, combining them to provide the operator with timely alerts of dangerous situations and degradation of the system (3). Examples of such integrity measures is the "route check" function, where the planned route is checked towards the safety contour (operator sets the safe depth of the vessel). The operator is warned if a route leg is crossing an area of danger or with groundings. An example of degradation of the system is the INS ability to warn the operator if one of the position sensors malfunctions. This is an automatic process, but the performance standards also appreciate the "manual means" of integrity monitoring, implying the operator is given access to data which provides information about e.g. the sensor status (3, p. 7).

Integrity in an INS is defined as the "ability of the INS to provide the user with information within the specified accuracy in a timely, complete and unambiguous manner, and alerts within a specified time when the system should be used with caution or not at all" (3, p. 36). This definition implies that the integrity checks are automated, but the user has to be ready to take over control in case the INS should not be used at all.

The integrated and automated technology within the INS is designed in order to reduce the workload of the navigator, and implies safer navigation. The assumptions are that new technology can be substituted for human action. Investigations of the impact of new technologies show that tasks and activities are highly interdependent and coupled in complex systems (43). This has changed the navigator's role from spending most of his time doing manual work, finding and fixing the vessels position, to evolve into integration and monitoring work towards the INS (11). An INS is capable of carrying out task autonomously in the absence of the navigator, such as route checks or autopilot steering. The navigator is supposed to rely on the feedback from the system providing the information needed to conduct the task of safe navigation. This has led to the term "automation surprise", which was coined by Sarter et.al in 1997 (43). Automation surprises explains the unintended side effects due to automation design that increases system coupling. Examples of automation surprise are the side effects due to loss of GNSS signals (14), or the unintended side effect of a turn not being conducted in track mode due to planned turning radius being set too low.

The navigator plays an important role in integrity monitoring of an INS, conducting integration work to compare the surroundings of the ships with the INS to support safe navigation. As an example, this comparison could be done by collecting data from both the radar and the ECDIS, or by comparing visual observations with the ECDIS. Integration work has been defined by Lützhöft and Nyce as "a process, initiated by and driven by the mariner, working actively to construct a workplace that works" (11, p. 10). The INS is argued to be a complex system, and the navigator is seen as a last line of defence for safe navigation. The navigator works actively to understand the information presented from the INS, making it meaningful and observable, providing information to support decisions to facilitate safe navigation. To support the integrity monitoring of the navigator, a control strategy for safe navigation is proposed.

1.2.2 Description of HSC Navigation

HSC navigation is recognized by the challenges induced with higher speeds. With higher speeds, the time to conduct the decision-making process of the navigator is decreased. The level of difficulty will also increase with the confinement of the waters, in which the vessel operates. The decision-making process is known as a control strategy for the navigator, and is an iterative process (40). The control strategy developed by the RNoN is known as the Phases of Navigation (44), and is shown in Figure 4:

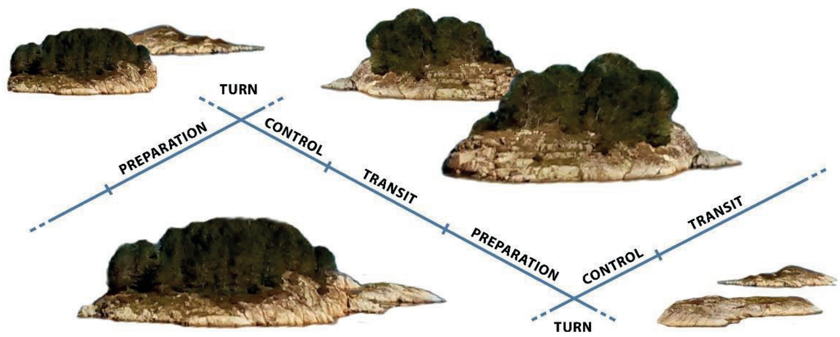

Figure 4: Overview of the control strategy Phases of Navigation (44)

The four Phases of Navigation is a continuous iterative process during the passage. The four phases consist of the preparation-, turn-, control- and transit phase as shown in Figure 5.

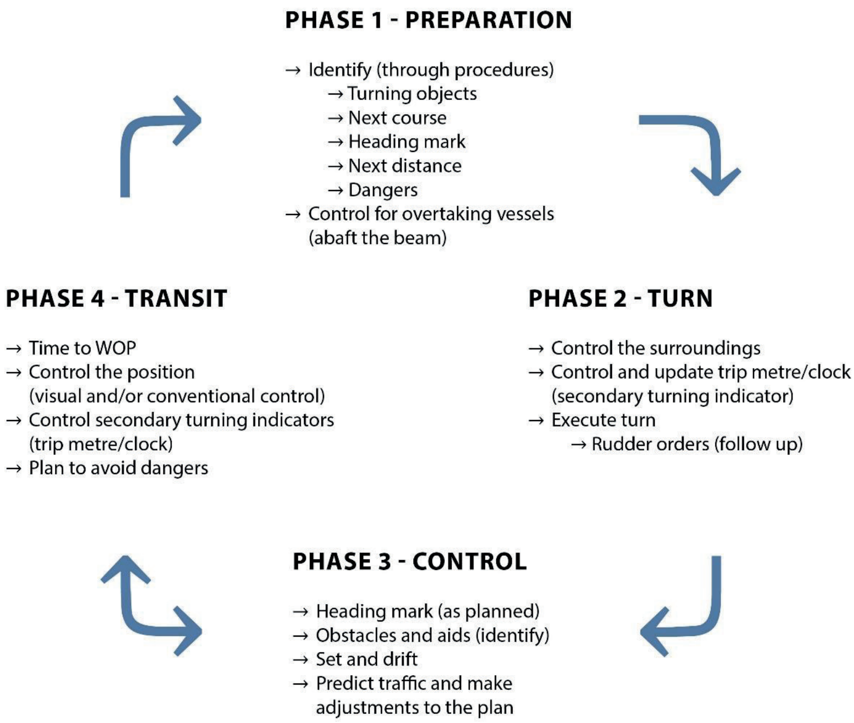

Figure 5: Phases of Navigation (44)

Phase 1 consists of the preparation before a turn is initiated. In this phase it is important that the navigator and/or navigation team gather and highlight all relevant information from the system to successfully conduct the turning phase of the vessel.

Phase 2 is the critical turning phase of the vessel, where the vessel alters course. In this phase it is crucial that the navigators' focus is on the surroundings and conning of the ship, to make sure the turn is executed correctly, i.e. to avoid automation surprise if the vessel is using autopilot or to control appropriate feedback from the rudder (43, 45).

Phase 3 consists of the control phase after an alteration of the course. Immediately after the turn, the navigator collects information to establish whether or not the ship is in the predicted (and correct) position. This information is primarily gathered from the surroundings of the ship, and secondly supported by the navigation systems. The navigator monitors the integrity of the navigation system, by comparing the integrated position from the navigation system, towards the surroundings of the ship by terrestrial means. This phase also consists of the reoccurring cycle of predicting the set and drift, also predicting the surrounding traffic pattern.

Phase 4 is the transit phase, where the vessel is transiting between two wheel over points (WOP). In this phase it is important that the navigator continuously conducts integrity monitoring of the position of the vessel, both by visual and conventional control methods (22, 46). Collision avoidance and the decision-making process of re-planning the voyage concerning other vessels, objects or changes is the task at hand within this phase. Phase 3 and 4 constitute an iterative process until the next planned WOP is reached and the phases of navigation starts over again.

Note that the four phases of navigation are utilized after a thorough planning process of the voyage (voyage plan) has been conducted before the voyage starts (47), being the methodology that the navigator uses during the watch. The methodology fits on any type of vessels, but the process is more demanding in confined waters and with higher speed.

The speed of the vessel and the length of each voyage leg specifies the time given to conduct the control strategy. The length of each of the four phases is dependent on the type of waters, in which the vessel operates. If the vessel is doing 60 knots, and the leg distance is 0.5 nautical miles, the navigation team has 30 seconds to complete the phases of navigation. When a vessel is doing 12 knots, with a leg distance of 0.5 nautical miles, the navigation team or navigator have 2 minutes and 30 seconds to complete the phases of navigation.

1.2.3 Definition of a HSC

The safety philosophy of the regulations for a HSC is based on the management and the reduction of risk, as well as the traditional philosophy of passive protection in the event of an accident (48). The IMO defines HSCs as crafts capable of maximum speed, in knots (kn), equal to or exceeding (49):

$$7.192\ x\ \nabla^{0,1667}$$

∇=volume of displacement corresponding to the design waterline (m^3)

If using meters per second (m/s), the formula is:

$$3.7\ x\ \nabla^{0,1667}$$

Using the Skjold-class with a displacement of 274 tons (t) (Figure 3), with a volume of displacement of 267 m^3, as an example (50):

$$7.192\ x\ 267^{0,1667} = 18{,}3\ kn$$

Which concludes that the Skjold-class is a HSC, since the top speed is more than 18,3 kn.

If we use a general HSC Ferry such as HSC INCAT 046 with a volume of displacement of 5480 m^3 (5617 t) (51):

$$7.192\ x\ 5480^{0,1667} = 30{,}2\ kn$$

This concludes that the general High-Speed Ferry such as the HSC INCAT 046 with a length of 91,3 meters and a beam of 26 meters is a HSC if the top speed is more than 30,2 kn.

One could generalize and say that any vessel operating in speeds above 20 knots is a High-Speed Craft (52).

1.3 Thesis contribution and structure

The main contribution from the thesis is a better understanding of the navigation process of the HSC navigator, supported by data collected with Eye Tracking Technology.

Chapter 1 contains an introduction to the thesis, where the background highlights the history and motivation for the conduct of the thesis resulting in the development of the research questions of the thesis. The specific craftsmanship of HSC navigation and the definition of a HSC is outlined.

The theoretical foundation is described in chapter 2, and describes the evolution in electronic navigation which implies new demands for the maritime navigator. The new demands must be seen in conjunction with an understanding of human performance and the situation awareness of the navigator. The chapter concludes with an analysis of state-of-the-art eye tracking technology in general and within the maritime domain, and the need for human-centred design and standardisation in the maritime domain.

The methodology is described in chapter 3, and starts with a presentation of the chosen research approach in the thesis. The apparatus used in the thesis and the qualitative and quantitative method are presented, before the analysis of the eye tracking data and the statistical model is elaborated.

Performed studies and findings are highlighted and elaborated in chapter 4, which is done by presenting the background of the research question together with the method used for exploring the corresponding research question(s).

A discussion of the contribution to research in this thesis is presented in chapter 5, emphasizing the contribution within eye tracking technology and HSC navigation. The novel approach is to utilize the eye tracking technology to map the visual distribution of the HSC navigator, to better understand the work of the HSC navigator.

Section 6 contains the concluding remarks, where the research contributions are listed to provide an overview of the thesis contribution. The main contributions are the comparison between live- and simulator navigation training and the use of eye tracking data to better understand the work of the HSC navigator and its' application in maritime usability studies. In addition a suggested route monitor window has been presented and evaluated. The conclusion and recommendations for further work are presented at the end of this section.

1.4 Research Question

The lessons learned from pursuing electronic navigation has led to this thesis, and the following research questions (RQs) were identified:

RQ1: Can eye tracking data be used to evaluate and compare the effectiveness of live- and simulator based navigation training?

RQ2: Can eye tracking data be used to map and better understand the visual attention of the HSC navigator?

RQ3: Is the visual scan pattern of the HSC navigator optimized in order to facilitate integrity monitoring of the INS by the navigator?

RQ4: Can eye tracking data be effectively used in the evaluation of the navigational bridge design and the corresponding graphical user interface?

RQ5: Can eye tracking data collected from ETGs be used to validate a design-review of a maritime HSC bridge.

2. Theoretical foundation

This chapter contains the theoretical foundation of the thesis, which comprises the evolution within electronic navigation with the current digitalization of the maritime domain. This implies new demands for the maritime navigator within the efficiency and performance of the navigation task, and the navigators' SA is highlighted. The eye tracking technology which can map the visual attention for the maritime navigator is outlined, followed by the Human-Centred Design process and standardisation of bridge equipment and interfaces.

The literature review within electronic navigation has been focussed on the sensors in use and how they are integrated in the navigation system. As the navigator is a central part of the navigation process, a literature review within human performance has been conducted. This is a large subject, and the focus has been within human performance in complex systems. Situation Awareness (SA) is imperative to facilitate safe navigation, and a general and domain specific literature review has been carried out. An important part has been to compare the maritime domain with other domains such as aviation and nuclear control rooms in order to gain knowledge from other domains. The literature review within eye tracking technology has been the most extensive, both with the use of eye tracking technology in general and within the maritime domain in specific. It has been identified an increased interest and user-driven call for standardisation and functional design on the navigation equipment, which is reflected in the final section concerning Human-Centred Design and standardisation.

2.1 The evolution in electronic navigation

To become a deck officer, an OOW and ultimately a captain of a ship, the education is conducted in the profession of nautical science. Choosing a career in nautical science prepares a person to become a deck officer, and can in general be obtained in two different tracks (53):

- A three years course on a university or university college that results in an undergraduate degree or diploma.
- Vocational school, comprising of a two-year theoretical foundation and a two-year apprenticeship.

The process of navigation for the OOW, is to always ensure the ship's safety (1). The craftsmanship of navigation has gone through an evolution with the introduction of electronic navigation, and especially with the use of satellite navigation. Satellite navigation dates back to 1957 with the first launch of an artificial satellite into orbit, Russia's Sputnik I (54). Declaration of full operational capability of the first GNSS, NAVSTAR GPS, was conducted on 27 April 1995. The evolution in integration of navigation equipment on the maritime bridge resulted in IMO's recommendation of the Performance Standards for Integrated Navigation Systems (INS) (55) in 1998. This further lead to IMO's adoption of the revised performance standard for Integrated Navigation System (MSC.252(83)) in 2007 (3). MSC.252(83) recommends all governments to ensure that INS, if installed on or after 1 January 2011, conforms with the revised performance standard for INS. The purpose of the INS is to enhance the safety of navigation by providing integrated and augmented functions to avoid hazards. This can be achieved by combining and integrating functions and information in the INS to provide "added value" for the operator to plan, monitor and/or control the safe navigation of the ship. An example of an INS is given in Figure 6. This shows the complexity of such a system.

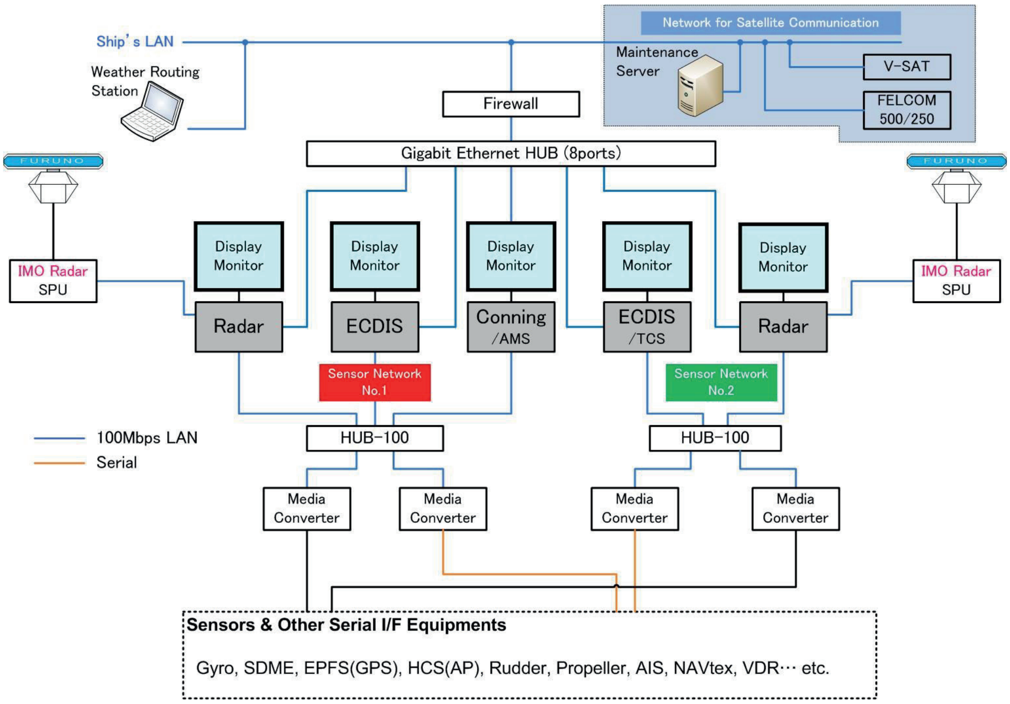

Figure 6: INS on board Platform Support Vessel (PSV) Stril Luna (courtesy of Rolls Royce)

Another characteristic development of the HSC navigator, and to some extent in merchant shipping as well, is the increased speed during the voyage. SES Crew Transfer Vessels (CTVs) and the Fast Patrol Boats (FPBs) have developed from speeds around 30 knots (55 km/h) to 60 knots (111 km/h) (39, 50, 56), which means that the navigation team is expected to conduct the journey in a more time-efficient manner. Figure 7 outlines the demands for safe and efficient navigation, and is based on five pillars, four navigational factors and one human factor (4).

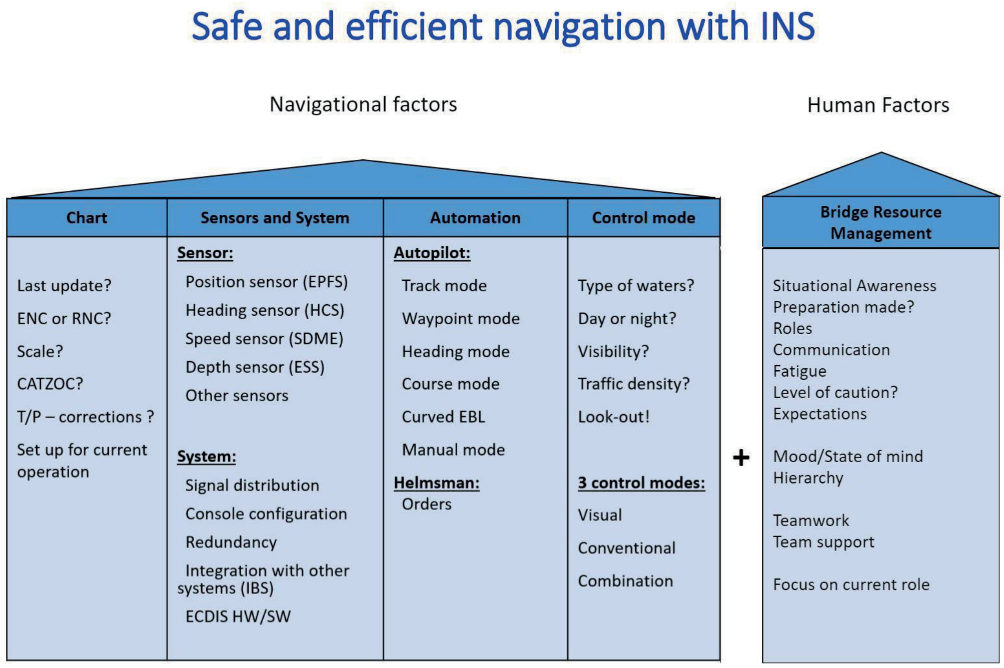

Figure 7: Safe and efficient navigation with an Integrated Navigation System (4)

To better understand the complexity in the conduct of a passage, Figure 7 outlines chart, sensors and systems, automation and control mode as the four navigational factors. Within each of these four components, some of the information which the navigator needs to comprehend are listed. In addition, navigation on an HSC is done in a team, and this underlines the importance of the human factor and proper Bridge Resource Management (BRM).

The Electronic Navigational Chart (ENC) can be used as an example within the chart component: One of the challenges with the ENC is that it holds much information, which might not be presented to the navigator due to the layers chosen for presentation. As an example, the data quality, known as Category of Zone of Confidence (CATZOC), is not normally presented. This is important information for the navigator to hold, as the difference between the data quality within CATZOC A and C is significant (57).

An example of the integration of sensors and systems has been shown in Figure 2 and 6, and the navigator needs to keep a high degree of system awareness in order to detect failures or errors within the navigation system (6). Each of the sensors which is integrated in the system has its' possibilities and limitations, e.g. the GNSS has a signal characteristics which makes it susceptible to signal interference (2).

Automation is introduced as a resource that provides the operator with several modes of operation for carrying out tasks under different circumstances. The human's role is to select the mode best suited to a particular situation, but to accomplish this, the operator must know more and must meet new monitoring and attentional demands to track which mode the automation is in and what it is doing to manage the underlying process (58). Automation mode awareness is thus important for the navigator. An example is if the vessel is in automation track mode, and the turning radius has been planned to sharp, the AP automatically shifts to heading mode. This will stop the planned turn, and the vessel will continue in a straight line. A turn is often made in demanding littoral waters to avoid dangers, and the turning phase of a vessel should be monitored closely by the navigator with reference to the turning phase in the phases of navigation (Figure 5).

Control mode is an important aid for the navigator in order to maintain a high degree of SA, while at the same time acknowledging that the awareness of the navigator cannot be held at a high level during the whole passage (41, 59, 60). There are three main control modes, used in different environmental conditions. With daylight and good visibility, visual control is used. If the passage is conducted during night hours, or the visibility is poor, Radar (conventional) control mode is used. Each control mode has a certain methodology when applied (4). Visual and radar (conventional) can be used in combination, which is the most commonly used mode, and it is important to understand the possibilities and limitations of the control modes. By utilizing the control modes, the navigator supports his role with integrity monitoring of the systems.

The fifth pillar contains the human factors, and will only be presented briefly in this chapter. Human factors in relation to BRM are important, especially in an HSC where the navigation task normally is conducted in a team of minimum two people. The roles in the team, communication and coordination of the tasks at hand is underlined as important for the resource management in the bridge team (61, 62).

The conduct of safe HSC navigation in demanding littoral waters, is in principle the same as in low speed in open (blue) waters. However, the importance of finding and fixing the accurate position of the vessel increases with more demanding waters and higher speeds to enhance the safe navigation of the vessel (1), and the time to solve this task decreases with the increase in speed. This implies that the demands for integrity monitoring from the navigator increases with the speed and the confinement of the area in which the vessel is operating.

2.2 New demands for the maritime navigator

The International Convention on Standards of Training, Certification and Watch keeping for Seafarers (STCW), published in 1978, sets qualification standards for masters, officers and watch personnel on seagoing merchant ships. The Convention came into being in 1984, and was significantly amended in 1995 (63). When becoming a deck officer and finally a master, one has to comply with the basic requirements laid down in this Convention. New technological and operational requirements call for amendments to the Convention, and the Manilla Amendments were effective as of 1 January 2012 (64). The STCW convention covers the basic requirements, and there have been discussions whether the Convention covers the new navigation competencies requirements (65).

Learning is broadly defined as *"*any process that in living organisms leads to permanent capacity change and which is not solely due to biological maturing or aging" (66, p. 3). Another definition which encompasses a paradigm shift defines learning as "a relatively permanent change in behaviour potentiality which occurs as a result of reinforced practice" (67). Learning as a process is defined as "the process of acquiring new, or modifying existing, knowledge, behaviours, skills, values, or preferences" (68). As learning is a complex matter, there is no generally accepted definition of the concept. The importance of learning for the navigator is imperative, especially as technology adds complexity to the conduct of safe navigation. The different definitions underlines the importance of the navigator's need for a capacity change due to introduction of electronic navigation, underlined by multiple maritime accident investigations cite a lack of training or familiarisation amongst the causes (27).

The ability to perform certain tasks is the individual's skills and are developed through education and practical experience (69). Competence is shaped within groups of people that work together, such as a navigation team (70). This competence may exceed the total sum of skills contributed by each of the individuals in the group. The evolution in the use of electronic navigation and integrated navigation systems introduces the need for new skills and competencies for the maritime navigator (71). Competence models are a descriptive tool that identifies the competences needed to form a role effectively (72). No matter what new skill we learn, there are learning stages each of us goes through. Being aware of these stages helps us better accept that learning can be a complex and slow process (73). The conscious competence theory and related matrix model is one of many such models which explain the process and stages of learning a new skill, as shown in Figure 8 (74, 75).

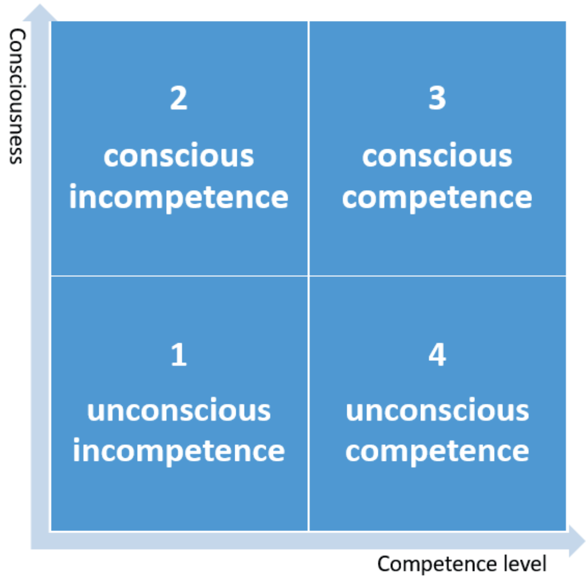

Figure 8: Conscious Competence Learning Model (75)

Figure 8 explains that learners or trainees tend to begin at stage 1, known as unconscious incompetence. They further pass through stage 2, conscious incompetence, then go through stage 3, conscious competence. Before they finally, and ideally, end at stage 4 with unconscious competence. The IMO Model Course 1.27 (ECDIS) and 1.32 (INS) (76) description supports the Conscious Competence Learning Model, and underlines the importance of the teacher knowing the knowledge status of the trainees when designing the courses. Using the ECDIS as an example for the navigator, the IMO Model Course 1.27 shifts the user from stage 1 to stage 2. Training on the equipment and training in a simulator provides a shift from stage 2 to stage 3. Finally, continuous use on board on duty over a period of time shifts the navigator to stage 4 (57).

When addressing a modern bridge and the modern navigator, there are several technological advantages taken place in the workplace during the past 10 years, where the INS could arguably be of high importance. The modern navigator needs to have the skills and competence to utilize the systems, and this competence has been questioned (12, 23). One could argue that there is a possibility that teachers and trainers can wrongly assume trainees to be at stage 2, and focus effort towards achieving stage 3, when often trainees are still at stage 1.

Recent maritime accident investigations, such as the Rescue Vessel (RV) *Bill* (77) and the chemical tanker *Ovit* (78), highlights the dangers of the navigation team being at stage 1. This implies that the navigation team thinks that they have sufficient knowledge of the operations and systems in use, when not having it. This could lead to wrong use of equipment or poor system awareness, leading to accidents or incidents.

2.3 Human (Navigator) Performance

Human Performance relates to the accomplishment of a task in accordance with agreed standards of accuracy, completeness, and efficiency. Human performance also relates to the quality of performance, typically described by the three following parameters (three big) (79):

1. Speed (faster is better)
2. Accuracy (higher is better) and
3. Attention demands (less is generally better)

This could lead to the assumption that the perfect design will allow the user to perform a task faster, accurate and with reduced attentional demands, in order to conduct other task concurrently. In practice it is shown that the three measures could be traded off. Several cognitive phenomena are not directly reflected in performance, such as the degree of learning or memory of a concept, the quality of a mental model of an equipment or the level of SA in a process (79).

There are many possible metaphors that describe human performance, and perhaps the most fundamental metaphor in performance psychology is the description of human cognition in terms of information processing (80). This infers that humans can be conceived as information processing devices, but with additional features compared to computers (81). It is argued that computers (inanimate objects) do not have the ability to process information to awareness of the situation. Computers (which presents information on a displays) are seen as repositories from which humans may gather information from various types, through various means at various times (82, p. 26). As an example, it has been best practice to use two different fixing methods in order to conduct an integrity check before establishing a vessels position. Before the introduction of electronic navigation, this could be done by taking visual bearings to create a fix, comparing it with the vessels estimated position (1). With the introduction of the INS, it is stated that "the integrity of information should be verified by comparison of the data derived independently from at least two sensors and/or sources, if available" (3, p. 7). This could be accomplished by comparing two EPFS, such as the GPS (position sensor 1) and Galileo (position sensor 2). When combining humans and computers, the integrity monitoring could be achieved by comparing the EPFS in the ECDIS and the visual sights conducted by the navigator. This adds an extra degree of awareness to the situation, as the human can collect information from different sources and evaluate them to better project a future state. Thus the navigator is conducting the information processing to conduct integrity monitoring, similar as a computer, but achieving a higher degree of awareness of the current situation (82).

Human perception is the organization, identification, and interpretation of sensory information in order to represent and understand the presented information, or the environment (83). The human as a system includes several senses (84), and most known are the "big five" senses as sensors: Vision, hearing, skin sensing, smell and taste (85, 86). In order to facilitate safe maritime navigation, the navigator utilizes the senses to perceive information during the passage. In accordance with the Collision Regulations (87), it is stated that the navigator should keep proper look-out with all available means, and both good visual acuity and unimpaired colour vision are essential for those undertaking lookout duties in accordance with STCW Code Table A-1/9 (88). One would argue that the vision is the primary sensor for the human when conducting the navigation task, as conducting the navigation task is an INS is defined as route planning, route monitoring, collision avoidance, navigational control data, status and display of the system and alert management (3). Without the ability to visually check the INS and compare it with the surroundings to conduct integrity monitoring, safe navigation is impossible to achieve. This does not imply that the other senses are not of importance, as research has shown that senses such as hearing and kinaesthesia (sense of movement) are important for the navigator to collect information in the conduct of safe navigation (11).

In HSC navigation, as described in section 1.2, the demands for human performance are high. With an increase in speed, the time to conduct tasks, with a given level of accuracy and attention level, is decreased. The navigator's vision is essential, as it is the primary sensor for information collection in the INS and in the surroundings to conduct integrity monitoring. The use of the vision system in different situations in order to discover, detect, track or follow the course of events, is considered of vital importance (85). Visual search involves finding something, e.g. a vessel on collision course or the speed of the vessel presented in the navigation system, with our eyes. The visual search task is different from the visual noticing task, as the target is typically defined in advance. Researchers have studied search intensively and over a variety of domains, such as human-computer interaction (89, 90). Visual search is closely related to the sequence of eye movements, and thus utilizing eye tracking technology is one method of better understanding the visual search of a subject (79).

The laws of most maritime countries require that all seafarers carry a valid medical certificate (88), in Norway the medical certificate is valid for two years and should be conducted by all persons above 18 years (91, §5). All navigators are conducting look-out duties and are screened with regards to vision acuity and colour vision (92), which are reported to be of importance when conducting a visual search (93). Vision relates to SA through Endsley's model, where level 1 is described as the perception level. Level 1 is the first step in achieving SA, and is conducted in order to perceive the status, attributes, and dynamics of relevant elements in the environment. This involves the processes of monitoring, cue detection, and simple recognition, which lead to an awareness of multiple situational elements, such as objects, events, systems, environmental factors, and their current states, such as locations, conditions, modes and actions (25, p. 36).

2.4 Situation Awareness for the maritime navigator

Situation awareness (SA) has become a widely used construct, especially within the human factors community, over the past 30 years. One of the major contributions is Endsley's development of the 1995 SA model (25). The research has been used to drive the development within information displays, automated systems and new training approaches for both individuals and teams (82). Endsley's 1995 SA Model has been criticised for being linear, not dynamic, without context and being a data-driven information-processing model (94). Terms such as sensemaking, Distributed Situation Awareness (DSA) and situated SA have been presented to provide a better understanding of the SA construct (94-96). Endsley argues that misconceptions and misunderstanding are related to the critics of the 1995 SA Model (94), and a large group of researcher still utilizes and appreciates the 1995 Model of SA in dynamic decision making (82, 97, 98).

SA is basically to be aware of what is happening around you and understand what that information means to you now and in the future (99). Endsley's definition of SA is "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (100, p. 97). According to Endsley's definition, SA consists of three levels (25, p. 36):

- *Level 1: Perception.* The first step in achieving SA is to perceive the status, attributes, and dynamics of relevant elements in the environment. Level 1 is the most basic level of SA, and involves the processes of monitoring, cue detection, and simple recognition, which lead to an awareness of multiple situational elements and their current states.
- *Level 2: Comprehension.* The second step in SA involves a synthesis of disjointed Level 1 SA elements through the processes of pattern recognition, interpretation, and evaluation. Level 2 requires integrating this information to better understand how it will impact upon the individual's goals and objectives. This includes developing a comprehensive picture of the world, or of that portion of the world which concerns the individual.
- *Level 3: Projection.* The third and highest level of SA involves the ability to project the future actions of the elements in the environment. Level 3 is achieved through knowledge of the status and dynamics of the elements and comprehension of the situation (Levels 1 and 2 SA), and then extrapolating this information forward in time to determine how it will affect future states of the operational environment.

Endsley (99) argues that SA is the engine that drives the train for decision-making and performance in a complex dynamic system, similar to a navigation system which is highly integrated.

Wickens argues that Endsley's SA construct is one of the most important contributions in engineering/applied psychology to emerge since World War 2 (97), but also underlines the fuzzy dichotomies with the construct. He further argues that the construct of SA is applicable for real-world problems, having to be understood in a context. "Allowing a certain fuzziness enables concentration to be redirected away from proving right or wrong, toward the utility of the concept in applications" (97, p. 90). Wickens (18) argues that SA consist of three components; spatial awareness, system awareness and task awareness. These components have impact on the real world, dependent on the domain. Spatial awareness concerning the environmental factors such as weather, system awareness for keeping the operator (the maritime navigator) informed about status (modes – mode awareness) and actions that have been carried out by automated systems, and task awareness for mission assurance, attention and task management. For the maritime navigator system awareness is imperative for knowing what state the navigation system and all sub-components are in.

In accordance with the revised performance standards for INS, one of the purposes of the INS is to support situational awareness (3), and the IMO further defines situation awareness as "the mariner's perception of the navigational and technical information provided, the comprehension of their meaning and the projection of their status in the near future, as required for timely reaction to the situation. Situation awareness includes mode awareness" (3, p. 38). This definition is closely related to Endsley's (100) definition. The term situation awareness comes from military aviation, where a high level of SA was found (and still is) critical in winning battles (99). This implies to most other domains, also for the maritime. Sarter and Woods' (58, p. 12) argues that "the term situation awareness should be viewed as just a label for a variety of cognitive processing activities that are critical to dynamic, event-driven, and multi task fields of practice." Sarter and Woods (58) study within aviation underlines the role of the human (pilot) in supervisory control of a system, and the importance of mode (system) awareness in human-automation interaction. They argue that the human (supervisor) must know more about the systems in use in order to choose the correct settings (modes) for the system. The loss of mode awareness resulted in several incidents and accidents within aviation, such as the Banglore accident, where the crew failed to acknowledge that the system had changed modes. Sarter and Woods also argue that SA is a panoply of the cognitive processes (58, p. 11), and that defining SA is not constructive and one should rather define it in the context in which it appears.

Dependent on the context, the complexity in maritime operations are high. Maritime Situational Awareness (MSA) is a construct that has been widely discussed in the maritime surveillance field. Van den Broek et al. (101) introduce and describe a MSA support system, which is focused on maritime security operations where sensor information is fused with intelligence data. The complexity of this support system is outlined, and they argue that the human operator is important to efficiently arrange and configure the support system. The situation awareness for the maritime navigator is comparable with the elements in the presented context model, where an important aspect is the SA of the human operator (the maritime navigator). The security threat from an adversary in the model by Van den Broek et al. (101), can be compared to the threat from the environment in which the maritime navigator operates. As an example the threat rises when the challenges in the topography increases, together with the environmental conditions such as harsh weather and darkness or restricted visibility, which will challenge the navigator's SA. The Portuguese Navy (PN) has conducted an analysis of MSA in their Operational Centre, based on the construct of SA. They found that an Information System (IS) to support MSA is a SA IS for the maritime environment (98, p. 12). When analysing different theoretical frameworks for SA, they found Endsley's approach to SA as the most similar and complementary model to the PN model on MSA construct. It is further argued that it is considered adequate to adopt Endsley's methodology for requirements definitions, but the construct of SA must be put into the context of the PN requirements for MSA (98).

To better understand SA, researchers have argued that SA cannot easily be defined or discussed in the abstract, devoid of context (97, 102). The task of maritime navigation in a sociotechnical system is complex (103), and there are several factors, such as the mission, environment, speed and technology, which contributes to the complexity. The complexity in the maritime system consist of large amount of variables, and can be seen as an open system, which underlines the importance of the context in the navigator`s SA model (104). With the increase in speed and more use of technology and displays, the importance of a high level of SA for the maritime navigator has been underlined. In the work of this thesis, the need for a contextual SA model has arisen. Inspired by the 1995 SA Model (25) and Wickens work within aviation (18), a model of the Navigator's SA has been established (105). The Navigator's SA model consist of spatial-, task- and system awareness, and is presented in Figure 9.

The concept of spatial awareness is inherent in the task of moving a vessel through a space filled with hazards. The environment represents the hazards. In demanding littoral waters, the topography is challenging. This could be represented by underwater rocks, or by headlands or islands hiding other vessels or dangers as the journey progresses. The weather, waves and tides constitutes an alternating challenge, which the navigator has to notice (Level 1), comprehend (Level 2) and project (Level 3) the status of to keep the vessel safe.

In aviation, the pilot has four different generic tasks to perform; Aviating, Navigating, Communication and Systems management (ANCS) (18, p. 131). In the maritime, this would adhere to Seamanship,

Navigating, Communication and Systems management (SNCS). Conflicting task requirements, unexpected events and several cognitive tasks challenges the navigator's task awareness.
As outlined in section 2.1, the modern ship bridge has complex and dynamic systems. One such system of several sub-systems is the navigation system, which is normally integrated and partly automated. Thus, increasing computer power has enabled the navigation system to perform many actions – status monitoring, integrity monitoring, automatic target tracking, and automated track control. In addition, the threat from cyber security in the maritime domain (Maritime Cyber Security – MCS) has arisen with the increased use of computers, and the close coupling between ICT and operations (105, 106). The complexity of a vessels navigation system coupled with poorly designed systems, makes system awareness difficult to maintain (18, 58). The Navigator's SA model is outlined in Figure 9, and is established to form a degree of applicability of SA to the real-world problems faced by a HSC navigator operating in demanding littoral waters (97). Note that the maritime system is an open system, with an uncountable amount of variables (104). The variables mentioned within spatial-, task- and system awareness in the above are some of the variables the navigator has to notice (Level 1 - perception), comprehend (Level 2) and project the future state of (Level 3) to achieve a high degree of SA. The bottom line in Figure 9 are examples of some of the most important variables the navigator has to appreciate, and could be supplemented.

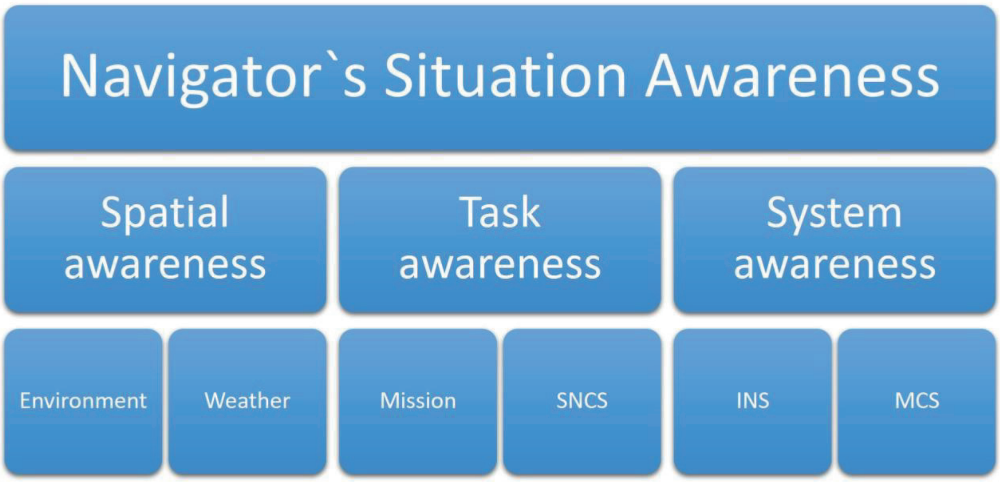

Figure 9: Navigator's Situation Awareness Model

Research in aviation states that utilizing an efficient scan pattern will improve the SA of the navigator (107). The visual scanning conducted by the navigator is related to situation awareness through the systematic and continuous effort to acquire all necessary visual information in order to build and maintain a complete awareness of activities and situations, which may affect the operator (108). In general, visual scanning consists of fixations and saccades, and thus interpreting eye tracking data can provide valuable insight into the situation awareness of the navigator.

2.5 Eye Tracking Technology

Eye tracking is the process of measuring where one is looking, the point of gaze, or the motion of an eye relative to the head. This collected data is known as eye tracking data, collected by eye tracking technology devices for measuring eye positions and eye movement (109). The academic researcher group is the oldest and probably the largest group using eye tracking technology, primarily used to conduct proper experimental set-ups and collection of statistics within e.g. reading and conduct of specific tasks. A large and more recent group is the media and advertisement consultants, who use eye tracking for fast collection of data to decide whether to say no or go to an advertisement campaign. The academic researchers within human factors is a small but traditional group using eye tracking technology, for example in usability studies in cars, nuclear plants, aeroplanes etc. There is also a newer and fast growing group of users utilizing gaze-guided interfaces by the use of eye tracking technology. For example if you cannot interact with a computer in any other way than by using gaze (110).

To better understand eye tracking technology, one need to understand the human eye and its basic movements, which are outlined in Figure 10. The eye lets light in through the pupil, turns the image upside down in the lens and then projects it onto the back of the eyeball known as the retina. The retina is filled with light-sensitive cells, known as cones and rods, which transduce the incoming light into electrical signals sent through the optic nerve to the visual cortex for further processing. The difference between cones and rods is that cones are sensitive to high spatial frequency, known as visual detail, and providing us with colour vision. Rods, on the other hand, are very sensitive to light, and therefore support vision under dim light conditions (110). Approximately 94% of the photosensitive cells in the eye are rods and approximately 6% are cones (111).

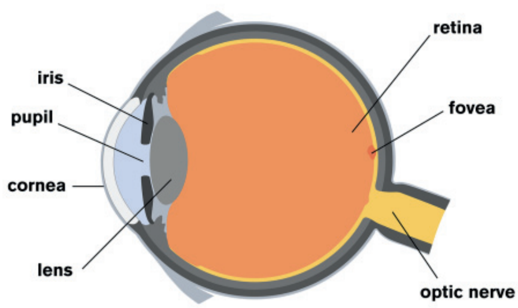

Figure 10: The structure of the human eye (112)

When using video-based measurement of eye movements, the pupil is important. Another important, but less known element, is the cornea. The cornea covers the outside of the eye, and reflects light. The reflection seen in someone's eyes usually comes from the cornea. When tracking the eyes of a subject, only one reflection from the cornea is desirable. To record only one reflection, infrared recording is used to avoid the natural light reflection (110).

2.5.1 Fixations and saccades

The most reported and known event is in fact not related to a movement, but to the unmoveable eye, and is known as a fixation. A fixation is the state when the eye remains still over a period of time, for example when the eye temporarily stops at an object during a visual scan of the outside environment (19). The length of a fixation can last from some tens of milliseconds (ms) up to several seconds. An important feature of a fixation is that when measuring a fixation, one also measures attention to that position. Figure 11 presents an example of a scan pattern. The circles are fixations, and the lines between the circles are saccades.

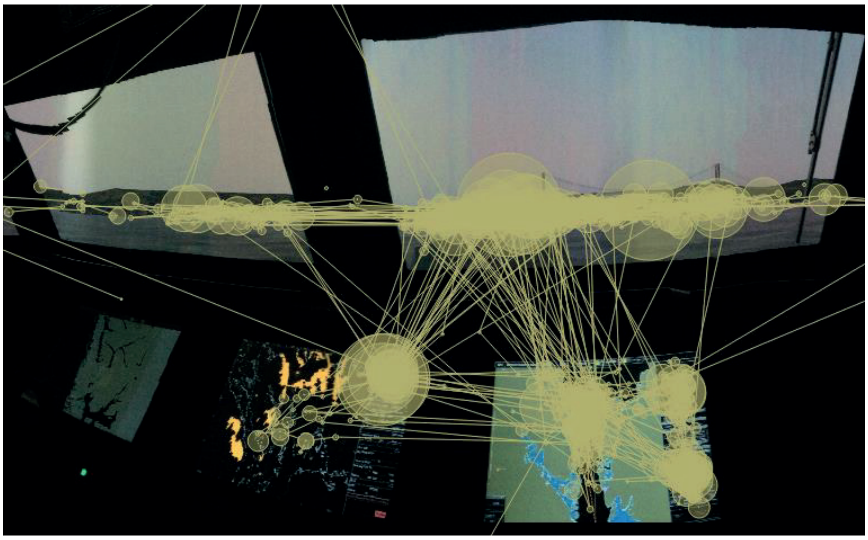

Figure 11: Scan pattern of the Navigator using the INS on board the Skjold-class Corvette (113)

The lines in Figure 11 represents saccades, and is characterized by the rapid motion of the eye from one fixation to another, for example from one word to another when reading a text (110). When analysing fixation and saccades from the eye tracking data, other positions and numerosity measures can be extracted such as number and duration of fixations, fixation rate, dwell rate, number of returns, look-backs and backtracks (110, 113).

2.5.2 Areas of interest

Areas of Interest (AOIs) can be defined in the eye tracking data, and can be used as a tool for the further analysis of eye-movement data. AOIs define regions in the stimulus where the researcher is interested in gathering data. AOIs also allow for further events to be defined and detected such as dwells (total time in a specific AOI), transitions and AOI hits (110). Figure 12 is an example of the defined AOIs on board the bridge of a Skjold-class Corvette.

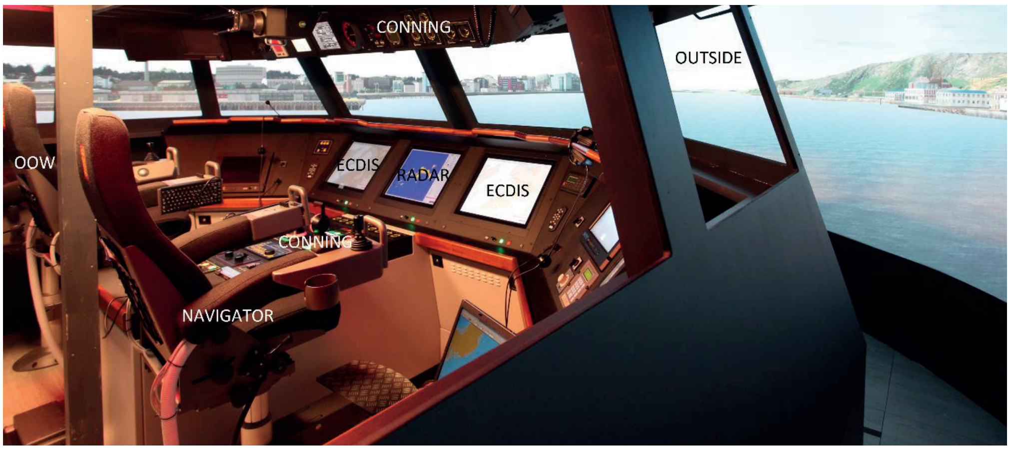

Figure 12: AOIs on the navigation bridge of a Skjold-class Corvette (44)

2.5.3 Visualization maps

Visualization maps of attention such as heat maps, focus maps, sequence charts and scan patterns can be used to represent eye tracking data. It does not represent attention per se, but the spatial distribution of eye-movement data. It is important to note that the spatial distribution is conducted over time, while the visualization is done on a picture of any one given time frame. Attention maps can provide quick, intuitive and in some cases objective visual representation of eye tracking data, from which can provide an immediate grasp of meaning.

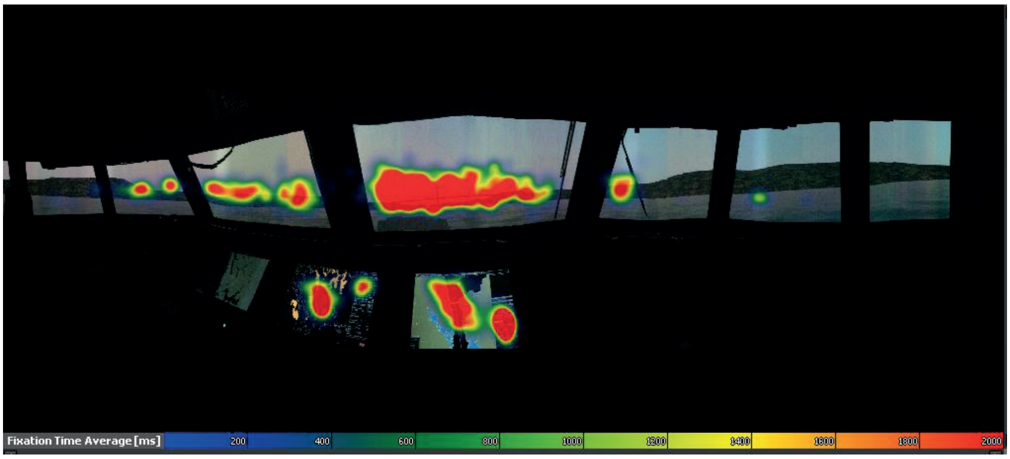

Figure 13: Example of heat map (113)

Heat maps visually display the areas where the participants looked, which implies which areas are important to the participant. It is possible to create a heat map with as few as one user or with many users, and it is also an option to choose to create heat maps showing the fixation length, in other words, time, or number of fixations. In Figure 13, the average fixation time is given in milliseconds. The average time is colour coded where the blue colour indicates “short” fixation time (~200ms), and the colour red indicates “long” fixation time (~2000ms). Visualization maps such as heat maps have been used in an inordinate amount in eye tracking research, and it is important to understand the possibilities and limitations by using heat maps. Heat maps are a very good start in exploring where to conduct further analysis, but must be taken as part of an entire process. Appraising a heat map alone can be a root of all sorts of misreads (114).

Figure 14: Example of focus map (113)

Heat maps and focus maps are related and focus maps visually "invert" heat maps to enable the visibility of the areas of viewer attention. Focus maps, as shown in Figure 14, are negative space representations, visualizing the negative space of the corresponding heat maps (115). Heat maps and focus maps are two related standard techniques that are useful for providing a synaptic view of eye movements aggregated over time and subjects. Pros and cons with the use of heat maps and focus maps are similar. In their basic configuration, heat maps or focus maps cannot convey the temporal order of eye movements.

Sequence charts is a visualization technique to better analyse the visual distribution in time concerning the different AOIs. The sequence chart shows the order and duration of dwells in the specified AOIs (110, 116, 117). The sequence chart has proved valuable in usability studies and could provide an indication of differences between novices and experts (117). Not all ETG manufacturers have sequence chart as a visualization technique in their software (113, 118).

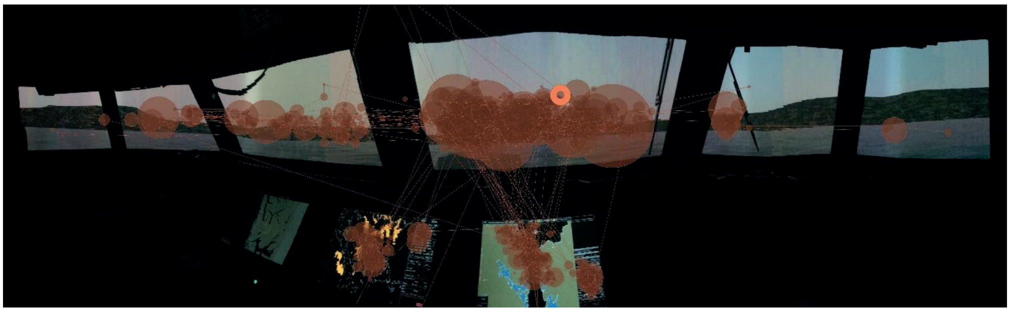

Figure 15: Example of scan pattern aggregated from one recording (113)

Spatial-temporal visualization with scan patterns connect consecutive fixations through saccade lines on the stimulus (119), and an example is shown in Figure 15. The term scanpaths and scan path are also used instead of scan pattern (120), and is used to describe any sequence of saccades and fixations on a stimulus. In a scan pattern visualization of each fixation is indicated by a circle, where the radius corresponds to the duration of the fixation, and the lines between the circles present the saccade.

Visualization maps such as those presented above could be used, by less experienced viewers, to jump to conclusions about why participants' visual search is as it is. Remember that visualization maps only show where participants look, not why they look there.

2.5.4 Numerosity- and position measurements

To further analyse and understand the eye tracking data, numerosity- and position measures can be extracted. As an example, one could extract numeriosity measurement such as fixation duration as shown in Figure 16.

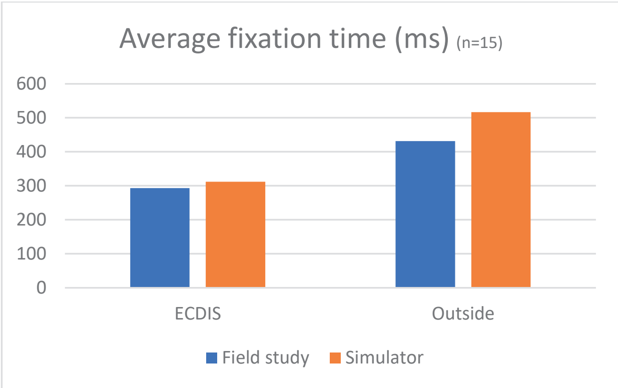

Figure 16: Comparison of average fixation time in AOIs *(121)*

The fixation time is presented as circles in the scan pattern in Figure 14, and the numerosity measurement of the fixation time can be used as an indicator of cognitive and mental workload for the participant in the given AOI (110, 122).

Other examples of numerosity measurements are how many fixations (amount) are conducted. Fixation rate is the number of fixations divided by a period such as the duration of the trials, and could give indications of task difficulty or performance quality (123-125). The number of fixations has been used as an indicator for e.g. search efficiency and difficulty (126), semantic importance (127), memory build-up (128), age (129) and experience (130).

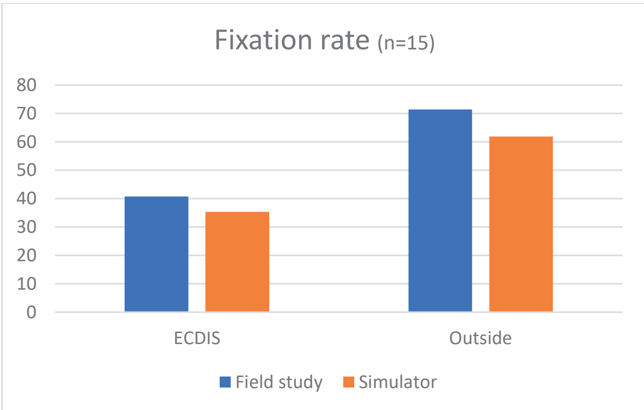

Figure 17: Comparison of Fixation rate in AOIs from Paper 1 (121)

Dwell rate is the number of entries into a specific area (AOI) per minute. This could imply the importance of the given AOI (122). The number of returns (re-fixations, rechecks) are a specific type of transition into an AOI, and to count as a return there has to be at least one previous dwell in the AOI. Look-backs are saccades to AOIs already looked at (also known as returns). Number of returns or look-backs can indicate informative areas or a need to confirm information in the given AOI (131). A backtrack is the specific relationship between two following saccades where the second goes in the opposite direction of the first. Look-backs and backtracks are further investigated when it comes to usability studies of bridge layout and Graphical User Interface (GUI). An example, using Figure 12, going from AOI Outside to ECDIS to Outside constitutes a backtrack. The eye movement from AOI Outside to ECDIS to RADAR to Outside constitutes a look-back to AOI Outside. The number of backtracks has been found to be one of the best predictors of usability, but one should be careful with using it as an indicator alone for poor usability of GUI (132). Look-backs can thus be utilized to collect further data in the understanding of the usability equipment, e.g. by looking at the need for confirmation of information (131).

2.5.5 Usability studies

The use of eye tracking data as a concept for interface usability and the enhancement of the design of complex system has shown a good potential (133). Enhancing the usability of a GUI would result in less fixations, scanning and making fewer regressions to previously scanned AOIs. This could ultimately improve SA and decision-making capabilities in high intensity operations. It is also highlighted that the eye tracking technology is still advancing to a truly reliable and accurate level, which is still a valid argument today (134).

The collection of eye tracking data has been most commonly conducted in a laboratory, but there is an increasing use of it live "in the wild" (135). This could provide a better understanding of the everyday behavior of the participants. The challenge is that experiments in the wild can be complex and consist of uncertainties that are not present in controlled laboratory conditions. Simulators can offer advantages over more restricted laboratory tasks, but there are still challenges with the realism in the scenarios and the fact that the subject is being monitored. Lappi (135) presents an extensive overview of the complementary advantages and disadvantages of using eye tracking in a laboratory, simulator and live, which outlines the challenges and underlines the importance of thoughtful methodology when collecting eye tracking data in the given environment. Lappi (135) further suggests that simulator studies could provide the best of both worlds.

2.6 Eye Tracking Technology in the maritime domain

The use of eye tracking technology such as ETGs in the maritime domain has been mainly used to better understand HCI techniques when an operator is addressing a display (136), such as in maritime warfare domains as anti-air warfare (125, 136).

The development of the ETGs during the past years has increased the freedom of movement for the subject, having thus increased the usability of the ETG as a quantitative data collection tool. From the first use of ETGs in the maritime domain, e.g. from Dukic et al. (137), who used Eye Tracking helmets which allow the subject "relative freedom of movement" up until today's second generation ETG, there has been a technological evolution contributing to wider and more extensive use of ETGs.

The first studies mainly focused on safety aspects, bridge design and training programs (138), and the data collection was conducted in bridge simulators. The data provided valuable insight in the understanding of the visual behaviour of a navigator, together with a better understanding of the cognitive workload for the navigator during a passage in different weather conditions. Dukic et al. (137) states that there is a clear difference beetween "looking" and "seeing", and that the visual search strategy for the navigator is important to understand. There are two main weather conditions which are applied in the data collection; conducting a passage in daylight and good weather conditions, and conducting a passage in poor visual condition such as fog. Initial studies in the maritime domain also highlighted the importance of understanding the difference between a novice and an expert navigator, in the conduct of a passage. There are indications that eye tracking data can provide information of the experience level of the operator, concerning the use of different AOIs (139, 140). More experienced operators focus more on the surroundings of the vessel than the displays.

Forsman et al. (140) used ETGs to investigate gaze behaviour between experienced and novice boat drivers during high- and low speed navigation at sea, with focus on the use of navigational aids. The study comprises 16 participants and was conducted in a live passage on board a 34 ft. Rigid Inflatable Boat (RIB). This study was conducted in a relative harsh environment, with sea spray, sunlight, wind and severe ship movements. The data collected was analysed and presented, and the discussion compares literature with the experience of the use of eye tracking data from mainly the automotive industry. The authors point out some of the challenges with using ETGs in a field study, such as sunlight, and the constraints by the field of view (FOV) of the apparatus. The study also highlights the use of navigation aids, such as the differences between using paper chart and an electronic chart. The finding suggests that the use of electronic charts increase the SA of a novice, but also underlines the importance of understanding the systems and the inherent errors in systems such as the GPS.

The understanding of the navigator (operator) focus has been an important motivation for using eye tracking technology, and this was used by Bjoerneseth et al. (141) to better understand the work of the Dynamic Positioning (DP) operator. The study was conducted in a ship simulator with ETGs, with the aim of mapping out the foci of attention during safety critical operations. This can in turn lead to more efficient simulator training and help towards improving the design of bridge equipment and bridge layouts, which was used in the Rolls Royce Unified Bridge (142). The findings from the collected data has clear indications that expert operators spend more of their total time during the operation fixating on the surroundings of the vessel and important equipment. This underlines the importance of experience when conducting safety critical operations, and the study found that the most important area is the outside environment. The study also presents findings on the importance of the bridge layout concerning critical information presented on Visual Display Units (VDUs), which is similar to MFDs. The use of Subject Matter Experts (SMEs) in workgroups with designers and use of simulator testing, to better understand the function of the bridge, supports the HCD principle in bridge design and GUI layout.

The mental workload and stress conditions for the navigator (operator) have also been analysed by the use of eye tracking data (139, 141, 143). Transitions between AOIs have been used as an indicator of workload, together with the distribution of eye fixations which is also known as scan paths or scan pattern. Pupillary response and eye blink frequency have been used to correlate towards cognitive processing and mental workload. Results from Di Nocera et al. (143) showed that the distribution of eye fixations changed with task load, and also indicated that individuals showing high attentional control reported low workload. An important finding is the frequent eye movement transitions found between the instruments monitored, suggesting that the information they provide could be integrated for improving the operators' performance.

The use of eye tracking data collected with ETGs have also shown efficient in a learning environment on a bridge simulator. The results indicate that ETGs are not a necessary tool when experts intervene and guide the novices, but it improves the efficiency of debriefing with great extent (144). ETGs has further been presented as a tool in a multi-sensor framework for improving situational awareness in training of DP operators (134), and the use of eye tracking data is shown valuable in debriefing of training. The evolution of ETGs to second generation, for example the Tobii Pro Glasses 2, with wireless live function for insights in the real-world environment and software tools for post-processing, provides valuable data for increasing the safety of operations.

The S-mode is an ongoing initiative in IMO, and the guideline aims to provide guidance on where and how standardisation can provide increased usability of electronic navigation systems. The standardisation of navigational systems could be one effective countermeasure to reduce the variability and system complexity (28). The Republic of Korea conducted a live eye tracking data recording in 2018, in order to organize a user test to support the S-mode guidelines. The aim of the test was to find out which navigational functions and information the navigator was interested in during a passage. 23 active Korean deck officers and masters participated. One of the studies collected data on board a Ro-Ro Passenger ferry in operation. The data was collected with Tobii second generation ETGs, and the data analysis indicates a low level of attention towards the outside of the ship during the data collection (4,1%), and navigation equipment was addressed 45,1% of the time. The data analysis further shows that 49,2% of the time the navigator's attention was towards other tasks than look-out and operation of navigation equipment at the bridge of the vessel (145). This study underlines the difference in the navigator's attention when conducting passages in open- and littoral waters.

2.7 Human-Centred Design and Standardisation

Human-Centred Design (HCD) is a design and management framework that develops solutions to problems by involving the human perspective in all steps of the problem-solving process (146). HCD has its roots in fields such as ergonomics and computer science. ISO 9241-210, "Ergonomics of human-centred system interaction", describes HCD as an "approach to systems design and development that aims to make interactive systems more usable by focusing on the use of the system and applying human factors/ergonomics and usability knowledge and techniques" (147, p. 2). HCD is the process that enables a design team to incorporate human requirements into the design of a system. Most commonly, HCD is scenario-based and prototype-based, and consist of gathering human factors issues from an appropriate community of users (148).

The shipping industry is known to be cost-oriented and conservative (149), and the push for improved HCD of a bridge layout and GUI often becomes a question of cost (150). With the introduction of electronic navigation, navigation systems increasingly provides a variety of information and services for enhancing navigation safety and efficiency. These systems require the connection and integration of on board navigational systems and involve the collection, integration, exchange, presentation and analysis of marine data and information. Research within maritime navigation equipment underlines the need for standardisation in order to avoid unnecessary variations of such equipment (12, 78, 151).

MSC.1 – Circ 1512 (Guideline on Software Quality Assurance and Human-Centred Design for e-Navigation) states that the overall merits of a navigation system can be found not only in their range of functions, but is also underpinned by their trustworthy software and overall usability (26). The basic premise of HCD is that systems are designed to suit the characteristics of intended users and the tasks they perform, rather than requiring users to adapt to a system. The process is iterative, and consists of five activities (26):

1. Understand and specify the context of use.
2. Identify the user requirements.
3. Produce and/or develop design solutions to meet user requirements.
4. Evaluate the design against usability criteria.
5. Maintain operational usability.

Usability Testing (UT) is a key component of HCD and uses methods that rely on including users to test the ability of systems to support user needs (activity four). UT helps to identify potential problems and solutions during design and development stages by using an iterative approach to testing where the design evolves through rounds of prototyping, testing, analysing, refining and testing again. Systems designed and developed this way improve user performance utilizing UT-methods, being stable and resilient, and support users in different workload environments, such as during challenging navigation and environmental conditions when users are most vulnerable to making mistakes and when error management and recovery is essential (26, p. 3). As integration of electronic navigation is seen as providing an information rich environment, setting in place the necessary foundation can be a complex activity. Usability in design can be used to balance complexity, and right level of user feedback needs to be considered. Taken this into account, the basic requirement for complex system is their need to be operational and functional in the most intense, worst case scenarios (27).

Vast variations in the design and navigation equipment user interfaces are found on a modern ship bridge, and there is an increased effort towards standardisation. Standardisation in the maritime domain is accomplished through the activities of the international organization. The United Nation (UN) Agency the International Maritime Organization (IMO) is the key organization for establishing safety at sea (152). The Sub-Committee on Navigation, Communications and Search and Rescue (NCSR) sixth session in January 2019 (NCSR-6) is invited to consider the report from a Correspondence Group (CG) providing the "Guidelines for the standardisation of user interface design for navigation equipment" (153). The guideline is commonly referred to as the "S-mode Guideline". The report is a joint effort from a large number of countries and organizations where it is recognized that "Improved standardisation of the user interface and information used by seafarers to monitor, manage and perform navigational tasks will enhance situation awareness and safe and effective navigation" (153, p. 9). The CG recognizes that competition between manufacturers is important to realize innovation, but the variation between systems and equipment produced by different manufacturers has led to inconsistency in the way essential information is presented, understood and used to perform key navigation safety functions. The guidance thus stems from a user need for greater standardisation to enhance usability across navigation systems and equipment, and has resulted in the following appendices:

1. Default and user settings
2. Standardized user terminology, abbreviations and icons for commonly-used functions (Hot Keys) and groups of functions (Shortcuts)
3. Logical grouping of related information
4. Access requirements for essential information and functions

Standardisation, in the context of these Guidelines, means the achievement of the optimum degree of order in the user interfaces provided by different equipment manufacturers for (essential) navigation functions and information. The optimum degree of order is that required for safe and efficient navigation, and to minimise the variation and complexity of navigation equipment for the user (153, p. 10).

If designed and implemented properly, standardisation is important for the reduction of the user's physical and mental workload (153). However, simply adding up a number of individually conforming parts in a standardized arrangement does not necessarily provide an effective and efficient work system by itself. To achieve that, comprehensive knowledge about the tasks and routines of bridge team work must be brought into play, and recognizing that bridge equipment often is supplied by a number of different vendors, inconsistencies or systemic shortcomings must be addressed and mitigated (154).

It is argued that no two ships are alike, nor are they bridges (11). When nothing else works the last effort is often said to be standardisation, but the manufacturers needs to have the ability to distinguish from each other. This has been a challenge in the standardisation work, which is shown with the Guidelines provided by the CG (153). The user interface is not standardised, but the appendices suggest standardisation within the topics the CG could agree on.

There are other initiatives aiming to provide user-friendly bridges and open up for digital innovation (155). The Openbridge project constitutes 20 partners holding a leading international position, and aims to develop an open platform that provides a better and safer user interface on ships. The project presents the challenge in maritime workplaces where digitally integrated multivendor ship's bridges often offer inconsistent user interfaces and suboptimal workflows for navigators. The aim of the project is to enable design consistency across multi vendor ship's bridge systems, and it is argued that there are compelling advantages for the maritime industry in systematically transferring methods, processes and tools from the web industry (156).

3. Methodology

To better understand the challenges of the navigator when using an INS, and to better answer the research questions, several research activities were conducted. The timeline for the research activities in the thesis is shown in Figure 18, being conducted within 4 years.

Figure 18: Research activities timeline

The first stage was to investigate and better understand the challenges that the modern HSC navigator is faced with when using and utilizing the navigation systems at the bridge. The insider perspective presented valuable knowledge, which was further investigated. This was conducted through a literature review and with qualitative measurements as informal interviews and observations in field- and simulator studies.

The second stage was to utilize eye tracking technology as a research tool. Eye Tracking Glasses (ETGs) was chosen to collect information about the visual perception of the navigator. This also included a thorough literature review to investigate and build an understanding of the use of ETGs, and how to analyse and utilize eye tracking data in maritime usability studies.

The third stage was to utilize the findings from the eye tracking data to better facilitate for the work of the navigator. This was done by using the HCD-process, described in section 2.7, shown in Figure 19.

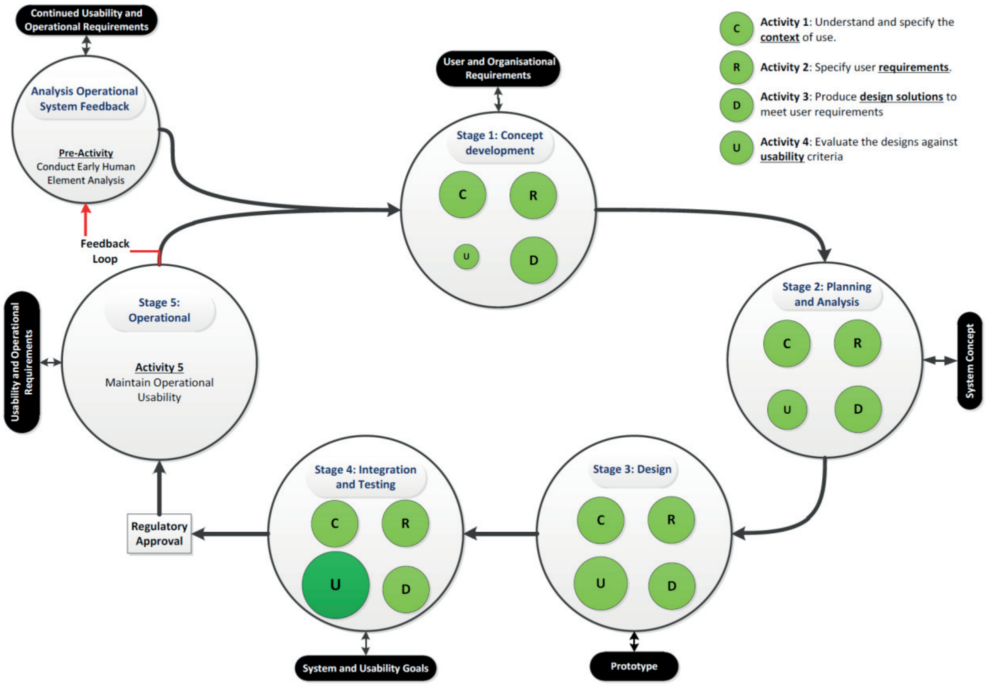

Figure 19: Overview of the HCD process (26)

The HCD-process was facilitated in order to ensure that human factors-related knowledge and techniques in system design and development processes were addressed, thus ensuring that user needs and safety were met (26). The HCD process was operationalised in a working group, which consisted of HSC navigator's (end-users), software engineers from the Original Equipment Manufacturer (OEM), Human Systems Integration (HSI) experts and HSC navigation experts. The HCD-process resulted in a new route information tool and a revised navigational bridge layout of a HSC.

3.1 Research approach

When preparing this thesis, it is important to note the pros and cons of the insider perspective. The perspective is a paradoxical one, as it is to be acutely tuned-in to the experiences and opinions of others, and at the same time the researcher needs to be aware of how own biases and preconceptions may influence what the researcher is trying to understand (157). The personal and professional role of the researcher will provide an important contribution to the research (158), and in this work the insider perspective was important to gain access to data and to provide an insight in the work of the HSC navigator. It is however important that the researcher is aware of being an insider, embedding it in the research design (159).

Research approaches are plans and procedures for research that involves the steps from broad assumptions to detailed methods of data collection, analysis, and interpretation (160). There are several research approaches that could have facilitated this thesis, e.g. a mixed method approach (161, 162) or a case study (163). The research approach in this thesis is grounded on Schneiderman's (164, 165) theory of Achieving Breakthrough in research through Collaboration (ABC), and the use of the combined science, engineering and design (SED) principle. The ABC principle is based on the combination of applied and basic research to produce higher-impact research, compared to doing them separately. Schneiderman further explains the SED principle, where the concept of blending Science, Engineering and Design is done to produce higher-impact research. The principles are based on a mixed method approach, and is shown in Figure 20.

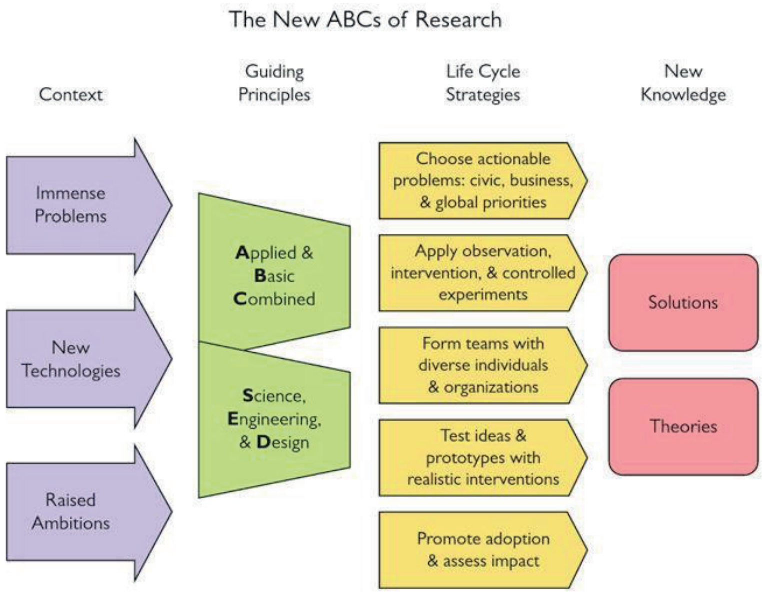

Figure 20: The New ABCs of Research (164)

Schneiderman encourages researchers to use the research methods observation, intervention and controlled experiments, in order to collect research outcomes as new knowledge. New knowledge can be in the form of practical solutions (e.g. devices or problem fixes etc.) and practical guidelines (best practise, how-to manuals etc.). New knowledge can also be presented as new theories (methodologies), which consist of a clear description, causal explanations and reliable predictions (164, p. 8).

The research approach in this thesis combines (mix) qualitative- (observations, interviews) and quantitative (experiments in field and simulator studies) methods to establish a better understanding (new knowledge) of the work of the HSC navigator.

3.2 Apparatus

The quantitative data was collected in field studies on board the Skjold-Class Corvette and in simulator studies by using navigation simulators, with the use of ETGs.

3.2.1 Skjold-class Corvette

The Skjold-class Corvettes is a SES 47,5 metres long, with a beam of 13,5 metres, and a top speed exceeding 60 knots. As a warfare tool, the high-speed makes the vessel a difficult opponent due to the large area of operation, and this is an important feature and advantage when utilizing the Skjold-class Corvettes. An important capability of the Skjold is its covert operation in littoral warfare, particularly in using Norway's coastal topography with its islands and fjords, to carry out surveillance and engage hostile forces while remaining undetected. The shallow draught of 0.9m (air cushion in force) to 2.3m (no use of air cushion) allows the ship to access very shallow waters denied to other vessels. This implies that the navigation crew on the Corvettes have got to have extensive knowledge of coastal navigation, in order to utilize the topography and the speed of the vessel. The navigation team of the Skjold-class conducts the challenging tasks of navigation in littoral waters under potential severe weather conditions.

Figure 21: Navigation team on board Skjold-class Corvette

The navigation team on board the Skjold-class Corvette consists of two persons, the Officer of the Watch (OOW) and the Navigator. The OOW is situated in the left-side chair (port), and the navigator (female in Figure 21) in the right-hand chair (starboard) on the bridge. The navigator conducts the passage, while the OOW monitors and holds a veto in the conduct of the navigation. The navigation tasks are partitioned in the team, and as an example the OOW is responsible for the ship technical monitoring systems during the passage. The navigation information is collected from a state-of-the-art navigation system, by integrating information and presenting it on MFDs. The navigator can choose between the main applications of the INS which is the ECDIS, Radar and Conning, and present it on any of the three MFDs in front of the navigation team (Figure 12). The aim is to ensure that the workload is kept within the capacity of the navigation team, to enhance safe and efficient navigation.

3.2.2 Bridge Navigation Simulator

The Royal Norwegian Navy Navigation Competence Centre (NCC) Simulator Department has seven bridge simulators, as shown in Figure 22.

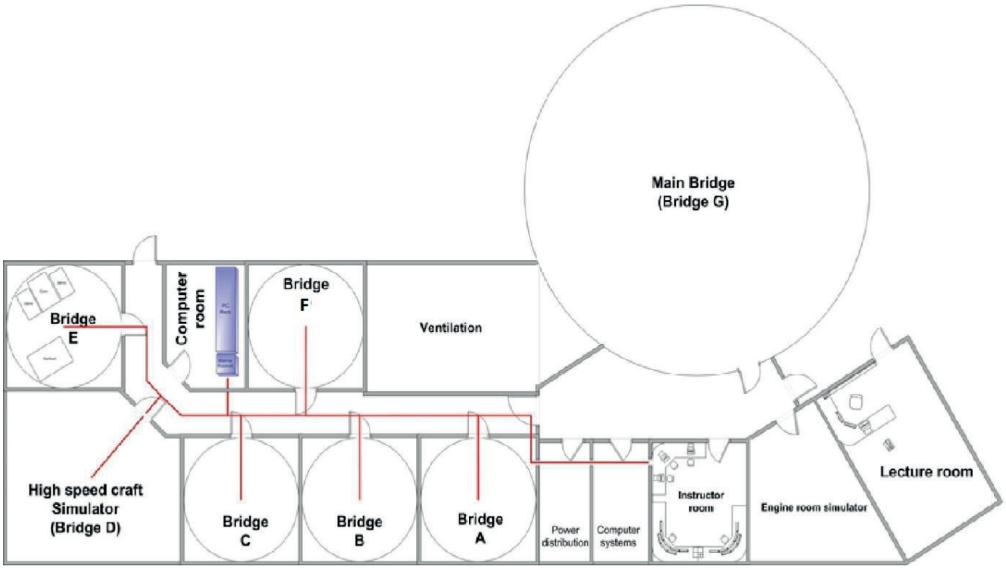

Figure 22: Navigation Simulator at NCC (courtesy of NCC)

One of the bridge simulators is a HSC simulator (Bridge D), where the commercial of the shelf (COTS) equipment is nearly identical with the actual navigation bridge of a Skjold-Class Corvette (1 to 1). The HSC simulator is shown in Figure 23.

Figure 23: Skjold-class bridge navigation simulator at NCC, bridge D (courtesy of NCC)

The Navigation Simulators (NavSim) are used to train the cadets at the RNoNA and staff that are manning the vessels of the RNoN. The NavSim has evolved steadily throughout the years, with the HSC simulator (Bridge D) as the latest addition, built and delivered in 2010. The NavSim has been a cost-effective and important tool in training the cadets and the officers in the craftsmanship of navigation (166). The Corvette Service extensively uses the Skjold-class bridge simulator for training and quality assurance. As an example, the highest level of navigation clearance is complete after completion of the Skjold-class OOW course. 50% of the practical navigation exercises are conducted in the Skjold-class bridge simulator, and the feedback from the end users on the use of the simulator is good (167). The importance of the 1 to 1 navigation simulator is highlighted by the RNoN Corvette service appreciating the Skjold-class bridge navigation simulator as their seventh vessel (35).

The simulator bridges are fitted with Kongsberg Simulators, with a K-Bridge installed on all seven simulators. The instructor station runs on Polaris, and the instructor sets the scenario based on the desired outcome of the exercise. Variables such as area, weather, visibility, traffic density, drift and sensor errors can be set by the instructor. Scenarios can be stored in a database, and the instructor can extract data from each run from the instructor database. The instructor station facilitates debriefs, and replays of scenarios can be conducted.

3.2.3 Eye Tracking Glasses

ETGs are head-mounted eye tracking technology devices, which have both illumination and cameras mounted on the head of the participant. These could be mounted on a helmet, cap or in a pair of glasses. A scene camera will take the role of recording the stimulus, which is the scene of view (110).

Eye Tracking Glasses used in this study were from two OEMs; Tobii and SensoMotoric Instruments (SMI), and the models in use were Tobii Pro Glasses 2 and SMI ETG 2w as shown in Figure 24 and 25.

Figure 24: SMI ETG 2w (courtesy of SMI)

Figure 25: Tobii Pro Glasses 2 (courtesy of Tobii AB)

Two different OEMs were used to gain more insight into different makes of ETGs. The two ETGs are compared in Paper 2 and the pros and cons of using ETGs in a maritime usability study are presented. However, there are several factors that the researcher must address when using ETGs. To facilitate a proper data collection, the study design is essential when setting up an experiment with ETGs (110). The main challenge is not necessarily collecting the data, but analysing the data to provide a good understanding of the data collected (168). The recorded eye tracking data can be analysed in the OEM software, such as the Tobii Pro Lab (169), or in statistical programs such as Microsoft Excel, SPSS, Matlab etc.

The average accuracy, precision and detected gaze values for an ETG are important for an understanding of the data quality provided. This could be presented by the OEM, and it is thus important to understand the method used when conducting the performance test. Tobii Pro Glasses 2 Performance Test Report (170) provides an overview of the Tobii Pro Glasses 2 Eye Tracker Performance Test results, and looks at the impact of several environmental factors on the accuracy and precision performance. The overall results are presented in Figure 26, and presents the average binocular accuracy, precision (RMS) and detected gaze results for all test conditions.

Conditions		N	Accuracy (°)	Precision (°)	Detected Gaze (%)
Ideal	≤15°	20	0.62	0.05	99
Large gaze angles	>15°	20	3.05	0.62	92
Lighting conditions	1 lux	20	1,86	0,14	98
	300 lux	20	0.62	0.05	99
	3000 lux	19	0.79	0.22	99
	Black background	20	0,86	0.06	99
Distance to target	0,5-3m	17-20	0.56-0.73	0.11-0.05	98-99
Glasses removal	Reposition	20	0.73	0.09	97

Figure 26: Overall results Tobii Pro Glasses 2 Performance Test Results (170)

In the performance test twenty participants were measured, and N is the number of participants with valid data. For the distance to target tests, where several tests were performed, the best and the poorest value are specified.

3.3 Qualitative method

Observations are defined as "the systematic description of events, behaviours, and artefacts in the social setting chosen for study" (171, p. 79). Observations will enable the researcher with the ability to describe existing situation using multiple senses, providing a "written photograph" of the situation under study. When using observations, it is important to be aware of the advantages and disadvantages of using participant observations. Advantages such as access to the "backstage culture" (insider perspective), providing opportunities for viewing unscheduled events in their natural working environment, and gaining important insight in the everyday work is outlined. Disadvantages such as only collecting the representation of events during the field study (which could not provide the full picture), observing only the outliers of the groups (amount of participants in the study), and also the observers' role should be considered (172).

Two field studies were conducted on board the RNoN Skjold-class corvettes, to conduct observations. This was done to better understand the working environment, and to discuss the challenges with the conduct of navigation with the navigators on board in their real environment. The field studies were conducted in 2016 and 2017.

The field studies were conducted in Norwegian littoral waters, and on board two different vessels. The use of several vessels was done to provide observations on several objects, for a better foundation of the understanding of the work of the HSC navigator. The data collection was conducted in the vessels area of operations and under normal conditions for that time of year. Note that the working environment could rapidly change in the maritime domain, and the amount of movement and challenges will provide different observations for the data collection. Observations were also carried out in the NavSim to better understand the use of the Skjold-class bridge navigation simulator.

The interviews were conducted as informal interviews during the passage, in order to collect information and gain a better understanding regarding the research questions. The characteristics of informal interviews are that the interviewer talks with people in the field informally, without use of a structured interview guide of any kind. The interviewer either tries to remember the information or use jottings to recall the information done during participant observations. Informal interviews may foster low pressure interactions with the participants, allowing them to speak more freely. Informal interviews are an essential part of gaining a better understanding of a setting, and the participants' ways of seeing it (173).

3.4 Quantitative method

Quantitative research is explained as the systematic empirical investigation of observable phenomena via statistical, mathematical or computational techniques. The quantitative measurements in this thesis is eye tracking data, collected by using ETGs which is presented in section 3.2 and through the theoretical foundation presented in section 2.5 and 2.6.

In this study there are three main data collections. The first data collection was conducted with SMI ETGs when preparing paper 1, which consisted of both a field study and a simulator study. The second data collection was conducted in a field- and simulator study with Tobii ETGs, and was done when preparing paper 2, 3 and 4. The third and final data collection with Tobii ETGs was done in the NavSim in order to validate the findings from the second data set, and are presented in paper 5. It has also been performed pre-studies in advance of the three main data collections, for the validation of the design method before the conduct of the data collection.

The timeline for the three data collections are shown in Figure 27, note that due to the spread in time, different participants attended the three data collections.

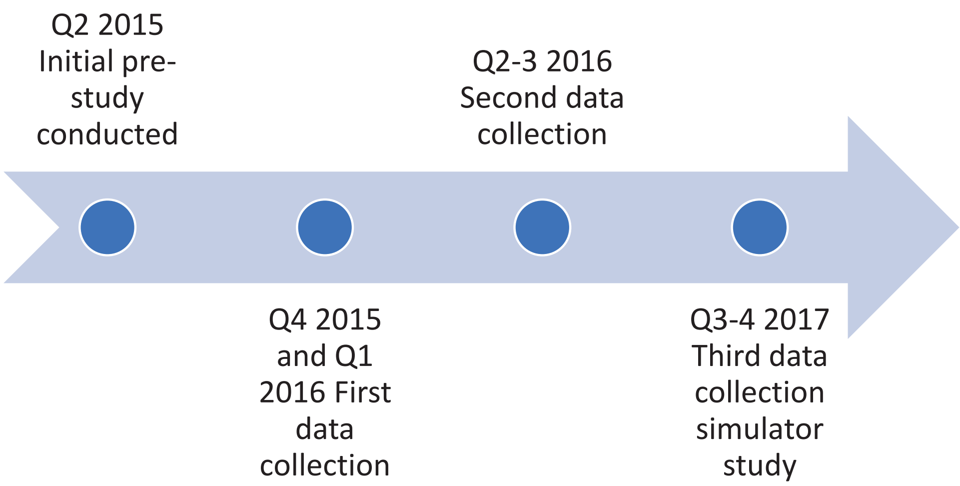

Figure 27: Timeline eye tracking data collection

The third data collection also consisted of a failed eye tracking data collection conducted in Q3 2017. The reason for failure was due to poor design and biased eye tracking data due to several late changes in the programme due to operational demands in the RNoN.

The scope of the collected eye tracking data has been relatively extensive. The first data set consisted of 2 hours and 25 minutes of recorded data, the second data set consisted of 2 hours and 57 minutes of recorded data and the third data set of 6 hours, 12 minutes and 24 seconds of recorded data. In total 11 hours, 34 minutes and 24 seconds, and in addition the pre-studies and the failed third data set has been analysed. As a rule of thumb, ten minutes of eye tracking data takes one hours to analyse. An approximate of 82 hours of pure analysing in the software has been put into the data presented in this thesis, in addition to the time used in statistical programs such as Excel to further interpret the eye tracking data metrics.

3.4.1 Participants

All participants were officers in active duty in the RNoN, and volunteered for the data collection. It has been important for the study to have personnel in active duty, to increase the validity of the data set. The pre-study was conducted with students at the RNoNA, and the data set indicated differences between students and active personnel; this could be due to experience level. The experience level of the participants varied from half a year as a navigator, to five and a half years as an HSC navigator on board the Skjold-class. To become a Skjold-class navigator, four years of education on the RNoNA has been completed. RNoNA syllabus is in accordance with the STCW-convention and provides the theory for Deck Officer Class 1 certificate, in addition to covering the demands for the military navigator (174). Some of the participants had experience from other vessels, and all the participants had experience from navigation training on smaller training vessels.

The participants span in age from 24 to 36 years, with a total amount of 14 males and 2 females. It has been challenging to get hold of participants due to the operational demands in their active duty, making the design of the data collection cumbersome. All participants were informed of the study and data collection and signed a consent form (appendix A).

3.4.2 Pre-studies

Before each of the three main data collections described in Figure 27, a pre-study was conducted. Holmqvist et al. (110) underlines the importance of a pre-study, in order to improve study design and obtain valuable experience both in the handling of the equipment and the design of the scenario. After the pre-study, a reiteration of the study design was conducted to optimize the scenario. The pre-study was the initial design of the data collection and was conducted to identify challenges or flaws in the data collection design. When using ETGs, the hardware and software is sensitive, and knowledge of the use of the equipment is essential to avoid loss of data. Participants used in the pre-study was not part of the main data collection, as they could be biased when conducting the main data collection.

The first pre-study with ETGs was conducted Q2 2015, and the experiences from this pre-study was valuable in identifying the challenges when collecting eye tracking data. The main findings from the initial pre-study was:

1. Calibration process on each participant
    a. Re-calibration during data collection
2. Sensitivity in data collection
    a. Wire- and wireless connections
    b. Movement of ETG during recording
3. The use of the ETG
    a. Reference point when collecting data
    b. Like wearing glasses
4. Battery time constrains
5. Creation of AOIs
    a. The quality of the data, especially concerning resolution
6. Time consuming process of analysing recorded eye tracking data

3.4.3 Field study

The first field study was conducted on board HNoMS *Storm* in November 2015, in the northern parts of Norway. The second field study on board HNoMS *Skudd* in May 2016. The working environment on board a Skjold-class Corvette is challenging, and the eye tracking data collection was conducted during ongoing operations of the vessel. The challenges of collecting eye tracking data is presented in paper 2, while paper 5 underlines the importance of a cost-benefit analysis before conducting an eye tracking data collection on board a vessel in ongoing operations. The demand for availability of vessels are high, and collection of eye tracking data competes with the daily activity on board. This implies that the researcher should not expect getting time in an already tight vessel programme for data collection, and the data collection design must thus adapt to the vessel programme. Collecting data in a field study is more difficult than in a simulator study, due to the nature of the changing environment (175).

During the eye tracking data collection, light conditions are a key factor for good data quality. As an example, the glare from the infrared sensors in the ETGs hampers the safe navigation during twilight and darkness in littoral waters. Northern parts of Norway are mainly dark during the winter period, and there is a time-constraint with data collection in daylight. When the participant got accustomed to using the ETGs, they did not take much notice of wearing it.

3.4.4 Simulator study

The simulator studies were conducted in the NavSim at the RNoN NCC as described in section 3.2.2. The simulator study has been designed to fit the field study, as most of the variables are controllable.

The geographical areas of data collection in the simulator have been different from the field study, due to limitations in the NavSim database. The database of the Norwegian coastline is continuously improving, and this challenge will improve with time. The simulator scenario was designed to be as closely related to the field study data collection as possible, but there were differences due to the availability of the exact area where the field study was conducted.

The simulator studies were conducted in the 1 to 1 Skjold-class bridge simulator (Bridge D, Figure 22). The bridge simulator has the exact same layout, hardware and software as on board the Skjold-class Corvettes and is shown in Figure 28.

Figure 28: Skjold-class bridge simulator at NavSim

3.5 Analysis of Eye Tracking data

When the data are collected with the ETGs, the next step is to import all data to the analysing software. Analysis of the data collected with the SMI ETGs was processed in the SMI software analysis software BeGaze (176). The data collected from the Tobii Pro Glasses 2 were analysed in the Tobii Pro Lab software (169), which is a software platform designed for extensive research into human behaviour. The eye tracking data collected with SMI ETGs were analysed in co-operation with the Institute for Energy Technology (IFE).

The data about participants and recordings, stimuli to use or be used, and study layout are all stored in the projects section in Tobii Pro Lab (169). Each project can contain numerous recordings, participants, timelines, snapshots, mapped data and events. To start an analysis, a project must be generated. When importing the data, a recording list will be presented. The recording list is the main content in the project overview, and it contains useful information about the recordings available in the project.

- Recording: The name of the recording
- Participant: The name of the participant (anonymised)
- Duration: The duration of the recording
- Date: Shows the time and date when the recording was performed
- Gaze Samples: The percentage is calculated by dividing the number of eye tracking samples that were correctly identified by the theoretical maximum. In an eye tracker with a 50 Hz sampling frequency, there will be 50 samples per second. If all samples could be used by the software to calculate gaze points, the value in the Gaze Samples column would be 100%. It is very unusual to get 100% in this column, as some samples will always be missing due to e.g. the participant blinking. Blinking usually causes around 5-10% data loss during a recording.

The data collector or the researcher can map eye tracking data onto a still image (snapshot) of the environment in use, and the snapshots images are typically created by using a digital camera. When conducting this process, dynamic data are mapped onto a static snapshot. The mapped data will be represented by squares with the width corresponding to the time between two samples from the eye tracker (e.g. 20 milliseconds for data from Pro Glasses 2 with a 50 Hz data rate). The process can be automatic, semi-automatic or manual. A diagram indicates how confident the Real-World Mapping software in correctly estimating each mapped gaze point for that position in the recording. A high value indicates high confidence and a low value low confidence level. A low confidence level does not necessarily mean that the data is wrongly mapped – just that the software is not entirely sure it is correct. The automatic mapping function does not function optimally when collecting data in a dynamic environment, thus the process needs to be controlled manually (semi-automatic). The semi-automatic process is conducted by clicking on the point of the snapshot where the gaze sample of the participant is directed. As each sample needs to be evaluated by the analysist, the process of mapping is time-consuming. A general rule-of-thumb is one hours of analysing 10 minutes of recording.

To better understand the eye movements, there is a section where it is possible to see if gaze data is recorded for that time on the timeline and, if there are data, how data are classified by the currently-used Gaze Filter (i.e. fixation, saccade, or unknown). Fixations are visualized as solid bars, saccades as thin lines, and unclassified data as grey bars.

The software provides an analysis tool, which gives you these options:

- Visualizations: To create visualizations (heat- and focus maps or scan patterns) based on the gaze data on top of your stimuli or snapshots. For visualizations to appear on a Snapshot image, data from Pro Glasses 2 must have been mapped onto the snapshot.

- AOI editor: Draw Areas Of Interest (AOIs) on your snapshot images. AOIs are used to enable numerical/statistical analysis based on regions. Once an AOI has been created, eye tracking metrics can be exported onto the snapshot.
- Metrics Export: In order to export the eye tracking metrics based on AOIs or Events for further analysis in third-party software, such as SPSS, Microsoft Excel, Matlab, etc.
- Data Export: In order to export the eye tracking data for further analysis in third-party software, like SPSS, Microsoft Excel, Matlab, etc. Unlike the Metrics Export, the data available in this export are not tied to AOIs. Instead, you get access to raw gaze data, such as gaze point in different coordinate systems, pupil diameter for each eye, the eye position, and information about the recordings, in general. Information about whether gaze data fell within AOIs are also included, but metrics regarding AOIs are not given.

A considerable amount of work is required to develop the use of eye tracking technology as a practitioner's method, especially when it comes to the analysis. It is argued that the analysis can provide valuable objective data about the impact of visual design on human performance (177). There are several methods of analysing the data, and using the OEMs software is only one of them (178). The pros of using the OEM software is the ease of use, and it does not require knowledge of coding when utilizing it. The cons of the OEM software are not having access to the full range of eye tracking data variables (e.g. eye blinking), and the range of visualization techniques are not complete. There are numerous methods of analysing and presenting the raw eye tracking data, which is outside the scope of this thesis.

3.6 Presentation of statistical model

There are several models which could have been used to analyse the collected eye tracking data, e.g. a likelihood model (179). The model chosen to best fit the collected data set in this thesis, has been developed in co-operation with a statistician from the Technology Department at the RNoNA.

The statistical analysis has been conducted in four steps:

Step 1: Establish model

Step 2: Check assumption (conduct test) concerning normal distribution

Step 3: Conduct F test (assumption of normality)

Step 4: Conduct t-test. Test the mean. Analysis of variation (ANOVA). Assumption of equal variance

The generation of the analysis has been conducted in Microsoft Excel, by using the eye metrics data which is generated for presentation in Excel.

3.6.1 Statistical model

This chapter presents a statistical model which outline how the eye tracking data set has been analysed. The statistical model in use embodies a set of assumption concerning the generation of the eye tracking sample data and the population in use.

The statistical model consists of two sets of data; X with n number of participants, and Y with m number of participants. The significance level is set to 5%.

The data sets can be any identical eye tracking metrics from two data sets, for example X is period of time in percentage in any given AOI in data set 1, and Y is period of time in percentage in the same AOI in data set 2. The X's and Y's could for example be the total time in AOI ECDIS for the two data set compared in the first or third data collection.

Data set 1		Data set 2	
n observations		m observations	
Variable	**Observation**	**Variable**	**Observation**
X_1	x_1	Y_1	y_1
X_2	x_2	Y_2	y_2
…	…	…	….
X_n	x_n	Y_m	y_m

Table 1: Presentation of data in statistical model

All variables/observations are assumed independent normally distributed random variables.

It is further an assumption that:

$$X_k \sim N(\mu_X, \sigma_X) \text{ for } 1 \le k \le n \text{ and } Y_k \sim N(\mu_Y, \sigma_Y) \text{ for } 1 \le k \le m$$

Which means the two data sets consisting of X's and Y's that are normally distributed, with means μ_X and μ_Y, and standard deviations σ_X and σ_Y, respectively. These four parameters are all unknown.

Without no further assumptions upon the parameters, the parameters are estimated by the averages and the empirical standard deviations in each data set.

$$\hat{\mu}_X = \bar{x} = \tfrac{1}{n}\sum_{k=1}^{n} x_k \text{ , } \hat{\sigma}_X = \sqrt{\tfrac{1}{n-1}\sum_{k=1}^{n}(x_k - \hat{\mu}_X)^2} \text{ , } \hat{\mu}_Y = \bar{y} = \tfrac{1}{m}\sum_{k=1}^{m} y_k \text{ and } \hat{\sigma}_Y = \sqrt{\tfrac{1}{m-1}\sum_{k=1}^{m}(y_k - \hat{\mu}_Y)^2}$$

The assumptions that the data in each group is independent identically distributed is not tested. However, the assumption of normality in each group will be tested. This assumption is crucial when a test for equal standard deviations is conducted. The last step will be to test for equal means in the two groups, which will depend on the conclusion from the equal standard deviations test.

3.6.2 Normality test

If $X_1, X_2, \ldots, X_n$, are random variables, it is of interest to test the hypothesis:

H_o= The probability distribution is normal against H_1 = The distribution is NOT normal

The procedure for a test based on normality plot is as follows (180).

1. Calculate the standardised values of the observations:
   $z_k = \frac{x_k - \overline{x}}{\hat{\sigma}}$ for k = 1, 2, … , n and let $o_{(1)}, o_{(2)}, \ldots, o_{(n)}$ be the z_k's in increasing order.
2. Define:
   $m_1 = 1 - \sqrt[n]{\tfrac{1}{2}}$, $m_k = \frac{k - \frac{127}{400}}{n + \frac{73}{200}}$ for k = 2, 3, … , n – 1 and $m_n = \sqrt[n]{\tfrac{1}{2}}$.
3. Calculate $q_k = \Phi(m_k)$ for k = 1, 2, … , n, where $\Phi(z)$ is the cumulative standard normal distribution function.
4. Establish the normality plot. That is: Plot the points $(q_1, o_{(1)}), (q_2, o_{(2)}), \ldots, (q_n, o_{(n)})$
5. Calculate the correlation ρ between the *q*'s and the *o*'s.

If the correlation ρ falls below a certain critical value, depending on the number of observations n and the choice of significance level, the hypothesis of normally distributed data is rejected.

Example with n = 9 $\rho^2 = 0.917 \Rightarrow \rho = 0.9576$
(Critical values from http://itl.nist.gov/div898/handbook/eda/section3/eda3676.htm)

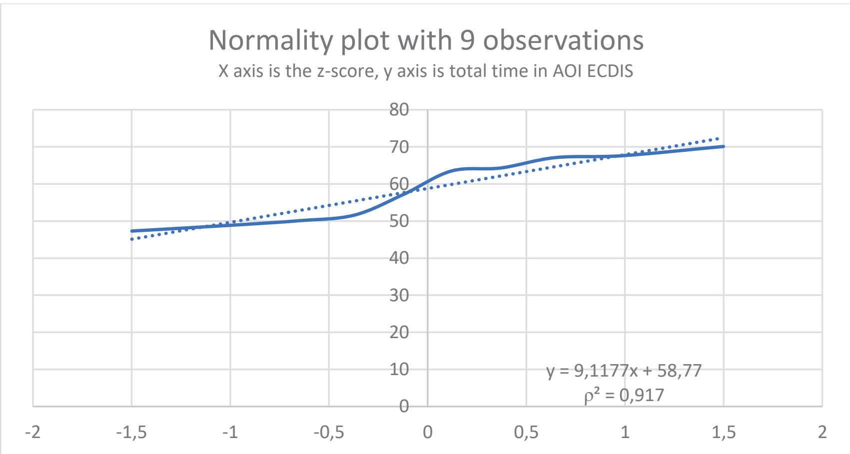

Figure 29: Normality plot third data collection of variable percentage of time in AOI ECDIS

3.6.3 F-test

The F-test is conducted to test for equal standard deviations (180), and can only be conducted with the assumption of normality (with reference to the Statistical Model):

$$H_0: \sigma_X = \sigma_Y \text{ against } H_1: \sigma_X \neq \sigma_Y.$$

The F-test is generated in Microsoft Excel, and the procedure is:

1. Calculate the F-statistic: $f_{obs} = \frac{\hat{\sigma}_2^2}{\hat{\sigma}_1^2}$, the ratio of the empirical variances.
2. When $\sigma_x = \sigma_y$ the distribution of f_{obs} is a F-distribution, with m − 1 and n − 1 degrees of freedom.

$$p\text{-value} = \begin{cases} 2 \cdot P(F \leq f_{obs}), \text{ if } f_{obs} < 1 \\ 2 \cdot P(F \geq f_{obs}), \text{ if } f_{obs} > 1 \end{cases}.$$

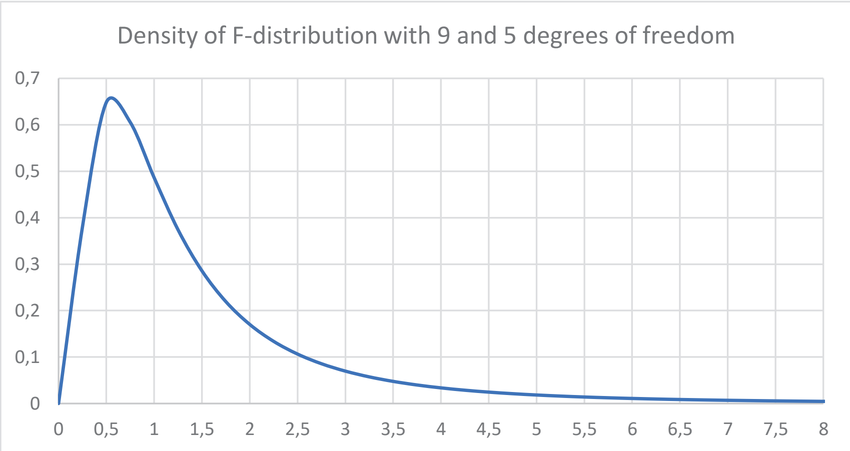

Figure 30: Example of F-test distribution

If the *p*-value is below 0,05 (5%), the null hypothesis is rejected with a 5% significance level. If not, the null hypothesis is not rejected.

3.6.4 t-test

The final step is an analysis of variances (ANOVA), and aims to test:

$$H_0: \mu_X = \mu_Y \text{ against } H_1: \mu_X \neq \mu_Y.$$

This is done with a two sample t-test (180).

1. T-test is based on equal variances when $H_0: \sigma_X = \sigma_Y$ is not rejected from the F-test. (If $H_0: \sigma_X = \sigma_Y$ is rejected a Welch's t-test must be conducted (180).)
2. The degrees of freedom (*df*) is the sum of the number of participants in each data set, minus two:

$$df = n + m - 2.$$

3. We calculate the T-statistic t_{obs}, based on the mean values of X minus Y, divided it by the group variance (S_p), multiplied it by the root of the sum of the inverse number of participants in each group:

$$t_{obs} = \frac{|\bar{x} - \bar{y}|}{s_p \sqrt{\frac{1}{n} + \frac{1}{m}}} \text{ where } s_p = \sqrt{\tfrac{1}{n+m-2}\left((n-1) \cdot \hat{\sigma}_X^2 + (m-1) \cdot \hat{\sigma}_Y^2\right)}.$$

4. The t-test is conducted with the Excel data analysing tool for t-test.

a. *p*-value = 2*P(T > t_{0bs}), where T is T-distributed with *df* degrees of freedom.
b. The data analysing tool for t-test based on equal variances generates an output for the variables with mean, variance, number of observations (participants), group variance, degrees of freedom, t-Stat, p-value one-tailed, critical T-value one tailed, p-value two tailed and critical t-value two-tailed. The input values are the eye tracking data variables selected (e.g. total time in AOI Outside in the two data sets to be compared).

5. The two-tailed p-value presented in the data generation used is normally compared to a significance level of 5% (α=0,05). If the *p*-value is below 0,05 (5%), the null hypothesis is rejected with a 5% significance level. If not, the null hypothesis is not rejected.

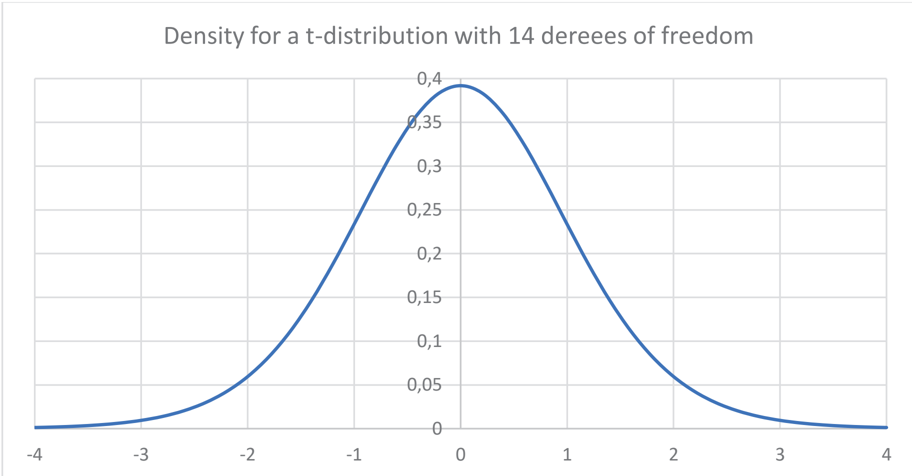

Figure 31: Example of T-test distribution

3.6.5 Challenges with the statistical model

The number of participants available for conducting the data collection has been challenging. Conducting research on personnel in active duty is cumbersome, due to their tight schedule. The number of participants could always be higher, but the percentage of available participants in the study is high. As an example, 13 subjects participated in the test conducting 19 runs. It would be beneficial with a higher number of test objects, but the number of relevant personnel is limited. The RNoN has six Skjold-class in service, with two navigation teams on each vessel. Thus 54.2% of available personnel participated in the third data collection. When collecting data from personnel in active duty, the operational demands will be prioritized over research.

The significance level of the statistical model is set to 5%. There have been discussions regarding the need for redefining significance. In 2016, the American Statistical Association (ASA) published a statement on p-values, noting that "the widespread use of statistical significance (generally interpreted as $p \leq 0.05$) as a license for making a claim of a scientific finding (or implied truth) leads to considerable distortion of the scientific process" (181). In 2017, a group of 72 authors proposed to enhance reproducibility by changing the p-value threshold for statistical significance from 0.05 to 0.005 (181). When using the term significant, we cannot automatically imply that the data is important. It is a term that is used to assess whether the evidence against the null hypothesis has reached the standard set by significance level (α) only (182). Practical significance is concerned with weather the results can be used in the real world (183). By presenting the results in technical workgroups with the end-users and the OEM engineers, the practical significance level is argued to increase.

It is further argued that an amount of 10 participants within an user test will find approximately 75% of all usability problems, and that the amount of participants must be chosen based on a cost-benefit analysis (184).

3.7 Reliability, validity and objectivity

The term reliability means dependability or consistency, and is related to the same thing being repeated or recurred under the same or similar conditions (185). Collecting eye tracking data in the wild with field studies, decreases the reliability of the data set, because of uncontrollable variables. When using the simulator, reliability increases, as the external variables can be controlled.

The term validity suggests truthfulness and is related to how well an idea "fits" the actual reality. Validity addresses the question of how well the social reality that is measured through research matches with the constructs researchers use to understand it (185). The data collection was conducted both in field studies and in simulator studies, in order to collect data to answer RQ1 (Can eye tracking data be used to evaluate and compare the effectiveness of live- and simulator based navigation training?). The Skjold-class simulator is a 1 to 1 bridge, and this increases the validity of the data collection. Collecting data in a simulator study will not provide the exact same results as in a field study, due to the nature of the simulator environment, but can serve as a suitable substitute. A simulator study is recommended when the testing focus is on the user interface and application-oriented usability related issues (175). The use of operational navigation crews compared to nautical students increases the validity of the collected eye tracking data.

Objectivity is defined as the opposite of subjective: external, observable, factual, precise and quantitative. It could also be defined as logical; created by an explicit rational procedure, absence of personal or arbitrary decisions, which follow specific pre-established rules (185). The author has been working in the RNoN for 16 years and did active service in the Corvette service up until 2012. It is thus important to underline the challenges with objectivity for the researcher. When in operational duty, the researcher experienced many of the design issues on the Skjold-class navigation bridge. The researcher could be affected by own experience, and this challenge must be faced by the research design. On the other side, the experience as a navigator puts the researcher (with domain knowledge) in a unique position where the understanding of the working environment and tasks of the navigator can be used to conduct a better design of the research methods. The background of the researcher is an important part of the synthesis when this thesis was founded. Bandura (186) states that his theories in many ways reflect his own life. Being exposed to external influences but also experiencing the power to making own decisions and governing own behaviour and hence influencing the external environment, led Bandura to make his own path of life. A combination of these influences both exposes the necessary experiences and examples to reflect on, the theory needed to "see", and the vocabulary needed to reflect on reality and the phenomenon in light of theory. The personal experiences of the author when working as a navigator and technical manager, has been imperative for the foundation of this thesis.

4. Performed studies and findings

This section will present each of the papers with the aim of underlining the research question which the paper is answering. This is done by presenting the background of the research question together with the method used for exploring the research question, before the findings of the papers will be highlighted and elaborated.

The aim of the papers is to answer the following research questions:

RQ1: Can eye tracking data be used to evaluate and compare the effectiveness of live- and simulator based navigation training?

RQ2: Can eye tracking data be used to map and better understand the visual attention of the HSC navigator?

RQ3: Is the visual scan pattern of the HSC navigator optimized in order to facilitate integrity monitoring of the INS by the navigator?

RQ4: Can eye tracking data be effectively used in the evaluation of navigational bridge design and the corresponding graphical user interface?

RQ5: Can eye tracking data collected from ETGs be used to validate a design-review of a maritime HSC bridge?

All papers are peer-reviewed (level 1).

4.1 Paper 1

Hareide, O.S., Ostnes, R. (2016). "Comparative study of the Skjold-class bridge-and simulator navigation training**"**, *European Journal of Navigation*, 14(4), 11-17. ISSN: 1571-473-X URL: https://brage.bibsys.no/xmlui/handle/11250/2425167

The background of the paper is the RNoN use of navigation simulators which has evolved and increased in the training of new students in addition to the training and assessment of operational navigation crews. The feedback from the students, the OOW and the Commanding Officers (COs) in the RNoN, collected through qualitative methods, has been that the simulator training is increasing the safe navigation of the vessel. The cost-benefit of using simulators compared to live navigation training is evident.

RQ1: Can eye tracking data be used to evaluate and compare the effectiveness of live- and simulator based navigation training?

In addition to RQ1, the eye tracking data set was analysed to better understand the visual distribution of the HSC navigator.

RQ2: Can eye tracking data be used to map and better understand the visual attention of the HSC navigator?

The data were collected with ETGs through a field study on board an operational Skjold-class Corvette, and the field study data was compared with the data collected in a simulator study at the NavSim. The field study was conducted first, in order to recreate the passage in the NavSim. The risk of not collecting operational eye tracking data in the field study resulted in the conduct of a pre-study in the NavSim, in order to gain experience and reduce the risk of data loss during the field study. The findings from the pre-study gained valuable knowledge which was used when designing the field study data collection, and AOIs were established (Figure 12).

The main findings consist of the analysis of visualization maps and numerosity measurements from the eye tracking analysis. As this was the first study conducted, the experience with the use of ETGs concerning possibilities and limitations, in addition to the differences between a field- and simulator eye tracking data collection, was valuable and highlighted. The nautical community took special interest in the visualization maps, which gained valuable insight in the work of the HSC navigator during a passage.

To answer RQ1, numerosity measurements were analysed in order to identify similarities or differences in the eye movement of the navigator. The numerosity measurements that stood out and were furthered analysed were dwell time, fixation time and fixation rate. The main findings in the numerosity measurements were:

1. 3,3% difference in the attention (dwell time) towards AOI Outside.
2. Higher average fixation time in the simulator study compared to the field study. In AOI ECDIS the difference is 19 milliseconds (ms), and in AOI Outside the difference is 86 ms.
3. 13% higher fixation rate in both AOI ECDIS and Outside in the field study compared to the simulator study.

The difference in attention towards AOIs in the field study and the simulator study is not clear. One suggestion is that the difference could be interpreted to be induced to the fact that the real world holds more details than a simulator. There were some differences in the traffic density in the scenarios, which could also be the reason for the difference. The major contribution of the dwell time was the knowledge of how much time the navigator spends in the different AOIs. HSC navigation is normally conducted in a team, and it is imperative that a proper look-out is always conducted due to the high-speed. The averaged collected eye tracking dwell time data shows that the navigator spends 58% of the attention towards the outside of the ship, and 22% of the attention towards the ECDIS.

When analysing the fixation time, the interpretation of a longer fixation means equal deeper processing (110, 121). In Paper 1 these measurements are discussed, and it is suggested that "one possible reason for this could be that the visual display in the simulator and the simulator database is more difficult to cognitively process than the real-life image of the surroundings of the ship. The navigator is accustomed to the real-life image presented in 3D with high definition, and good colour contrasts. The virtual reality, presented on the projectors in the simulator, is in 2D with lower definition and less colour contrast. This could contribute to the more demanding cognitive process in the simulator study compared to the field study" (121, p. 6).

The lower fixation rate in the simulator study compared to the field study is shown in Figure 17. This could indicate that interpreting the visual picture in a simulator is more difficult than doing it in reality, concerning the correlation between fixation rate and task difficulty (123). This finding also supports that the mental workload, due to a more demanding cognitive process of processing the simulator image compared to reality, is higher in the simulator (125).

The main challenges identified concerning eye tracking data collection from the field studies were:

1. Calibration process
    a. Each participant, new calibration, in ongoing operations.
    b. Sensitivity of movement on apparatus.
2. Data loss due to technical failures – Demanding environment for data collection concerning movement and stress.
3. Limitations imposed by the ETG
    a. Light pollution (not usable in twilight or during darkness)
    b. Participants not used to wear glasses
    c. Reduced mobility due to wiring
        i. Not a problem in normal operations, but if a condition arises that induces movement, wiring is a challenge. The solution was to disconnect the equipment, thus hampering the data collection.

The three main challenges identified from the field study are manageable in the simulator, due to control of the time and scenario. However, challenges due to available time of officers in active duty arises. The operational demand supersedes the demand for eye tracking data collection in NavSim, and thus the amount of and type of participants for the data collection did change on short notice. The simulator design was made in order to replicate the field study, however the change of participants on short notices contributed to sub-optimal data collection design.

Paper 1 concludes that the use of a 1 to 1 bridge simulator is efficient when it comes to navigation training and provides the same training outcome as on board the Corvettes. The main differences in eye movements between the field- and simulator study are fixation time and rate. This could indicate that the use of bridge simulators involves a more demanding cognitive process leading to a higher mental workload for the navigator. This should be considered when designing navigation training scenarios, and long training sessions should be avoided. A higher degree of details in the simulator database and a higher simulator display resolution should be investigated in order to compensate for this distinction.

4.2 Paper 2

Hareide, O.S., Ostnes, R. (2017). "Maritime Usability Study by Analysing Eye Tracking Data", *The Journal of Navigation*, 70(5), 927-943. DOI: https://doi.org/10.1017/S0373463317000182

The design and layout of an HSC craft bridge has been evolving, and at the same time the software in use has been adjusted to better adhere to the user needs. When the Skjold-class Corvettes were inaugurated in the RNoN in 2008, with a state-of-the art navigation system, this was a paradigm shift for the military HSC navigator. By utilizing quantitative methods through informal interviews in 2015/2016, several bridge design issues were identified by the navigators. Paper 2 aims to conduct a usability study with the use of eye tracking data, to reveal usability problems and sub-optimal design in the navigation system of the Skjold-class Corvettes. In addition, two different makes of ETGs were tested in order to better understand the possibilities and limitations of ETGs.

The study design builds on the knowledge gained through paper 1, and the study design is the same with some improvements. The main difference is an additional field study data collection conducted with Tobii Pro Glasses 2. The second data collection was conducted in an area which corresponds to the previous data set, in order to compare the two data sets from the different manufacturers of ETGs (SMI and Tobii).

Paper 2 aims to support the research question regarding the amount of Head Down Time (HDT) for the navigator, and if eye tracking data can be used to evaluate bridge design and GUI.

RQ2: Can eye tracking data be used to map and better understand the visual attention of the HSC navigator?

RQ4: Can eye tracking data be effectively used in the evaluation of navigational bridge design and the corresponding graphical user interface?

In order to further support RQ2 (HDT), the eye tracking data were analyzed and attention towards the different AOIs presented. Paper 2 presents an accumulated average of 64.8% of the navigator's attention directed towards the outside of the ship, 26.6 % towards the ECDIS, 4.4% towards the radar and the remaining 4.2% towards information from the displays, consoles and autopilot related to the propulsion and steering of the ship (conning). This supports the findings from paper 1 regarding HDT.

Visualization maps and numerosity measurements were analyzed in order to evaluate the bridge design and software GUI, and three observations were of particular interest.

1. The use of the heading repeater in the radar application GUI.
2. The use of the trip meter display.
3. The use of the ECDIS application GUI.

The attention maps provided valuable insight into where the attention of the navigator was directed in order to better understand which equipment the navigator addressed during a passage. A combination of heat map and sequence chart provided valuable insight into which areas the navigator focused the attention. Especially when identifying time-stealing displays, which are highlighted by the three observations stated above. Combining this with numerosity measurements as look-backs and backtracks, could indicate difficulties with interpreting information in that given area. When analyzing dwell time and look-backs, a ratio of 4.4 was found in advantage of look-backs in AOI Radar. Concerning backtracks, 23.1% of all backtracks were conducted to AOI Radar. In the attention maps, it is shown that the information primarily collected from the radar in the recording was information about the vessels heading. To better understand this finding, the context of use is important. The heading of the vessel is an important part of the control phase, as explained in section 1.2.2, which is a part of the phases of navigation. Thus, the navigator needs to check the heading after each turn. The analysis of the eye tracking data revealed a challenge for the navigator to understand and interpret heading information, which is compensated by revisiting (look-back) and backtracking to the AOI to avoid a misunderstanding. This indicates sub-optimal design of the information presentation of the heading of the vessel. In the same manner, the trip meter was identified as a sub-optimal design of presenting trip distance. The GUI of the ECDIS software was analyzed in the same manner and revealed sub-optimal design of the presentation of route monitoring information to the navigator.

Finally, the usability of the ETGs in a maritime usability study was identified. The use of the ETGs in the study design is highlighted, and the importance of features such as the wires, battery capacity and physical size and weight of the ETGs are presented. The practical use of ETGs must be considered, and it is a recommendation that the participants who are not used to wearing glasses spends some time accustoming to the ETGs. During twilight or darkness, the ETGs induce light pollution and partly hampers the use of binoculars for those not accustomed to wearing glasses. Bright sunshine induces a glare in the ETGs, which could be disruptive for the navigator and hamper the collection of eye tracking data. The method for eye tracking analysis presented in the paper is:

1. Analysis of ocular behaviour (visual perception).
    a. Dwell time
    b. Attention maps
    c. Sequence charts
2. Analysis of scan path events.
    a. Look-backs
    b. Backtracks
3. Identify sub-optimal design and GUI solutions in the working environment of the navigator.
    a. Present a possible solution to compensate for the sub-optimal design.

It is further outlined that this method should be conducted as an iterative process in accordance with the principles in HCD for interactive systems (147).

The difference between manufacturer software is highlighted, and the usability of sequence chart to map attention in different AOIs is recommended. The manufacturer software automatic mapping process is found to be immature to meet the requirements of a maritime usability study.

4.3 Paper 3

Hareide, O. S., & Ostnes, R. (2017). «Scan Pattern for the Maritime Navigator", *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, *11*(1), 39-47. DOI: http://dx.doi.org/10.12716/1001.11.01.03

Introducing electronic navigation on vessels is seen as a paradigm shift for the conservative maritime industry. The RNoN has been training students with the aim of making them as ready as possible for their operational service as navigators (174). One could argue that there is a possibility that teachers and trainers wrongly assume trainees to be at stage 2 in the Conscious Competence Learning Model, and focus effort towards achieving stage 3, when often trainees are still at stage 1 (Figure 8). This is a fundamental reason for the failure of some of the training and teaching within SA of the modern navigator. The primary task of the navigator is to find and fix the position of the vessel, in order to conduct safe navigation. With the introduction of electronic navigation, the navigator has moved from finding and fixing the position to monitoring the position integrated and presented in the navigation system. There has been a concern that the navigator relies solely on the position presented in the navigation system, not checking the position towards visual cues. Thus, the need for a recommended scan pattern for the maritime navigator occurred. When further developing the navigator's craftsmanship, one could look for learning outcomes from another domain such as aviation.

RQ3: Is the visual scan pattern of the HSC navigator optimized in order to facilitate integrity monitoring of the INS by the navigator?

The eye tracking data used in paper 3 is the accumulated data from paper 1 and 2. The data was re-analysed with consideration on the visual scan pattern of the navigator, and visualization maps were the primary analysing method.

The paper compares the visual scan pattern in aviation with the maritime and compares this with the analysis of the eye tracking data. Aviation has clear recommendations for the visual scan pattern, which is divided into two main conditions, good and poor visibility. In poor visibility, navigation is conducted on instruments (IFR), and in good visibility (VFR) a recommended visual scan pattern is in place. The RNoN procedure of phases of navigation, which is a decision-making process in navigation, is presented. In the RNoN navigation procedures, the control phase of the vessels position is divided into two different modes: Visual and radar control. This is comparable with IFR and VFR in aviation, and the paper further presents a suggested visual scan pattern for the navigator with good visibility conditions, as shown in Figure 32.

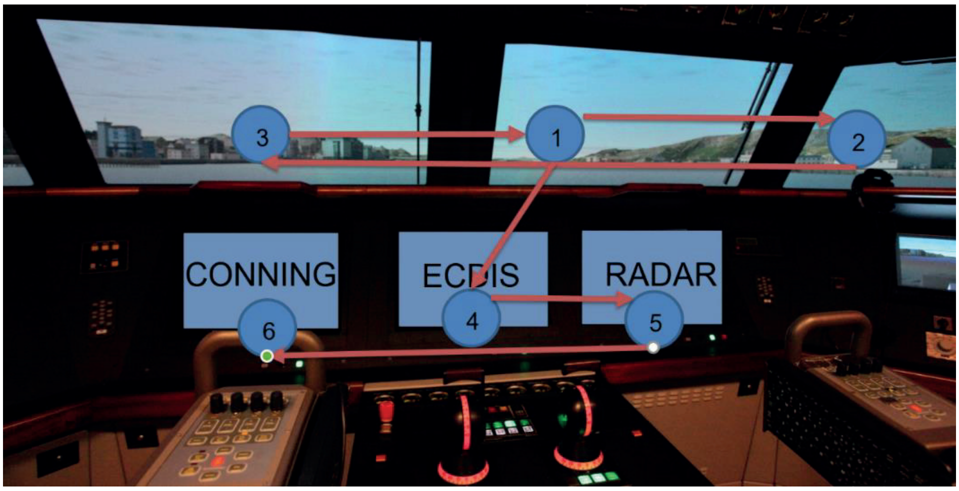

Figure 32: The Maritime Scan (44)

The importance of speed as a factor when establishing the scan pattern is highlighted, as the amount of side scan to identify vessels on potential collision course decrease with speed. Using the surroundings of the vessels to conduct continuous integrity monitoring by checking and comparing the position towards the position in the navigation systems are emphasized. Finally, a recommendation on how much attention the navigator should address towards the relevant AOIs during navigation in good (Visual Sailing Mode – VSM) and poor (Conventional Sailing Mode – CSM) visibility is presented in Table 2.

Area of Interest (AOI)	VSM	CSM
Outside	80%	5%
ECDIS	10%	15%
Radar	7%	75%
Conning	3%	5%

Table 2: Attention in AOIs in different metrological conditions (44).

4.4 Paper 4

Hareide O.S., Mjelde F.V., Glomsvoll O., Ostnes R. (2017) "Developing a High-Speed Craft Route Monitor Window". *Augmented Cognition. Enhancing Cognition and Behaviour in Complex Human Environments. AC 2017. Springer, Cham*, 461-474. DOI: https://doi.org/10.1007/978-3-319-58625-0_33

The planning process on a paper chart was conducted by drawing the passage plan with a pencil and writing notes on how the execution of the passage should be conducted. Since the beginning of the RNoN using the ECDIS, there has been feedback on sub-optimal design in the ECDIS concerning route monitoring information (presenting the written notes from the paper chart). With the increase in speed with the Skjold-class, this issue became more evident. The time-consuming process of collecting route monitor information has been identified, and the RNoN initiated a project with the Mid-Life Update (MLU) of the Skjold-class in order to upgrade the software to better adhere to the navigator information needs.

RQ4: Can eye tracking data be effectively used in the evaluation of navigational bridge design and the corresponding graphical user interface?

The method used in the article is a combination of the eye tracking data collected in the preparation of paper 1 and 2, and the use of the HCD-process within a technical working group. The technical working group consisted of end users, software manufacturer engineers and human factor specialists.

The route monitoring information is vital for the navigator, and the RNoN has established a Standard Operating Procedure (SOP) in order to support the navigation team in establishing and maintain a high degree of SA in order to support safe and efficient navigation. The SOP is aligned with the decision-making process in HSC navigation, phases of navigation. The primary information requirement for route monitoring, with reference to the route monitor information GUI in the Kongsberg ECDIS software is shown in Figure 33:

1. Information about turning object and next heading mark
2. Time to Wheel Over Point (when the turn of the ship is to be conducted)
3. The course on the next leg
4. The distance of the next leg
5. Cross Track Deviation (XTD) which provides information about the ships actual position compared to the planned route

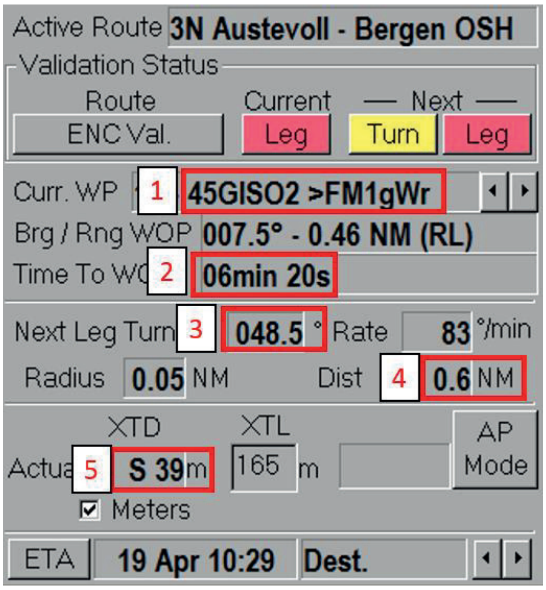

Figure 33: Route Monitor window in Kongsberg GUI before design review (118)

With the information provided from the first eye tracking data sets, the RNoN decided to put effort into redesigning the route monitor window in the Kongsberg ECDIS, shown in Figure 33. This was done as a HCD-process in the technical working group. The end users provided feedback on the software in use, and this was aligned and supported by the eye tracking data, which built up a better understanding of the context in use for the software manufacturer engineers. The development of the route information tool (High Speed Craft Route Monitor Window - HSCRMW) faced the sub-optimal design which was revealed and presented in paper 2, and the three main challenges were:

1. Presentation of current heading
2. Challenges with the HCI with the trip meter
3. Sub-optimal GUI in route monitor window.

Challenge 1 and 3 were addressed in the route information tool. Challenge 2 concerning bridge layout, the trip meter reset button was highlighted as sub-optimally designed, and should be moved to within arm's reach of the navigator. The technical working group suggested moving this button to the arm-rest panel of the navigator, and this was conducted in the MLU of the Skjold-class bridge.

The new route information tool was aligned with RNoN SOPs, in order to support the communication conducted in the navigation team. The information in the route information tool was presented in the same order as the SOP, and a clear separation was made between current information and future information as shown in Figure 34.

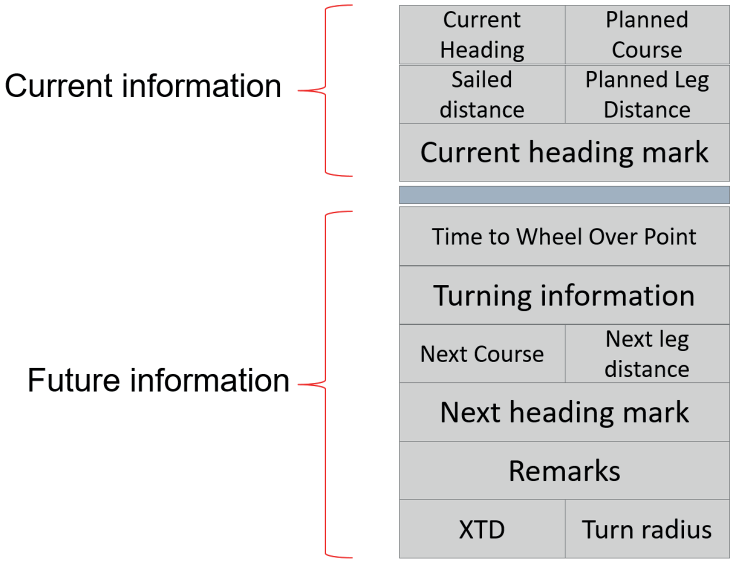

Figure 34: HSCRMW content (187)

Current information holds vital information for the navigator in the phases of navigation (control and turning phase):

1. Current heading, aligned against planned heading
2. Trip metre distance, aligned against planned leg distance
3. Current heading mark

Future information is aligned with the communication procedures, and holds vital information for the navigator in the preparation phase of the next turn:

1. Time to next wheel over point, calculated based upon Speed Through Water (STW)
2. Next turning mark
3. Next course and leg distance
4. Next heading mark
5. Remarks from the navigator in the planning process (e.g. dangerous sea areas, traffic, radar notations etc.)
6. Cross track distance and planned turning radius

This work resulted in the development of a beta version of the route information tool in the Kongsberg ECDIS, which was implemented in version 8.0.1 of Kongsberg software, and is shown in Figure 35.

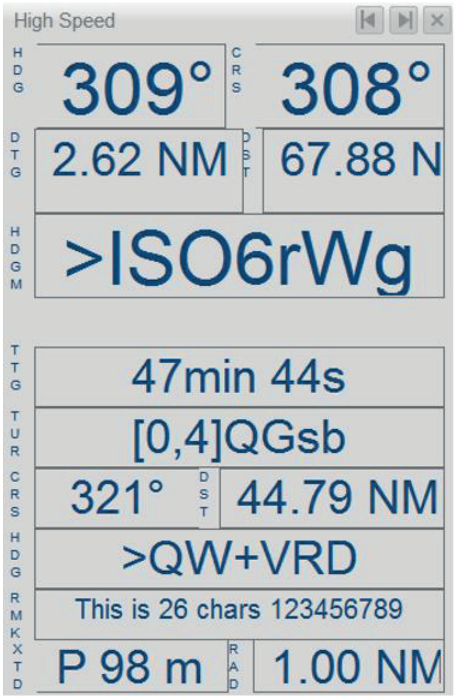

Figure 35: Beta version of HSCRMW (187)

4.5 Paper 5

Hareide, O.S., Ostnes, R. (2018). «Validation of a Maritime Usability Study with Eye Tracking Data», *International Conference on Augmented Cognition. Springer, Cham*. DOI: https://doi.org/10.1007/978-3-319-91467-1_22

The Skjold-class bridge navigation simulator (Figure 23) carried out an MLU according to the new bridge design and software updates on board the Skjold-class Corvettes. This was conducted in Q3 and 4 2017, and the verification study on the updated Skjold-class bridge was conducted in December 2017. The MLU process on board the Skjold-class Corvette is an ongoing process, and the simulator was the second of seven vessels implementing the update, which implies that there are few navigators familiar with the software and hardware updates in the MLU.

The aim of the verification study was to measure if the suggestions for improvement of bridge layout, design and software interface, analysed and outlined in paper 2 and paper 4 in this work, and implemented in the MLU, have been effective.

RQ4: Can eye tracking data be effectively used in the evaluation of navigational bridge design and the corresponding graphical user interface?

RQ5: Can eye tracking data collected from ETGs be used to validate a design-review of a maritime HSC bridge?

The verification study had the same design as the second data collection, in order to compare the two data sets to identify if the changes made in the MLU had any impact. The first data set identified three main design issues:

1. Poor availability of the presentation of heading bearing in radar GUI
2. Challenges with the HCI with the distance measurement unit (Electromagnetic Log – speed log)
3. Sub-optimal GUI in route monitor window

When preparing the article work was conducted to better understand the maritime navigator's SA requirement, and a suggestion for a model for the Navigator's SA was developed and is shown in Figure 36 (105).

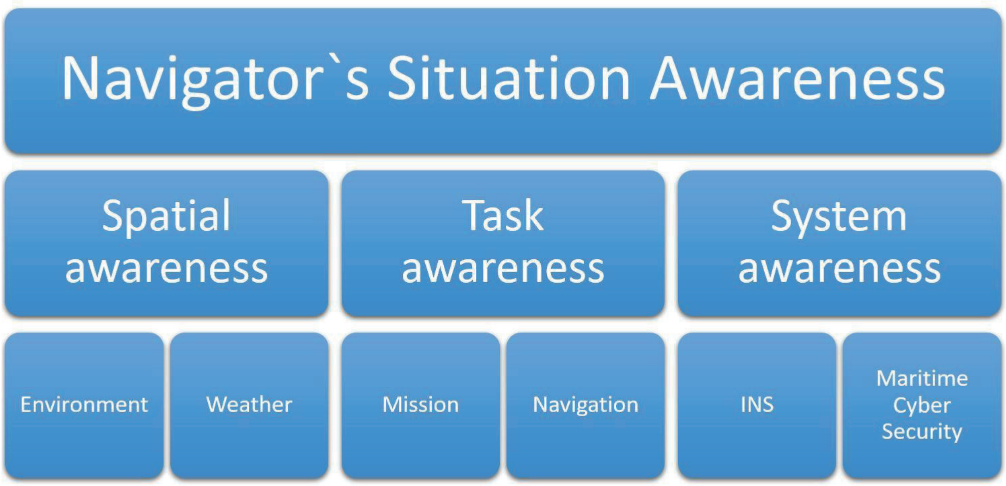

Figure 36: Maritime Navigator's SA model (105)

The bottom line in Figure 36 is used as examples and could be supplemented. The Navigator's SA model is based on the work of Wickens (18) with SA and workload in aviation, and is altered to better fit the maritime domain. The model aims to highlight the complexity of the Navigator's SA, by presenting the three main pillars on which the navigator's SA is dependent. The complexity of these factors will affect the navigator's workload. Spatial awareness consists of the environment and weather conditions in which the navigator operates. Task awareness concerns the mission and the navigation task, while system awareness regards the understanding of the systems in use, e.g. the INS.

The beta version of the route information tool was presented to the working group and analysed on a laptop, and suggestions for improvement were discussed. The second iteration resulted in some changes and amendments to the tool, and version 2 of the route information tool is shown in Figure 37, and implemented in software version 8.1.3 of Kongsberg software.

Figure 37: Version 2 of HSCRMW tool (188)

The changes were towards the use of type and size of fonts, and the three extra tools concerning the voyage plan was amended as buttons on the bottom of the route information tool:

1. A function that enables the navigator to prepare in advance of the voyage (look-ahead). Enabled by a previous (P) and next (N) button
2. Information about the alarms and warnings in the route check (validation) of the voyage on the current and next leg and turn
3. Estimated Time of Arrival (ETA) tool in order to aid the navigator with arrivals calculation along the planned voyage

These three functions are accessed by operating the mouse on the arm-rest panel. In addition, a reset button for the trip meter was introduced in the arm-rest panel, easy accessible for the operator.

The main challenge of the verification study was to conduct data collection on an MLU navigation system, where new hardware and software had some difficulties cooperating with original hardware. As known with all upgrades, there are teething problems that need to be solved before the new software and hardware are operational. This resulted in alarms and technical issues when operating the simulator. The data set is expected to have a higher quality if the system got time to mature, and declared stable and operational, before the data collection. Due to time constraints and delays in the installation, this was not possible to obtain.

The purpose of the design review was to free time for the navigator to control the surroundings of the vessel (AOI Outside) and contribute to a better SA for the HSC navigator. The collection of the eye tracking data set was conducted on the upgraded system in the Skjold-class bridge simulator, with six participants. The participants had different experience in the use of the system, and the general navigator experience level of the participants varied.

The findings from the eye tracking data analysis were not as expected, but gained valuable insight into how eye tracking data can be used when assessing a design review of hardware and software. The expectations for the analysis was to find a clear indication of how the new route information tool (HSCRMW) would aid the navigator, and free time for the navigator to increase the attention towards the surroundings (AOI Outside) of the vessel.

Analysing the visualizations maps, with emphasis on the scan path, there is a clear indication of a tidier scanning pattern for the navigator, and it adheres to the recommended scan pattern for the maritime navigator as presented in paper 3. AOI Outside, ECDIS and Radar are the main focus areas, and there are less fixations in the less important AOIs (Heading, Display and Consoles). From the heat map analysis, there is a clear indication that the ECDIS is divided into two subareas; the chart and the route information tool. In the AOI radar, the attention of the navigator has been redirected from the heading information towards the radar picture. This is an operational important area in order to conduct integrity monitoring and in the conduct of collision avoidance. The three design challenges, which were addressed in the HCD-process, are not apparent in the eye tracking data set of the design review.

When analysing the numerosity measurements, the findings are not clear. The total average time spent in the AOIs in the data set shows a decrease in the attention towards AOI Outside, and an increase in the attention towards AOI ECDIS. The attention towards AOIs Heading, Consoles, Display and Radar are less than 1.5%. The aim of the design revisions was to support more attention towards AOI Outside, and the post mid-life update data set indicates the contrary. To better understand this finding, a thorough analysis of each participant was conducted.

The span in experience level in years as navigator, and experience level with the new software, has a clear indication of an important variable to the results of the eye tracking data analysis. To highlight the extremes, the most experienced navigator with the most time on the new software was compared towards a less experienced navigator which was not familiarized with the new software. The results showed a 41.3% difference in the attention directed towards the surroundings of the vessel (AOI Outside). This provides a clear indication of the importance of familiarisation with new software before a validation of a design review can be conducted with good validity. It also highlights the importance of experience as a factor when addressing changes to or new software. The pre- and post-MLU eye tracking data sets standard deviation was analysed, and there is a clear increase (48.2%) in the standard deviation in the post MLU data set. The difference in standard deviation could be a measurement of the familiarity with the software and GUI.

The design of the method when conducting a validation of a design review with the use of eye tracking data is emphasized. Due to operational constraints, only five of the subjects participated in both the pre- and post-MLU data collection. The number of participants should be increased, even though for this particular case 54.2% of available personnel participated. To support a significance level of 5%, with the assumptions of similar values as in the current data set, the number of participants must be four times higher. This would not be achievable in a validation study in the RNoN. However, the strength of the process is that the eye tracking data analysis is done in conjunction with the technical working group. The HSC navigators in the technical working group (Subject Matter Experts – SMEs), support the indications of improvement in the MLU of the bridge design and software to support a higher degree of SA for the navigator. The qualitative measurements from the workshops are emphasised as an important support for the quantitative measurements.

5. Discussion

The performed studies and findings are highlighted in chapter 4, and this section will provide a discussion of how these findings contribute to the research in the domain of maritime HSC navigation. It will also discuss the theoretical implications of the findings into the syllabus of the RNoN. The first part will discuss the use of eye tracking technology, and the second part will discuss the implications of the findings from the eye tracking data to HSC navigation.

5.1 Eye Tracking Technology

The researcher's position as an insider in this thesis has implications for the results. A challenge is that the results could be biased by the insider's point of view, which have been faced by the research design. Combining qualitative and quantitative measurements has been important to assure that the insider perspective has not influenced the results. The position of the insider has gained valuable access to participants and apparatus that would have been difficult to achieve for an outsider. Collecting eye tracking data when a vessel is in operation is a challenging task, and thorough planning and contingency plans must be made in order to facilitate proper data collection. This would have been difficult to achieve within the same timeframe without the insider perspective. The insider perspective also gained valuable insight when driving the HCD-process in the design review, being able to better understand the different participants in the process, and increase the gap between academia, engineers and end-users.

The use of eye tracking data in the maritime domain has been slowly evolving during the past years, as shown in the theoretical foundation in section 2.6. The ETGs are mainly used within training, education and design in the maritime domain, having shown a clear potential. It is expected that the use of the eye tracking technology will increase as the technology matures, which has indications of rapidly maturing with the increasing interest from large technology companies in eye tracking technology. This is emphasized by Apple acquiring SMI in 2017. It is also expected that eye tracking technology will take an important role in the rapid evolution within Virtual and Augmented Reality (VR and AR), underlined by the eye tracking add-on from Pupil Labs to commercial AR products. The use of eye tracking to increase the efficiency in training and education in simulator training in the maritime domain is evident, and companies such as Smart Eye provides integrated simulator solutions. A test version of this was set up at the RNoN NavSim in 2017, showing good potential.

The findings in this thesis shows a good potential in the quantitative measurements collected with ETGs, but it also delineates the ambiguities when analysing the eye tracking data. Establishing a better understanding of the eye tracking data analysis process could be introduced with domain knowledge and the use of combined qualitative and quantitative measurements. The process of analysing eye tracking data is today time-consuming, but the manufacturers are promising more automated functions for faster and better analysing in the future. The accuracy and data quality of the eye tracking data from ETGs are predicted to increase, which will increase the resolution of the eye tracking data to provide more accurate analysis. The benefits of using eye tracking data in this study is underlined with the thesis contributions in chapter 6.1, and with easier accessible use of ETGs, the amount of use in the maritime domain are expected to rise.

In training and education, the visualization maps which are produced in the manufacturer software has provided a quick and intuitive overview of the scan pattern and attention areas which the navigator addresses. This could be further utilized if integration of eye tracking technology could be done in maritime bridge navigation simulators. The use and understanding of the eye tracking data in a maritime educational context could then be further utilized.

The reliability of an eye tracking data usability study depends on the research design and statistically on the number of participants. Using a navigational bridge simulator increases the reliability as more of the variables are controllable, compared to field studies. When having access to a 1 to 1 simulator, data collection is beneficial in the simulator. As most navigational bridge simulators are universal and not designed to fit one specific class of vessels, the researchers must evaluate the pros and cons of the apparatus, and if it is feasible to conduct a field study. If the research design is towards a specific class of vessel, it is beneficial to conduct field studies to increase the reliability of the eye tracking data set. If the research design is aimed to be universal and generalizable, a navigational bridge simulator would serve the cause best. When conducting operational eye tracking data collections in the maritime domain, the number of relevant participants can be limited. There is a clear distinction between using students and operational crews familiar with the navigational task and procedures. The availability of operational crews will be challenging, due to operational demands and tight (and changing) vessel schedules. It can be challenging to attract a high number of participants from operational crews, which is important for the reliability of the eye tracking data collection. The combination of qualitative and quantitative measurements can compensate for this limitation, and the qualitative data may provide a better understanding of the quantitative measurements.

The two primary challenges for increased use of eye tracking technology in the maritime domain are argued to be cost and ease of use.

5.1.1 Plan, Procedure and impact on Results in Eye Tracking data collection

In research, you plan a study, perform it, and evaluate the effects of the possible differences (164). As highlighted in section 2.5, there are challenges when conducting eye tracking data collection both in a bridge navigation simulator and in field studies.

The plan for eye tracking data collection is shown in Figure 27, and had several challenges. When relying on eye tracking technology for the data collection, there are several fall pits which could be encountered. These were faced by conducting pre-studies (section 3.4.2) in order to gain experience in eye tracking data collection, and the possibilities and limitations within the eye tracking technology before conducting the data collection in field studies or simulator studies. The pre-studies gained valuable insight, but was limited to pre-studies in the simulator. In the simulator studies (section 3.4.4), most variables are controllable, and the sole purpose of the simulator scenario was eye tracking data collection. This was not the case when conducting the field studies (section 3.4.3), and eye tracking data collection had to fit into a busy vessel schedule. To conduct a valid eye tracking data set, thorough planning needs to be conducted. It was found valuable to brief the management and participant on board early, in order to gain a clear understanding of when the eye tracking data collection (and in which area) must take place. The navigator's on the vessels used for data collection were interested and cooperative, which was essential for the data collection. When collecting eye tracking data on board a vessel in operation, one must be prepared for re-scheduling of data collection events and be aware of the variables which could influence the eye tracking data collection. Weather and amount of daylight have been important variables, which could hamper data collection. When comparing the simulator studies and the field study, a limitation was the simulator database. When designing the data collection, one should emphasise similar areas of data collection to increase the reliability of the data collection.

Between the second and third data collection (Figure 27), a planned upgrade of both the vessels and simulator hardware and software took place. The third data collection was planned well after the upgrade, to ensure that the software was operational and that the participants were familiar with the new bridge layout and software. Due to availability on technicians and delays in delivery, the scheduled upgrade was postponed, which resulted in less time to fix software bugs and less time for familiarisation for the participants with the new bridge layout and software. As presented in Paper 5 (section 4.5), this resulted in interesting results from the eye tracking data collection. The importance of familiarisation and experience was salient, which is arguably an important finding in the research. On the other hand, it would be beneficial to postpone the data collection, but this was found to be difficult within the given timeframe due to the participants and vessel schedule. As stated in section 3.4, two eye tracking data collections were conducted in Q3-4 2017, and the first one was rejected due to the participants not being familiar with the new software. Even though the next eye tracking data collection was postponed several months, the participants did not get enough time to familiarize. The timeframe within a project is a limitation, and at one point one has to decide whether to conduct a data collection or not. The data collection was conducted, and even though the results were unexpected, they were of much value.

The value of conducting eye tracking data collection with operational crew in both field studies and simulator studies has been a clear goal for this thesis. When trying to answer the research questions, it was found beneficial to utilize operational crews as participants instead of nautical students. The operational crews has more experience, and is familiar with their equipment, which increases the validity of the collected eye tracking data. It is important to note that this comes with a price, and the planning process of eye tracking data collection must be thorough. The management and participants of the crew must be well informed and incorporated in the plan, and contingency plans must be in place.

The process of analysing the eye tracking data sets is time-consuming. This is mainly due to the automatic mapping process in the software not being applicable for dynamic environments such as HSC navigation. The semi-automatic mapping process should be conducted in cooperation with a SME, in order to interpret the eye tracking data in a consistent manner. The resolution of the ETGs is not good enough for high detailed usability studies, but provides a good overview of the visual distribution of the HSC navigator.

5.2 High-Speed Craft Navigation

Safe navigation is the goal of any navigator, and all navigation systems should be designed to support the human in the process of safe navigation. In this thesis the state-of-the art integrated and networked navigation system on board the Skjold-class Corvettes has been studied with the use of eye tracking technology. The AOIs defined and used in this thesis is based upon the Skjold-class navigation system, which is a COTS navigation system. There are numerous manufacturers of integrated navigation systems in the maritime domain, and even though performance standards are in place from IMO, there is a distinct difference in the layout and GUI from the different manufacturers. Initiatives such as the S-mode Guideline and the Openbridge project are pushing for standardisation within the maritime domain, but the initiatives has not yet taken operational effect. It is important to promote the existence of the guidelines and such projects, and to encourage the use of them in new projects. The collected eye tracking data in this thesis emanate from the Kongsberg INS software, and there will be differences when compared to other manufacturers. The general AOIs (Outside, ECDIS, radar, conning) are established on the basis of a vessel equipped with an ECDIS, radar and a conning application (INS) (3). These are normally presented on three different MFDs, but the design and layout of an HSC navigation system will vary with the specific demands from the ship owner, and from yard to yard. Most HSCs are unique, as even vessels produced in series could have individual differences in the layout and design of the navigation system.

With electronic navigation comes an information rich environment, and usability in design is required to balance the complexity. This substantiates the basic requirement for complex systems to be fully operational and functional in the intense, worst case scenarios. Integration of navigation systems is aimed to increase the SA of the navigator, and a contextual SA model is presented as the Navigator's SA model. The context when utilizing the construct of SA has been argued to be important, and the navigator needs to better understand the term which is often used. The Navigator's SA model argues for the importance of spatial-, task- and system awareness of the navigator when conducting safe navigation, and is inspired by Endsley`s 1995 SA model (25) and Wickens' work within SA in aviation (18).

The findings are argued to be generalizable, but it is important to understand that the context from which the data has been collected, is extreme. Very few HSCs are capable of speeds up to 60 knots, as most are operating around 30 knots. In addition, the Norwegian coastline is challenging for navigation, but demanding littoral waters can be found elsewhere in the world. The challenges when operating in different waters will vary, and the complexity will change. However, the work of the navigator is the same, conducting and securing the safe navigation of the vessel. The main difference will be the time available to conduct the information management and the phases of navigation, due to a change in speed. HSC navigation is normally done in a navigation team, like the set up in an aviation cockpit. In commercial shipping, the conduct of the passage can partly be done by one navigator supported by a lookout. A reduction in manning will obviously increase the workload, and thus the requirements for an efficient workflow.

To present an exact suggestion of the visual distribution between the AOIs is a difficult task, as there are many variables present. The most important variable is the visibility, especially when it comes to the use of radar. The amount of attention towards the AOI radar will vary significantly with a drastically change in visibility, which could happen quickly. Another important variable is the confinement of the water, exemplified in the theoretical foundation when comparing the Korean S-mode study against the eye tracking data in this thesis. In an overseas passage, the OOW will increase the attention to other tasks than the navigation task. The development of the suggested Maritime Scan (Figure 32) provides a comparison and insight from aviation to a modern ship navigation bridge, together with the analysis of the collected eye tracking data. When presenting the Maritime Scan (Paper 3), there have been discussions of the importance of the radar in the maritime scan for the navigator. The radar is recognised as a crucial aid for both navigation and collision avoidance, and a revised Maritime Scan is presented in Figure 38.

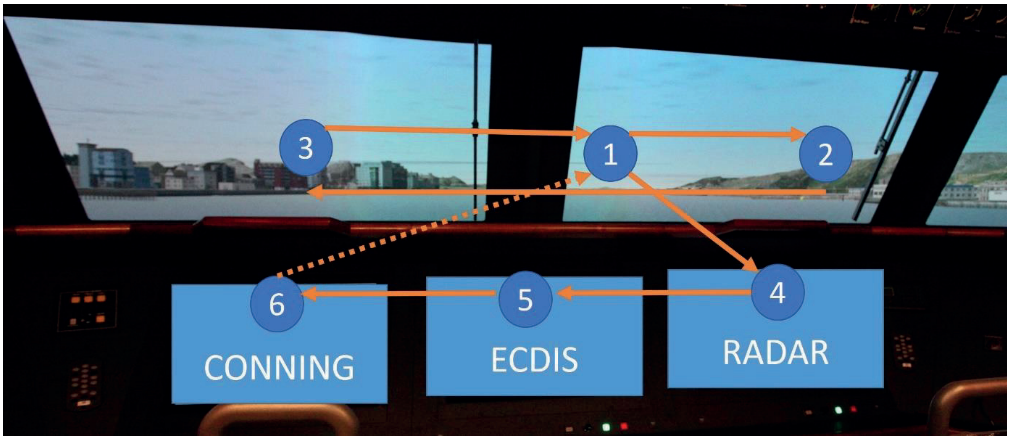

Figure 38: The Maritime Scan revised

The revised Maritime Scan emphasizes the importance of the radar both in navigation and in collision avoidance, as the radar is a crucial tool when conducting integrity monitoring for the navigator. This is conducted by comparing the surroundings (represented by circle 1, 2 and 3) towards the terrestrial picture presented on the radar (circle 4). If the bridge is set up with three MFDs, as shown in Figure 38, the scan pattern for the navigator is more efficient as it moves from right to left through the displays (4, 5 and 6), before the maritime scan starts over again. It is also emphasised that the maritime scan is an iterative process, mainly related to the control and transit phases of navigation. The results from the analysis provide a better understanding of the visual distribution of the navigator on an HSC, and this has been used to further develop the curriculum of the Skjold-class OOW course and the curriculum of the navigators at the RNoNA.

The main difference between civilian and military HSC navigation is the area of operation. Military HSCs is operating in a large area of operation, while the commercial HSCs often operate in the same area, giving the civilian HSC navigators an extensive local knowledge of the waters operated in. Even though the waters are known to the navigator, the complexity of the navigation process lead to accidents, which are underlined by several maritime investigations such as RV *Bill* (77) and HSC *Sleipner* (189). The need for a well-established and functional decision-making process or control strategy in the conduct of the navigation task is recommended and presented with the phases of navigation. The phases of navigation are established in the RNoN procedures in order to support the navigator in the conduct of safe navigation and is an iterative process. The procedure is established on the foundation of conducting navigation in demanding littoral waters in high-speeds, but it is applicable to other vessels and operation areas. The main difference will be the time at hand to conduct the phases of navigation, and the amount of communication requirements within the navigation team.

Route information is a part of the performance standard for all ECDIS and INS, but the representation of the information varies from manufacturer to manufacturer. A general problem with all manufacturers is the readability and accessibility of relevant information for the navigator in the route monitor tool to support safe navigation. The presentation of the route information tool (HSCRMW) is aligned with the RNoN SOP phases of navigation and bridge communication procedures, being incorporated on the manufacturer software. The requirements for navigation information can vary with vessel operators, but the importance of providing visual attention towards the surroundings of the ship is emphasized in the theoretical foundation. The navigator’s visual attention towards the surroundings utilize the human as an integrity monitoring tool in the navigation system, which requires a certain level of system awareness to maintain the navigator's SA. This is incorporated in the syllabus at the RNoN, but there have not been performed any studies into the appreciation of this at other maritime universities.

6. Concluding remarks

The evolution of electronic navigation has been challenging for the maritime domain in general and for the RNoN specifically. The introduction of electronic navigation has been paved with good intentions, but the role of the human within electronic navigation has been challenging to understand. The importance of electronic navigation as a contribution for safe navigation is clear, but the further development of the bridge design and GUI should be done as an HCD-process in order to facilitate the role of the human in the complex conduct of safe HSC navigation.

The use of eye tracking data collected with ETGs has shown a good potential for a better understanding of the visual attention of the HSC navigator, but it has also underlined the importance of thorough method design when collecting the eye tracking data. The eye tracking technology is rapidly evolving, and the use of the technology should be considered within a cost-benefit analysis when designing bridge and GUIs for the modern navigator.

6.1 Research Contribution

The overall objective of the thesis is to better understand, and possibly improve, the work of the HSC navigator with the use of eye tracking data, with the Skjold-class Corvettes as a case study. Considering the research questions, the findings, the papers, and the existing literature, the following specific contributions (C) can be listed:

C1: A 1 to 1 bridge simulator training has been evaluated towards live navigation training with the use of eye tracking data and is assessed to provide similar training outcome.

C2: A better understanding of the HSC navigator's visual attention distribution has been established with the use of eye tracking data.

C3: The use of ETGs to collect eye tracking data in maritime usability studies has been proven useful.

C4: A proposed scan pattern for the maritime navigator has been established.

C5: Better information management for the modern navigator by developing an improved route information tool (HSCRMW-tool) has been implemented.

C6: The use of the HCD-process as a tool in the design and design reviews of bridge design and navigation equipment software is recommended.

C7: Familiarisation with new navigation software and equipment is emphasized, supported by eye tracking data.

C8: With the knowledge gained through the analysis of the eye tracking data, an update of the RNoN curriculum in electronic navigation has been conducted in the subjects Navigation Systems, Military Navigation and in the curriculum of the Skjold-Class OOW course.

C9: A control strategy for the conduct of a passage, the Phases of Navigation, has been presented.

C10: A model for better understanding the Navigator's SA has been developed.

C11: Improvement of the design of navigation training simulator scenarios has been suggested.

Contribution	Paper	Research Question
C1	P1	RQ1
C2	P1, P2, P3, P5	RQ2
C3	P2, P3, P4, P5	RQ4, RQ5
C4	P3	RQ3
C5	P4, P5	RQ4, RQ5
C6	P4	RQ4, RQ5
C7	P5	RQ2, RQ3
C8	P1, P3, P5	RQ1, RQ2, RQ3
C9	P3, P5	RQ2, RQ3
C10	P5	RQ2, RQ3
C11	P1	RQ1

Table 3: Relationship between contributions, papers and research questions.

List of papers and research questions are redistributed below to provide a better understanding of Table 3.

P1: Comparative study of the Skjold-class bridge- and simulator navigation training.
P2: Maritime Usability Study by Analysing Eye Tracking Data.
P3: Scan Pattern for the Maritime Navigator.
P4: Developing a High-Speed Craft Route Monitor Window.
P5: Validation of a Maritime Usability Study with Eye Tracking Data.

RQ1: Can eye tracking data be used to evaluate and compare the effectiveness of live- and simulator based navigation training?

RQ2: Can eye tracking data be used to map and better understand the visual attention of the HSC navigator?

RQ3: Is the visual scan pattern of the HSC navigator optimized in order to facilitate integrity monitoring of the INS by the navigator?

RQ4: Can eye tracking data be effectively used in the evaluation of navigational bridge design and the corresponding graphical user interface?

RQ5: Can eye tracking data collected from ETGs be used to validate a design-review of a maritime HSC bridge?

6.2 Conclusions

The daily job of the navigator has changed significantly with the introduction of electronic navigation and integrated navigation systems. The navigator has progressed from using most of his time to find and fix the position, to operate and monitor complex systems designed to increase situation awareness and facilitate safe navigation.

This paradigm shift could imply alterations in the training needs and requirements for information management for the navigator. The shipping industry is known to be conservative, and there are several indications of lessons to be learned from other domains, such as aviation. With increased demands for efficiency, the workload for the navigators is increasing. It is thus essential that the bridge design and digital displays at the bridge contributes to a higher degree of SA for the navigator.

The HSC navigators' conducts the challenging task of safe and efficient navigation in demanding littoral waters 24/7 – 365 days a year. This thesis aims to better understand this challenging task, and to present suggestions to increase the SA for the navigator. The use of eye tracking data to better understand the challenges for the maritime HSC navigator is presented. Eye tracking technology has been used for several years, and with the introduction of Eye Tracking Glasses (ETGs), the mobility when collecting eye tracking data has been increased.

The main contributions are:

By utilizing eye tracking data, findings indicate that a bridge navigation simulator provides efficient training, and that the 1 to 1 Skjold-class bridge navigation simulator provides the same training outcomes as if on board training was conducted. The cost-benefit of such a simulator is not quantified, but there is clear evidence that it is high. Findings in the eye tracking analysis support that the use of bridge navigation simulators involves a more demanding cognitive process leading to a higher mental workload for the navigator. Using the simulator makes the spatial-, task- and system variables controllable, which leads to a better study design.

The use of ETGs has been examined in this thesis, and the ETGs is proven to be a functional tool when measuring information about the navigator's point of gaze. However, the technology is still evolving, and the following aspects are important to consider:

1. The use of ETGs hampers the detection of objects during dark hours, due to the glare from the IR-sensors. This induce that ETGs are only used during daylight.
2. Using the ETGs during daylight when the sun is close to the horizon, induce a glare in the ETGs which is disruptive for the navigator, making the ETGs not usable in this state.
3. Use of ETGs in conjunction with binocular is challenging and needs practice to get accustomed to.
4. Limitations due to battery capacity and wiring. This can be solved by using battery banks or wireless functions in the ETGs, but must be considered when designing for an eye tracking data collection.
5. The calibration process is challenging and time consuming. The background and light conditions when conducting the calibration is important, making the calibration process sensitive which could affect the quality of the data.

The analysing of eye tracking data in the supplied software is time-consuming. However, the results with visualization techniques and eye tracking metrics indicate a good potential.

1. The quality of the data could be difficult to interpret, and it is important to check the usability of the data in the analysis process.
2. The automatic mapping software of eye tracking data is immature and cannot be used efficiently. A rule of thumb is 10 minutes of eye tracking data takes 1 hours to analyse.

3. The use of other programmes and scripts to interpret the eye tracking data is possible but not investigated in this study.

A better understanding of the Situation Awareness (SA) of the maritime navigator by using Endsley's model (25) together with Wickens' (18) suggestion of introducing spatial, task and system awareness as part of the SA. The presented model for the Navigator's SA puts the SA construct into the navigator's context, and provides the navigator with an understanding of the elements that constitutes his or hers SA. This leads to a deeper understanding of the control strategies and the phases of navigation for the HSC navigator. Comparing the maritime domain with aviation, together with analysing eye tracking data, resulted in a suggestion for a Scan Pattern for the Maritime Navigator. The suggestion also holds a rule of thumb when it comes to the distribution of the navigators' visual attention, related to the four primary Areas of Interest (AOIs) in the conduct of a safe passage by using an integrated navigation system: AOI Outside, ECDIS, Radar and Conning.

The development of graphical user interface for the presentation of information related to route monitoring is aligned with the standard operating procedures and control strategies in use. The product is a High-Speed Craft Route Monitor Window (HSCRMW) in the Kongsberg ECDIS SW, designed for and implemented in the mid-life update of the Skjold-class Corvettes.

The use of eye tracking data collected by ETGs in validating a maritime usability study is shown not to be sufficient alone and needs to be supported by qualitative measures. When comparing quantitative and qualitative measures, findings indicate that valid conclusions can be made.

The thesis highlights the importance of efficient information management and standardisation in the maritime navigation system to increase the SA for the navigator. The S-mode Guidelines and Openbridge project highlights the need for and importance of standardisation within the workplace of the navigator on a maritime bridge. The system awareness of the navigator when using the maritime navigation system will contribute to an increase in SA, ultimately supporting safe navigation. Continuous integrity monitoring of the systems and visual checks towards the surrounding of the vessel is an imperative task for the navigator to enhance safe navigation.

6.3 Recommendations for further work

Bridge navigation simulators have been evaluated to have a significant impact on the training of new and existing navigators, and eye tracking technology can further enhance the efficiency of this training. The possibilities in the use of remote eye tracking technology systems in the training of navigators on bridge navigation simulators to provide more increased efficiency in training, should be further investigated.

Further refinement of the information management of the navigator, such as the current S-mode Guideline and Openbridge project, to support a higher degree of navigator SA should be supported. The use of bridge simulators in design reviews and software development and quality assurance in the maritime domain by the use of the HCD-process has proven valuable. As the RNoN sees the Skjold-class bridge simulator as the seventh Corvette, it should be utilized better in research in developing further the GUI and layout of the bridge and bridge equipment. This also adheres to equipment manufacturers, yards and other ship-owners.

Further investigation into technology on how to reduce HDT for the navigator, by shifting the visual attention towards the outside of the ship. This could be done by the use of Augmented Reality, and Maritime Augmented Reality (M-AR) should be investigated further.

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Paper I

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Comparative Study of the Skjold-Class Bridge- and Simulator Navigation Training

Abstract

This paper presents a comparative analysis of the visual focus of the navigator during a passage in Norwegian littoral waters and in a maritime bridge simulator. The research project collects time distribution data of the navigator's visual focus on the primary components in the Integrated Navigation System (INS) and looking out the vessels windows. Data is collected by the use of Eye Tracking Glasses (ETG). The ETG registers the visual focus of the navigator, and this is used to generate statistics on which Area of Interest (AOI) the navigator is focusing on. Based on the ETG data AOI and Key Performance Indicators (KPI) are selected to further analyze the difference and similarities between navigation training on board and in a simulator. Findings indicate that use of a simulator is efficient when it comes to navigation training, and provides the same training outcome as on board navigation training. The results also indicates that a simulator passage is a more demanding cognitive process requiring a higher mental workload.

Key Words

1. Simulator 2. Military navigation 3. Eye Tracking 4. High Speed Craft

1. Introduction

Both ship owners and maritime education establishments are using simulators in greater extent to provide the navigator and navigation team with better preconditions in conduct of the on board job. Simulator training provide specialized navigation training and is used for efficiency reason compared with on board navigation training.

The maritime industry and users has been through a paradigm shift with the introduction of electronic navigation aids. Electronic Chart Display and Information System (ECDIS) has become mandatory on most ships to provide increased situational awareness for the officer of the watch (OOW).

This article provides a comparative field- and simulator study, to identify differences and similarities in visual attention, cognitive and mental workload of the navigator, based on the collected Eye Tracking data. Mental workload measurements, as part of team performance evaluations, has been found to correlate between simulator and field exercises (1). The hypothesis of the article is that field study data is similar to simulator study data, and thus simulator navigation training is efficient and should be further developed.

2. Method

2.1. Skjold-class Corvette

The Royal Norwegian Navy (RNoN) launched the Skjold-class corvettes in 2010 (2). The vessels are built for rapid deployment along the Norwegian coastline and in Norwegian territorial waters, with speeds exceeding 60 knots.

Figure 1: Skjold-class Corvette in Norwegian Littoral Waters

The Norwegian coastline presents challenging waters for navigation, making the demand for navigation training high in the RNoN.

The Skjold Class navigation team consist of a navigator (starboard seat) and an OOW (port seat). Three screens are placed in front of the OOW and the navigator, set up shown in figure 2. The navigator plans and conducts the passage while the OOW monitors and controls the passage.

Becoming an OOW involves passing several navigation test, several of which are performed in a simulator. A Skjold-class navigator receives approximately 80% onboard training during operation and 20% specialized simulator navigation training (estimates from Norwegian Corvette Service).

2.2. Simulator

In 2008 the Royal Norwegian Naval Academy (RNoNA) inaugurated a full scale Skjold-class bridge simulator with the same software and hardware as on board (1:1), with the purpose to gain effective navigation training for Skjold-class navigation crew. The visual scene provides a 210-degree image for the navigation team, all in 1280x1024 resolution. The visual database covers the majority of the Norwegian coastline. The topography and man-made objects are similar to reality, but there is less level of detail when it comes to buildings and non-navigation related objects.

2.3. Eye Tracking

The data set is collected by second-generation ETG from SensoMotoric Instruments (SMI ETG 2w©). Calibration and recordings were conducted in accordance with operation procedures, and is processed utilising the BeGaze software (3).

A challenge was identified using the ETG during twilight and in use together with binoculars. The ETG limits the normal use of binoculars, and the glare in the glasses prevented optimal detection of small objects in twilight.

Eye Tracking equipment has been used to evaluate and improve the training process on ships`s navigational bridge simulator (4), and also for stress classification (5). Furthermore ETG has been used by Forsman et.al (6) to evaluate the conduct of a passage with regards to experience of the navigator. It has also been used for validation of simulator for assessing difference in information interfaces (7).

2.4. Participants

The experience of the participant was between 2 and 6 years of active service as a navigator on board a Skjold-class corvette. The participants have conducted the four-year Naval Academy navigation and officer training. All participants were accustomed with the use of the Skjold-class bridge simulator.

2.5. Design

The field study and the simulator study were conducted in two different parts of Norway, due to vessel program limitation. The area where the field study and the comparative simulator study was conducted is similar concerning topography, but not identical.

The field study data collection was conducted in late November 2015, and the area of operation stretched from Sandnessjoen in north to Bergen in south. The weather was challenging, with rapid shifts of visibility from more than 5 nautical mile (NM) to 0,5 NM in seconds. The field study involved three navigators. Eight recordings were conducted, each with approximately 9 minutes recording time.

The area specific of the data collection in the simulator consisted of the littoral waters on the west coast of Norway between Maaloey and Sognefjorden, which is an area where the simulator database has a high resemblance to the real environment. The simulator study involved three navigators, seven recordings were conducted, each with approximately 10 minutes recording time.

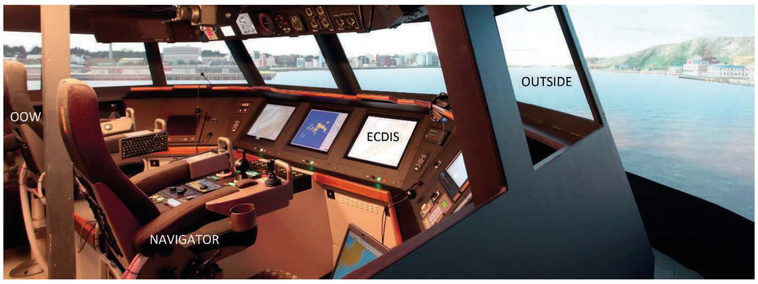

Figure 2. Skjold-class simulator at RNoNA. Navigator is places in the right seat, OOW in the left seat.

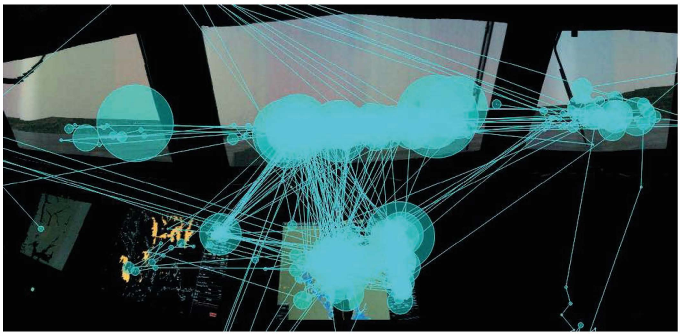

Figure 3: Scanpath of participant 4

It was a challenge to replicate the exact weather conditions in the simulator. Weather conditions were fixed at; wind 5 m/s from northwest, 0-0,5 metre wave height, good visibility with lights visible (20% darkness in simulator). Traffic density was set to normal in accordance with the area the ship operated.

Some of the navigators participated in both the field study and the simulator study. The navigational experience of the personnel participating in the comparative studies is similar. Table one outlines the differences between the variables experience, area, visibility, traffic density and period for each trial.

AOI was defined through a pre-study in the simulator, where eye movement data was analysed to identify which areas on the bridge took the navigators attention. For the comparative study of the Skjold-class bridge navigation and simulator training, AOIs Outside (AOI_O) and AOI ECDIS (AOI_E) has been identified as the two primary areas, illustrated in figure 2. This is because the main difference of navigation training in the field and in the simulator are the projected reality on screens in the simulator, and the working environment concerning noise and movement.

3. Result analysis

15 datasets were collected among the participants with a total duration of 2 hours and 25 minutes. KPIs in the AOIs, scanpaths, sequence charts was generated,

Table 1: Outline of the eight trials conducted.

Trial	Participant number	Experience	Area comparison	Visibility field study	Traffic density	Period
#1	1	2 years	Similar	>5NM	High traffic areas	F: 9min S: 10min
#2	F: 2 S: 3	F: 3 years S: 3 years	Start of field study more challenging	Varying	F: Demanding situation S: 2 vessels	F: 9min S: 11min
#3	4	7 years	Similar	>5NM	Normal	F: 11min S: 10min
#4	1	2 years	Similar (1)	0,5 - 5NM	Low	F: 11min S: 10min
#5	1	2 years	Similar (1)	>5NM	Low	F:10min S: 10min
#6	1	2 years	Similar (1)	>5NM	F:5 vessels S: 2 vessels	F:11min S: 10min
#7	F: 2 S: 4	F: 3 years S: 7 years	Similar	>5NM	F: None S: 2 vessels	F: 3 min[1] S: 11 min
#8	F: 2 S: 3	F: 3 years S: 3 years	Similar	>5NM	F: High S: 3 vessels	F: 7min S: 10min

F= Field study, S=Simulator, 1= Field study unfamiliar open area. Simulator familiar confined waters.

1 Aborted due to disconnection of ETG

in addition to statistics in Excel for eye movement data (3). An example of a scanpath is shown in figure 3, identifying fixations and saccades. Fixation is defined as the state when the eye remains still over a period of time (>80 ms), and saccade is defined as the rapid motion from one fixation to another (8). In figure 3, fixation time is given by the size of the circles and saccades is illustrated by the lines between the circles.

Based on the hypothesis, three out of nine KPI were identified for use in the further analysis with comparison of the field study data and simulator study data. Dwell time could reflect the importance of an AOI (9). Average fixation time is used as an indicator of cognitive and mental workload for the navigator in the AOI and fixation rate is an indicator of task difficulty (8).

The statistical model consisted of a normality test, an F-test and a t-test to control if the values disprove the hypothesis that field study data and simulator data is similar within a significance level of 5%. The F-test is conducted to control the p-value for validation of similarity of the data set. The t-test is conducted to control if the expectations values in the data set are valid.

All values are above the significance level of 5% and the statistical test does not disprove the hypothesis that field study data is similar to simulator data.

3.1. Dwell time

In AOI_O there is a difference of 3,3% between the field study and the simulator study. A reason for this difference could be that the real world has more details than the simulator, leading to a higher dwell time in the field study. Table one shows that there is more traffic in the field study than in the simulator study, which could also be a reason for the difference between the dwell time. The difference for dwell time in AOI_E is 0,3%.

KPI dwell time indicates that the visual attention of the navigator when it comes to the defined AOIs is coinciding.

Military high-speed navigation in inshore waters of the Norwegian coastline is conducted in a navigation team (10). Two persons conduct the navigation, and this is due to the high workload of the navigator, and the vessel speed. The collected data show that the navigator uses 60% of the time looking outside the window, correlating the vessels position with the surroundings and comparing this with the information presented in the INS primarily in the ECDIS.

When analysing dwell rate, which is the number of entries into a specific area of interest per minute, the findings supports the similarity between the field study and simulator study (9).

3.2. Average fixation time

Figure 5 illustrates a higher average fixation time in the simulator study compared to the field study. In AOI_E the difference is 19 ms, and in AOI_O the difference is 86 ms.

The average fixation time for the eight trials indicates that the participants has a longer average fixation time in simulator compared to the field study for AOI Outside. This finding could indicate that a navigation task in the simulator is associated with a deeper and more effortful cognitive process (8, 9). One possible reason for this could be that the visual display in the simulator and the simulator database is more difficult to cognitively process than the real life image of the surroundings of the ship. The navigator is accustomed to the real life image presented in 3D with high definition, and good colour contrasts. The virtual reality, presented on the projectors in the simulator, is in 2D with lower definition and less colour contrast. This could

Table 2: KPI variables for AOI with p-values.

KPI AOI	Trial	Dwell time	P-value	Average Fixation	P-value	Fixation Rate	P-value
Outside	Field study	59,7%	0,69	432 ms	0,96	71,4	0.98
	Simulator study	56,4%		517 ms		61,9	
ECDIS	Field study	22,4%	0,09/0,62[1]	293 ms	0,26	40,7	0,08/0,19[2]
	Simulator study	22,1%		312 ms		35,3	

1 P-value of 0,62 ignores outlier in Field Study Participant 4 due to software problem.

2 P-value of 0,19 ignores outlier in Field Study Participant 7 due to software problem.

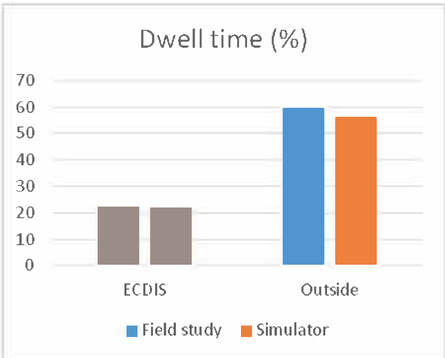

Figure 4: Comparison of average dwell time in AOIs.

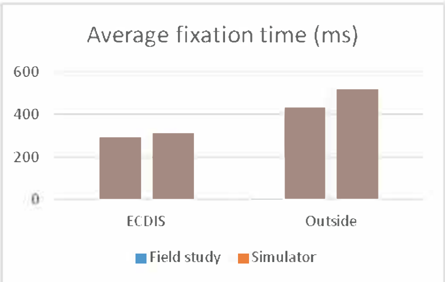

Figure 5: Comparison of average fixation time in AOIs.

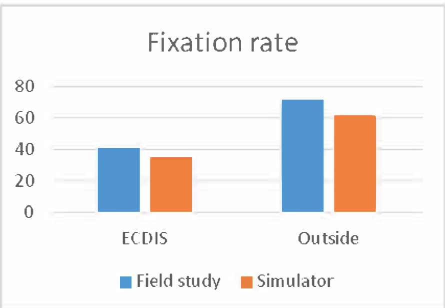

Figure 6: Comparison of fixation rate in AOIs.

contribute to the more demanding cognitive process in the simulator study compared to the field study. Note also that the navigator conducts most training on board while in operation, and is more accustomed with reality. This finding suggest continuous work on updating details and improving resolution of simulator database would improve realism in simulator navigation training. Further, this would decrease the cognitive strain on the navigators.

3.3. Fixation rate

Figure 6 illustrates a 13 % higher fixation rate in both AOIs in the field study compared to the simulator study. Comparison of the fixation count in the AOIs ignores fixation duration. Due to the difference in trial time, fixation rate is selected.

The analysis indicates that there is a lower fixation rate in the simulator study compared with the field study. Fixation rate is found to be negatively correlated with task difficulty (11). This indicates that interpreting the visual picture in the simulator is more difficult than in the field study. This supports the finding that the mental workload, due to a more demanding cognitive process of processing the simulator image, is higher in the simulator (12).

4. Conclusion

The aim of this article was to present a comparative study of bridge navigation and simulator training to evaluate possible disparities between bridge simulator training and on board training. Findings indicate that the use of a 1:1 bridge simulator is efficient when it comes to navigation training, and provides the same training outcome as on board. It has been identified that the average fixation time in AOI_O is higher in the simulator. A lower fixation rate also indicate that the use of bridge simulators involves a more demanding cognitive process leading to a higher mental workload for the navigator. Instructors should consider this when designing simulator navigation scenarios. A higher degree of details in the simulator database and a higher simulator display resolution could compensate for this distinction.

It has also been identified that use of ETG hampers the detection of dark object during twilight, further research with the use of ETG in twilight must consider this.

4.1. Future work

The current data set is not 100% coinciding when it comes to variables outlined in table 1, and developing a new data set without these limitations could substantiate the findings in this article. The current dataset indicates that further elaboration on the time distribution of the navigators` visual attention is of interest.

Acknowledgement

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Paper II

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Maritime Usability Study by Analysing Eye Tracking Data

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The aim of the Integrated Navigation System (INS) on a ship bridge should be to provide the navigator with added value and aid in the complex task of conducting a safe and efficient passage at high speeds in demanding waters. This article presents a method for analysing eye tracking data to reveal sub-optimal design in the bridge layout and in the software graphical user interface on a maritime navigation display. The analysis of eye tracking data with a focus on scan path events indicates sub-optimal design, and the paper provides suggestions for improvement in design and interfaces. Pros and cons of using Eye Tracking Glasses in a maritime environment are presented. The importance of not affecting the normal behaviour of the navigator by collecting data is stressed, and how the software should provide good visualisation and interpretation of the eye tracking data.

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KEYWORDS

1. Eye Tracking. 2. Maritime usability study. 3. Navigation. 4. High Speed Craft.

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1. INTRODUCTION. Maritime ship bridges are becoming increasingly complex (Luraas, 2016), and Integrated Navigation Systems (INS) are being fitted on most new ships. The International Maritime Organization (IMO) recognises the need to "enhance the safety of navigation by providing integrated and augmented functions to avoid geographic, traffic and environmental hazards" (IMO, 2007, P.1). This provides the navigator with added value when it comes to planning, monitoring and controlling the safe progress of a ship. The information presented by the INS should be correct, timely and unambiguous. In addition, the design of the INS "should ease the workload of the bridge team and pilot in safely and effectively carrying out the navigation functions incorporated therein" (ibid., P.8).

With new technology aiding the Situational Awareness (SA) of the navigator, bridge layouts have evolved. On modern ship bridges information is presented on Multi-Function Displays (MFD), which consist of several applications that can be chosen based on what information is necessary for the navigator. The most common applications are the Electronic Chart and Display Information System (ECDIS), radar and conning displays, which are part of the INS. A variety of other MFDs may also present essential navigation information such as position, heading, speed, Automatic Identification System (AIS) information, wind data and more. The ship bridge has thus evolved from stand-alone analogue information with the use of paper charts to a digital display-based presentation of all relevant maritime information on MFDs.

A concern from both government institutions and industry is that this technological evolution actually decreases the SA of the navigator (Wingrove, 2016). There is also a concern that the navigator is addressing too much of his or her attention to digital displays (Norris, 2010; Hareide et al., 2016; MAIB, 2008).

This paper presents a usability study conducted on board the world's fastest littoral combat ships, the Royal Norwegian Navy corvettes. Collected eye tracking data is analysed with regards to the usability of the bridge layout and the Graphical User Interface (GUI) of the software incorporated in the INS. Eye tracking data is used and presented to conduct a usability study of the working environment of the navigator on the ship bridge. Eye tracking data is collected with two different types of Eye Tracking Glasses (ETGs). The advantages and challenges of collecting eye tracking data are presented together with a method for collecting, analysing and interpreting eye tracking data with regards to understanding usability. The objective of the research is to identify any specific issues with regards to usability in the bridge design and GUI in the working environment of the navigator.

1.1. *Previous Findings and Limitations.* In the maritime community there is not much research when it comes to understanding the navigator's visual perception, utilisation of this and time distribution with regard to Areas Of Interest (AOIs). The authors have written an earlier article presenting a comparative study of bridge and simulator navigation training (Hareide and Ostnes, 2016), with a follow up on understanding the visual perception and time distribution of the navigator (Hareide et al., 2016).

Limitations in the data set are related to the use of bridge navigation equipment on board the corvette which has been defined as AOIs for the navigator. This includes the ECDIS, radar, trip meter, controls (conning information) and the surroundings of the ship (outside). The data was collected during day time with a good visual detection range, and the use of radar is thus not representative. The data presented is collected from the navigator. Military navigation cannot rely on Global Navigation Satellite Systems (GNSS), and consists of traditional navigation techniques (Hareide, 2013, Appendix G). The data is collected on a high-speed craft with a length of 50 metres, and there could be deviations in this data when compared with that for larger and slower vessels.

There are more than 30 different ECDIS producers in the market today (ECDIS Limited, 2016), all with different GUIs. This study is undertaken on the Kongsberg ECDIS version 3.4.

2. BACKGROUND. Eye tracking has shown to be promising in the analysis and development of a human-centred bridge design approach for an advanced Dynamic Positioning

bridge (Bjørneseth et al., 2014), where eye tracking data has been used regarding a usability study of the Dynamic Positioning Operator (DPO) workstation. The use of eye tracking has also proven to be useful in differentiating the performance between expert and novice high speed navigators (Forsman et al., 2012). Analysing scan path events such as look-backs (revisits), indicates differences between experts and novices. A higher number of look-backs can indicate a larger degree of control and thus novice mistakes can be avoided (Rosengrant et al., 2009). Van Westrenen (1999) reported on the visual perception of pilots in Rotterdam and concludes that at times of high workload, up to 90% of the time is spent observing the surroundings of the ship (fairway in front of the ship), while Bjørneseth et al. (2014) reveal that the DPO spent an average of 35% of their time looking outside. The amount of time spent looking out of the window will be differentiated depending on the type of operation.

Several studies have also been conducted in other safety critical domains, such as power plant control rooms and aviation (Holmqvist et al., 2011). The effectiveness of using eye tracking data in a multi-model approach has also been outlined in usability evaluations of a ship's bridge (Papachristos et al., 2012). The car industry has used eye tracking data for optimisation of design and layout with good results (Chisholm et al., 2008).

Eye tracking is widely used for user interface design, and the purpose and usefulness of it is not much questioned (Bergstrom and Schall, 2014). If the goal of the usability evaluation is to assess if a user interface enables a human to conduct a specific task or operation, eye movements might provide a valuable insight into human behaviour. However, it should be noted that it might also provide limited information on evaluating whether a particular design facilitates task resolution (Groen and Noyes, 2010). Bergstrom and Schall (2014) point out some general considerations and drawbacks when it comes to using eye tracking in usability studies. They highlight that it is a time-consuming process, that it is an investment in both hardware and software, and that by purely using the equipment one could affect the techniques and user groups in a usability study.

There are several Original Equipment Manufacturers (OEMs) which produce different supportive equipment to be used in the conduct of safe navigation on board the ship bridge. The lack of standardisation of this equipment on the ship bridge has been pointed out as a concern (Meck et al., 2014). Kataria et al. (2015) points out the use of human-centred design and evolving it to crew-centred design as a solution in designing a better integrated navigation system. The International Organization for Standardisation (ISO) has published a standard on the "Human-centred design for interactive systems" (ISO 9241-210). This standard provides requirements and recommendations for human-centred design principles and activities, which outlines terms and definitions and the principles of human-centred design, and the importance of an iterative process in the plan and activities of designing for a human-centred system (ISO, 2010). There is also ongoing work with regards to standardisation with the initiative of drafting the Guideline for S-mode, which is scheduled for completion in 2019. The S-mode guidance aims to address matters not already mentioned in relevant IMO documents and to provide detailed requirements on presentation and the HMI (IMO, 2016).

Wiener (1989) introduced the term "clumsy automation" to describe automation that places additional and unevenly distributed workload, communication and coordination demands on pilots without adequate support. In short, clumsy automation is automation that makes easy tasks easier and hard tasks harder in challenging situations.

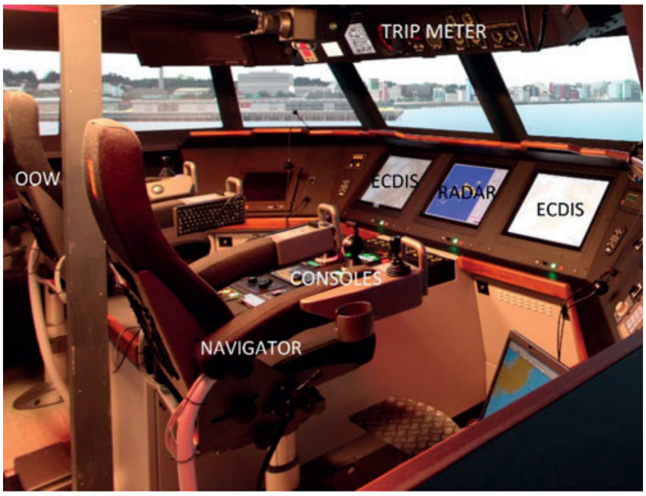

Figure 1. Corvette bridge layout.

3. EXPERIMENTAL DESIGN AND METHODS. Eye tracking data is valuable because it shows both conscious and unconscious processes of people looking at a specific area (Bergstrom and Schall, 2014).

3.1. *Study Design.* Collection of the data was undertaken on board the Royal Norwegian Navy corvettes. The corvettes' INS consists of radar, ECDIS, trip meter with navigation information and the consoles with conning information concerning the ship's propulsion and manoeuvring system. This is illustrated in Figure 1.

Based on the INS and the navigator's use of the different sub-systems, AOIs were identified in a pre-study (Hareide and Ostnes, 2016), and five areas of interest were identified:

1. Outside (AOI_O): Consists of the surroundings of the ships, and are defined by the boundaries of the windows on the ship's bridge.
2. ECDIS (AOI_E): The Electronic Chart and Display Information System (ECDIS) which is presented on the MFD in front of the navigator.
    a. Route Monitor (AOI_M) window is in the lower right corner of the ECDIS software.
3. Radar (AOI_R): The radar picture, presented on the centre MFD on the ship's bridge.
4. Trip meter (AOI_T): The Electromagnetic Log (EML) which presents speed and distance is located on a display above the navigator.
5. Consoles (AOI_R): Ship's propulsion control (water jets) and autopilot (AP).
6. White Space (AOI_W): The other areas than those defined by the AOIs.

The areas of interest are illustrated in Figure 1. The navigation team of the Corvettes consists of two persons, the Officer of the Watch (OOW) and the Navigator.

3.2. *Eye Tracking.* The eye tracking data was collected with two different sets of Eye Tracking Glasses (ETGs), as shown in Figures 2 and 3.

The two different technologies are compared in Table 1 (Tobii, 2016, SMI, 2016).

Figure 2. SMI ETG 2w (Photo courtesy SMI).

Figure 3. Tobii Glasses 2 (Photo courtesy Tobii AB).

Table 1. Comparison of Eye Tracking Glasses.

	SMI ETG 2w	Tobii Pro Glasses 2
Sampling rate	60 Hz/120 Hz	50 Hz/100 Hz
Field of View	60° horizontal, 46 vertical	82° horizontal/52 vertical
Calibration	1/3-point calibration	1 point calibration
Gaze tracking accuracy	0,5°	0,5°
Gaze tracking range	80° horizontal, 60° vertical	>160° horizontal, 70° vertical
Scene camera resolution	Resolution:1280x960p@24 fps 960x720p @30 fps	1920 × 1080 at 25 fps
Frame dimension (WxH)	173 mm × 58 mm	179 mm × 57 mm
Weight	47 g	45 g
Interchangeable nose piece	Yes (3)	Yes (3)

3.2.1. *Eye Tracking Data Collected With Tobii Pro Glasses 2.* The dataset collected with the Tobii Pro Glasses 2 (Tobii, 2016) was collected on board one of The Royal Norwegian Navy corvettes in spring 2016, and the outside surroundings and weather conditions correspond to those collected with the SMI 2W ETGs (SMI, 2016; Hareide and Ostnes, 2016).

A precondition for interpreting the two datasets is that the outside surroundings and weather conditions are similar.

3.3. *Eye Tracking Metrics And Data.* "Fixation" is defined as the state when the eye remains still over a period of time on a specific point (Holmqvist et al., 2011), and in this data set the period is given as more than 80 milliseconds (ms). Fixation time is the time period of a specific fixation. "Saccade" is defined as the rapid eye motion between two

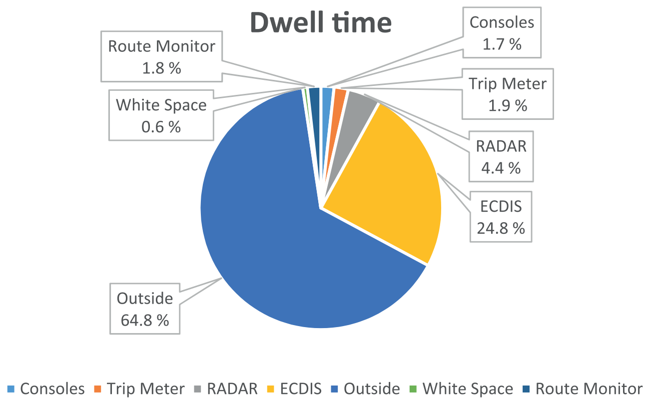

Figure 4. Dwell time in the AOIs.

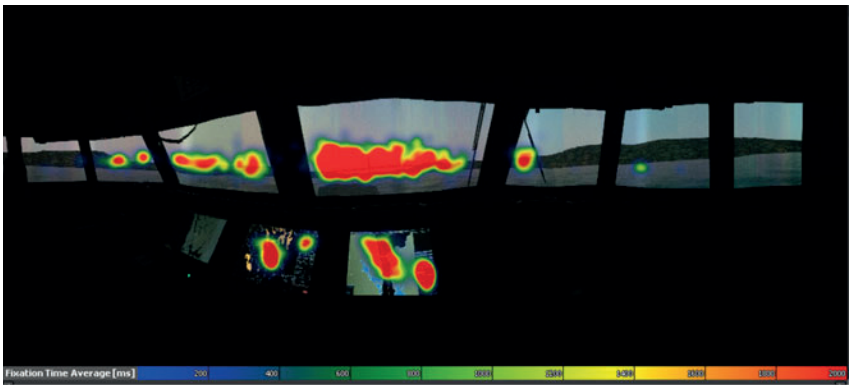

Figure 5. Heat Map of Eye Tracking data.

fixations, understood as from one fixation to another (ibid.). A “Dwell” is defined as a visit in an AOI, from entry to exit (ibid.) The “dwell time” is defined as the total amount of time spent in the specific AOI. The dwell time in each of the AOIs from the eye tracking dataset is presented in Figure 4.

“White space” is all the area not defined by the AOIs in Figure 1 where the participant’s eye movements are recorded. Dwell time in all the above AOIs and white space should sum up to 100%, but there could be a 10–13% deficit due to eye tracking data loss. The reason for this loss could be blinking, eye position outside the tracking range of the eye tracker and connection losses in the device.

“Attention maps” are visualisations and representations of the eye tracking data, and could also be defined as the presentation of spatial distribution of eye-movement data. Examples of attention maps are heat maps or focus maps. These attention maps are generated by the eye tracking software. Heat maps show area with many fixations or data samples highlighted with warm colours (red) and regions with less data are marked with colder colours (blue), see Figure 5. The bridge layout is presented in Section 3.1 and can be compared with Figure 1.

Figure 6. Focus Map of Eye Tracking data.

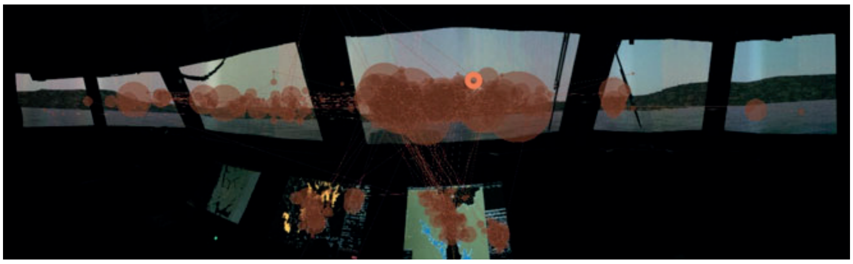

Figure 7. Scan Path presentation of the collected Eye Tracking data.

Focus maps are similar, but they present areas with few or no fixations as blind zones, see Figure 6.

"Scan path" is defined as the route of oculomotor events through space within a certain timespan (Holmqvist et al., 2011). A fixation is shown as a circle, the size of which defines the period of the given fixation. The lines between the fixations represent a saccade. This is shown in Figure 7.

A "sequence chart" is a representation of the AOIs over time. The sequence chart shows the order and duration of dwells in the AOIs, and is shown in Figure 8 (ibid.).

"Look-backs" are operationalised as saccades to AOIs already looked at, and are also known as returns and refixation. Look-backs are closely related to "inhibition of return" which is the observation that attention is unlikely to be re-directed to previously inspected areas (ibid.). A look-back could constitute a failure of memory (Gilchrist and Harvey, 2000), but one must also account for the fact that working memory has a limited temporal capacity. When using look-backs one must define how long ago the AOI was previously looked at for fixations there to count as a look-back, which is typically 10 seconds. In web-page interaction interpretation of the number of times a user looks at a link before clicking it, this represents confusion concerning the purpose of that link. The user looks back at the link (revisits) several times to make sure it is the correct link for their task (Bergstrom and Schall, 2014). Look-backs can also indicate that the user is rechecking the information in the given area, and could be interpreted as importance of information in the given area (Mitzner et al., 2010). Whether and when looking at how often a participant is looking back/rechecking the content they were seeking in a given AOI could imply a difficulty in

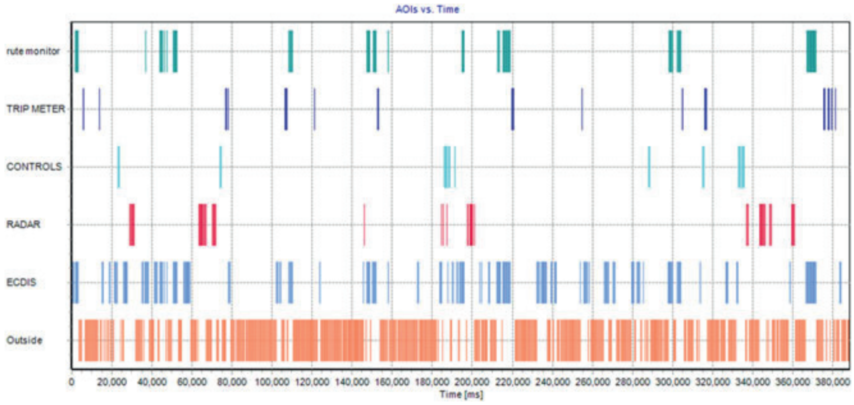

Figure 8. AOI Sequence Chart from Eye Tracking data from SMI software.

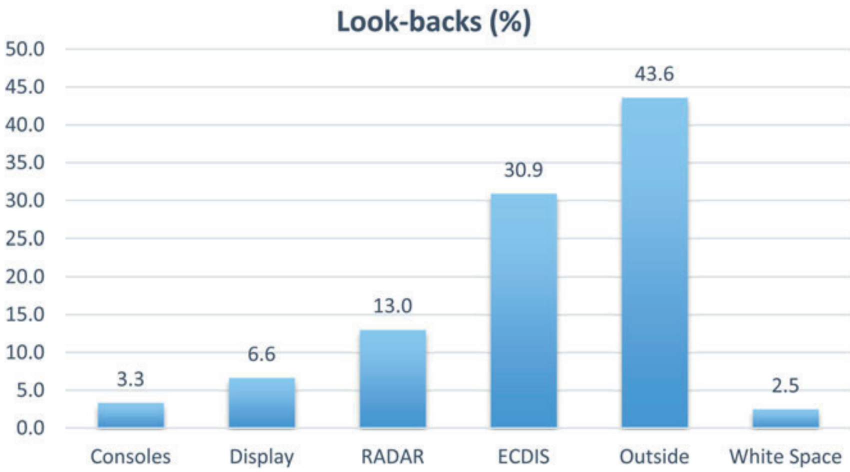

Figure 9. Look-backs in percentage in AOIs.

understanding its content or a specific user attraction to the AOI (Bergstrom and Schall, 2014). The number of returns could also indicate a semantically informative area, which aligns to the number of dwells (Holmqvist et al., 2011). In a complex environment like the maritime bridge, the look-back or return/refixation will indicate the importance of the AOI. The look-backs for the eye tracking data collected in this study are presented in Figure 9.

A "Backtrack" is the specific relationship between two subsequent saccades where the second goes in the opposite direction to the first (Holmqvist et al., 2011). It is also known as a regressive saccade which is rapid eye movements that are backtracked so that a user looks back at content previously seen. This behaviour can be indicative of confusion or uncertainty (Bergstrom and Schall, 2014). Holmqvist et al. (2011) point out that backtracks are notoriously ambiguous events, and must be related to other scan path events or eye tracking data when analysed.

For usability studies, one could argue that the use of backtracks is a better representation due to changes in goals and an indication of a mismatch between the users' expectation

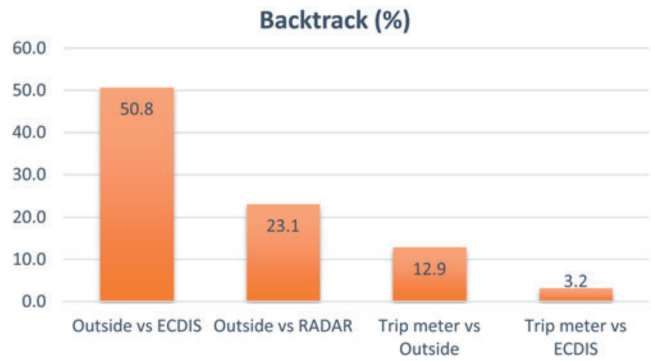

Figure 10. Backtracks in percentage between four AOIs.

and the interface layout (Goldberg and Kotval, 1999). With the AOIs defined in this study (Figure 1), a backtrack will be interpreted as an eye movement from a specific AOI to another, and back to the specific AOI. This can indicate that the navigator finds it challenging to interpret the information in that AOI, and thus needs to backtrack to the AOI to validate the assumption. The number of backtracks in Figure 10 is given in percentages to identify the relative relationship between the different backtracks. More than 50% of the backtracks are concerning outside and the ECDIS, which could represent a challenge for the navigator to interpret or understand and to memorise the information given from the ECDIS.

3.4. *Methods.* In order to conduct a study to identify usability issues in the bridge layout and in the GUI, the following methods were selected:

1. Analysis of ocular behaviour (visual perception).
   a. Dwell time.
   b. Attention maps.
   c. Sequence charts.
2. Analysis of scan path events.
   a. Look-backs.
   b. Backtracks.
3. Identify sub-optimal design and GUI solutions in the working environment of the navigator.
   a. Present a possible solution to compensate for the sub-optimal design.

This should be conducted as an iterative process in accordance with the principles in ISO 9241-210.

4. FINDINGS. In the findings three interesting observations are presented from the eye tracking data regarding the bridge layout and software GUI together with the pros and cons with the use of eye tracking data in maritime usability studies.

4.1. *Maritime Usability Study Of Bridge Design And Software GUI With Eye Tracking Data.* To understand how the bridge is laid out, it is important to understand the context of use. The context of use is defined as “hardware, software and materials, and the physical and social environments in which a product is used” (ISO, 2010). The corvettes

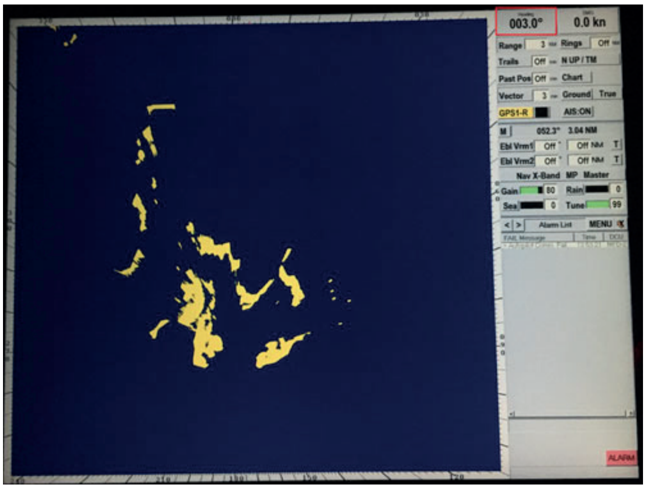

Figure 11. Radar GUI, heading information in upper right corner.

are warships, and their use in navigation is outlined in earlier work (Hareide and Ostnes, 2016).

4.1.1. *Heading Repeater.* When analysing AOI Radar ($\mathrm{AOI_R}$), an interesting observation is made in the attention maps in Figures 5, 6 and 7. All the attention maps indicate an extra attention drawn to the upper right corner of the $\mathrm{AOI_R}$. Looking at the GUI of $\mathrm{AOI_R}$, the upper right corner is presenting the current heading and speed, shown in Figure 11.

Comparing dwell time and look-back in Figures 2 and 9 for $\mathrm{AOI_R}$, there is a ratio of 4·4 in advantage of look-backs compared with dwells for $\mathrm{AOI_R}$. 23·1% of all backtracks (Figure 10) were conducted to $\mathrm{AOI_R}$, indicating difficulty in interpreting the information. To understand if this is due to difficulties in understanding or interpreting the AOI, or if it is due to rechecking, the context of use has to be known. The context of use in $\mathrm{AOI_R}$ is during the turn and control phase of the navigation, when the navigator conducts the turn as a helmsman and controls the heading of the vessel. This is done by the navigator after every turn, and the frequency is high when navigating at high speeds in littoral waters. The navigator compares the planned course with the current heading, and assesses whether the ship is in the correct and expected position. This is an important control mechanism for high speed navigators in littoral waters, and it is thus essential that the heading is easily available for the navigator. Based on the number of look-backs and backtracks, the context of use does not explain the high numbers even though one should expect a high number of look-backs due to the frequency of turns. The eye tracking data have revealed a challenge for the navigator to understand and interpret heading information, which is compensated by revisiting (look-back) and backtracking to the AOI to avoid a misunderstanding.

To better provide heading information for the navigator, a more accessible heading repeater should be integrated in the navigation system.

4.1.2. *Trip Meter Layout.* The context of use of $\mathrm{AOI_T}$ is as a distance measurement tool for the navigator. When conducting a turn, the navigator should plan and conduct the turn with more than one turning indication, known as primary and secondary turning indication. This could be the trip meter and a visual bearing. The navigator uses the trip meter on each leg to verify the distance before starting on a new leg, which is known as

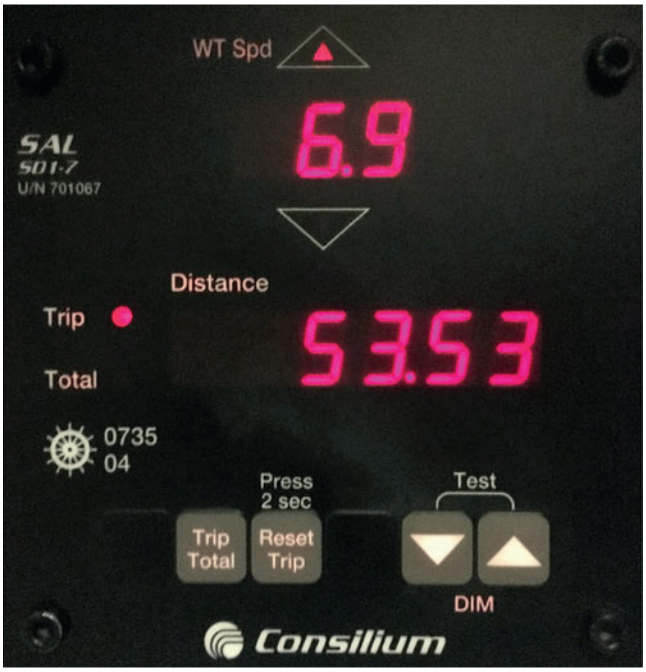

Figure 12. HMI Electromagnetic Log.

a primary or secondary turning indicator. The Electromagnetic Log (EML) could also be used in position fixing by the means of bearing calculations known as a four-point bearing (Hareide, 2013, Appendix G).

Figure 4 shows AOI_T consuming 1·9% of the navigator's visual attention. Analysing backtracks in Figure 10 shows that 12·9% of the backtracks are between AOI_T and AOI_O, and this could indicate poor usability. Looking at the ratio of look-backs compared with the dwell time, the ratio is 5·2. This ratio also indicates either confusion or double checking from the navigator.

The attention maps and the sequence chart also indicate that the AOI_T is drawing navigators' attention.

The physical placement of AOI_T is above the navigator shown in Figure 1. The navigator interacts with the display by reading out the values of the trip counter and by resetting the trip counter. This is shown in Figure 12.

The EML display is designed with six soft key buttons, which have the same size and shape, on a line at the bottom of the display. One of the buttons is used for resetting the trip meter. Both during daytime and especially during night time it is difficult for the navigator to select the correct button without giving the AOI_T visual attention. The procedure of resetting the trip meter is safety critical as it has a function as a primary or secondary turn indicator, the navigator puts extra effort into doing this task. To be sure that the trip meter is reset, the navigator changes their focus and shifts the head position to monitor that the trip meter is reset. In addition, the button needs to be pressed for 2 seconds in order to reset it, which further hampers the procedure.

From the eye tracking metrics of look-backs and backtracks, together with an understanding of the context of use, it is shown that the navigator must double check AOI_T. The scan path events of backtracks and look-backs has identified poor usability and sub-optimal bridge design. A possible solution for this challenge is a reset button and read out display for the trip meter which is more available and efficient for the navigator.

4.1.3. *Usability Study of Software GUI.* The dwell time could represent the importance of an AOI (Jacob and Karn, 2003). In the challenging environment of high speed navigation in littoral waters, the main focus of the navigator must be in the surroundings of the ship. This is supported by navigation techniques, such as the Dynamic Navigation (DYNAV) concept (Forsman et al., 2012). Related to the eye tracking data, most of the navigator's attention should be in AOI_O. Dwell time identifies which AOIs the navigator spends the most time focusing on. 24·8% of the navigator's attention is drawn to the ECDIS, making it the largest contributor for visual attention drawn away from the outside of the ship.

When analysing look-backs in Figure 8 compared with dwell time in Figure 3, it is identified that the navigator revisits the AOI_E more than the AOI_O with a ratio of 1·9. This ratio could indicate a difficulty in interpreting information in AOI_E, or simply a need for the navigator to verify the information. This double-checking could also be an indication of problems with collecting the relevant information from the ECDIS GUI. One could also argue that the ratio of 1·9 is not significant compared to the ratios from AOI_R and AOI_T. Analysis of backtracks in Figure 9 reveal that more than 50% of all backtracks are between AOI_O and AOI_E, which could indicate a challenge in the usability of the ECDIS GUI. Backtracks must be used with care due to the ambiguity of the event, but used together with other scan path events or eye tracking data provides accumulated information pointing towards a GUI usability challenge.

For further analysis of the AOI_E, we use the scan pattern in Figure 6. Most of the attention is drawn towards the chart, but it is also identified that the navigator's attention is attracted to the lower right corner of the AOI_E GUI. Usability studies should be an iterative process, and based on this finding, a need for redefining the AOI is identified and conducted as shown in Figure 14.

Redefining the AOI identifies the new AOI Route Monitor (AOI_M) window. The purpose of the Route Monitor window is to present the position of the ships against the planned route for the navigator. When looking at the dwell time in Figure 3, it is identified that the navigator spends 1·8% of the time interpreting the data from this AOI. $AOI_M$is attracting the navigator's attention shown by the visual distribution of time in the sequence chart in Figure 7.

The navigator's context of use of the route monitor window is to collect information regarding turning information (1), heading mark information (1), time to Wheel-Over-Point (WOP) (2), course information (3), distance on leg information (4) and cross-track distance (5) which is the shortest distance between the own-ship and the intended route. This is shown in Figure 14. This information is also incorporated in a voice procedure in the navigation team.

The Route Monitor Window is in the bottom right corner of the ECDIS GUI, and is at a distance of approximately 2 metres from the navigator. The numbers and letters are too small for the navigator to read, and the navigator must use extra attention and focus on interpreting these data. The large number of backtracks also indicates a challenge in usability in the AOI, and a redesign of the GUI should be considered. A better GUI with

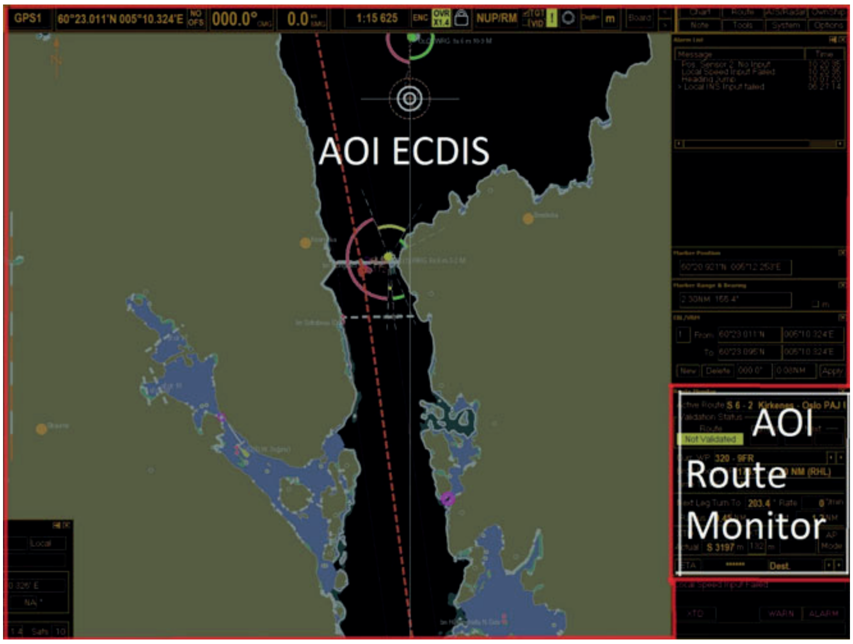

Figure 13. Redefining AOIs with AOI Route Monitor.

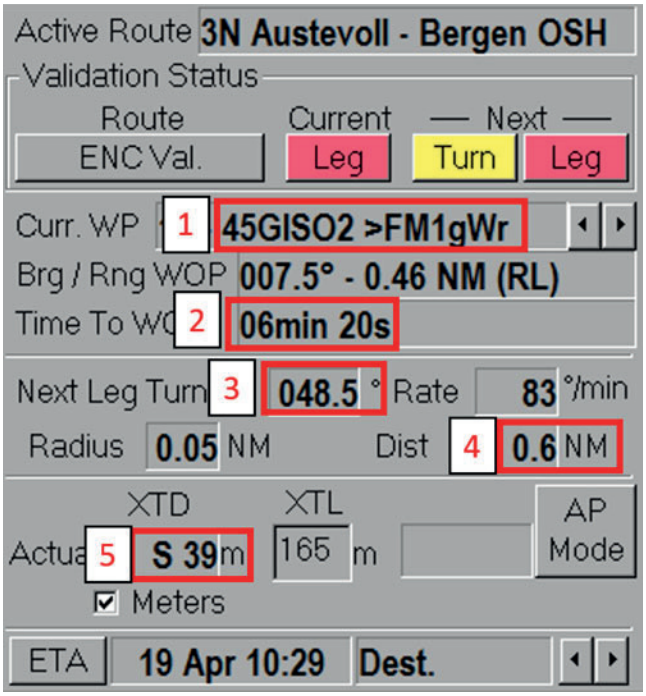

Figure 14. Content of the Route Monitor window.

Figure 15. Glare in ETGs.

regards to presentation of relevant information to the navigator would reduce the effort and time for the navigator in collecting this vital information for the voyage.

4.2. *Maritime Usability Study with the use of ETGs.* It is important not to disturb the techniques and behaviour of the user group when collecting eye tracking data with ETGs. A challenge was identified with regard to loss of data due to the participants looking outside the frame dimension. This is caused by the navigator looking over or under the glasses; mostly under due to the angles from the operator to the screens. The physical reasons for this is the size of the frame where the eye movements are collected, in addition to the distance from the eye to the lenses. Figures 2 and 3 show a difference in the thickness of the frames, which could influence the navigator. If the distance is too long, there is a higher risk of the participant looking under the glasses. This can also be adjusted by the different nose pieces that come with the ETG, but they are primarily used to conduct a calibration of the equipment before starting the recording and should not be changed. The producers suggested setting up a physical barrier so that the participant did not look outside the frame of the ETG, but this was not conducted as it was considered to affect the natural behaviour of the navigator.

The use of ETGs together with binoculars is challenging, especially for those who are not accustomed to wearing glasses. The use of binoculars is safety-critical in high speed operations in littoral waters, and the subject has to be trained and comfortable with using ETGs together with binoculars before collection of the dataset to prevent interruptions in the data collection.

When using the ETGs in twilight, the light pollution from the scene cameras is distressing for the navigator. During dusk the binoculars are frequently used to identify objects during the passage. The light pollution in addition to the challenges with the use of binoculars makes the use of current generation ETGs impossible in twilight and during night time.

When using the ETGs during daytime, particularly when the sun is close to the horizon, a glare in the ETGs occurs which is shown in Figure 15. This is disruptive for the navigator, and makes the use of ETGs a challenge.

Collecting eye tracking data, especially in a field study in a dynamic environment such as on board the Norwegian corvettes, is challenging with limited battery capacity and the use of cables for ETG connection and charging. This can be mitigated with the use of power banks and wireless connections, but must be accounted for in the design of the study.

When collecting data in a dynamic environment on board a ship, it is important that the calibration process is simple, accurate and quick. The calibration process can be challenging if there is a considerable contrast in the brightness of the light between the environment and the background of the calibration. This is often the case on board a ship where the bridge is more dimmed than the outside during daytime. This could result in lost calibration, and thus extra post-process work which also could make some of the data ambiguous.

The software presentation concerning visual presentation of the attention maps is important to better understand and analyse the eye tracking data. The use of a sequence chart, shown in Figure 8, is an important feature which not all producers provide. The sequence chart is a good visualisation of time-stealing displays and areas when optimising the design of the bridge layout and software GUI on an integrated navigation system.

When using automatic eye tracking data processing, there are indications that this process is not thorough and can be considered as not fully developed. The manual work of analysing eye tracking data is a time-consuming job, where approximately 60 minutes of processing goes into every 10 minutes of recorded eye tracking data. When the automatic eye tracking data processing function is fully developed, this will make the use of eye tracking data more accessible.

5. CONCLUSION. Work as a navigator on a high speed craft is a demanding job, and in the past few years several new displays and technologies have been introduced to aid and provide added value for the navigator. When introducing new technology to the navigator, it is important to make a good interface in accordance with the human-centred design concept. The design of the bridge must facilitate the attention of the navigator to the surroundings of the ship for continuous control and monitoring of the safe passage of the ship.

This article shows how eye tracking data, with a defined method utilising scan path events and attention maps, can be used to identify which areas of interest attract the navigator the most. The data set presents an example of sub-optimal bridge layout concerning placement of equipment, together with two examples of sub-optimal GUI in radar and ECDIS software. The eye tracking data identifies areas of interest which draw too much of the visual attention of the navigator, and we have presented suggestions for improvements in the bridge layout and software GUI based on the findings. Eye tracking data shows good potential for analysing the usability of a bridge layout and software GUI on a ship bridge when using the correct methods.

Some advantages and challenges with using ETGs are laid down, with emphasis on the importance of not affecting the normal behaviour of the navigator by collecting data, and also how the software should provide good visualisation and interpretation of the eye tracking data.

Further work includes implementing the current findings on board with development and optimisation of software GUI and bridge layout, contextualising and developing a recommended navigator scanning pattern when conducting navigation on an integrated navigation system and concept and development of a graphical user interface for presentation of relevant information to the navigator.

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ETHICAL STANDARDS

The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008. Consent forms were used in all data collection.

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Paper III

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Scan Pattern for the Maritime Navigator

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ABSTRACT: The maritime high speed craft navigators` ultimate aim has for decades been to safely and efficient navigate the vessel to its destination. The last decade an increased use of technology has arrived at the maritime ship bridge. The use of Electronic Charts and Integrated Navigation Systems has revolutionized much of the work of the navigator, with the aim of enhancing the safety of navigation. The amount of information has drastically increased, and the need for a proper information management and an efficient visual scan pattern has been identified. Looking to other industries this has been introduced with success, and in this paper the authors present a proposed scan pattern for the maritime navigator. The analysis is based on an eye tracking data set collected from simulator- and field studies on board the world's fastest littoral combat ship.

1 INTRODUCTION

The aim of the INS, and e-navigation, is to enhance safety of navigation, by collecting and providing vital information in a user friendly manner for the navigator. It has raised concern that navigators look more at the displays than controlling the surroundings of the vessel, and concerning the visual focus of the navigator there are not any industry standard or recommendation on the use of the integrated navigation system. Based on the Eye Tracking data set and cross-section knowledge from aviation and other high-risk industries (power plants), this article aims to present a recommended visual scan pattern for the maritime navigator.

1.1 *Integrated Navigation Systems*

New vessels today are highly technological, also at the ship bridge. The use of new sensors and technology, which are highly integrated, are widely used. An example of such is the Rolls Royce Unified Bridge (Rolls-Royce, 2015) in Figure 1 or the K-Bridge INS (Kongsberg, 2016), which goal is to increase the operational safety by efficient workflow which reduces the cognitive workload for the navigator.

The purpose of an Integrated Navigation System (INS) is to enhance the safety of navigation, this is done by providing integrated and augmented functions to avoid geographic, traffic and environmental hazards (IMO, 2007, p. 2). An INS is defined as such if workstations provide Multi-Function Displays (MFD) integrated with at least the following navigational tasks/functions:

- Route Monitoring
- Collision avoidance

and may provide manual and/or automatic navigation control functions (IMO, 2007, p.3)

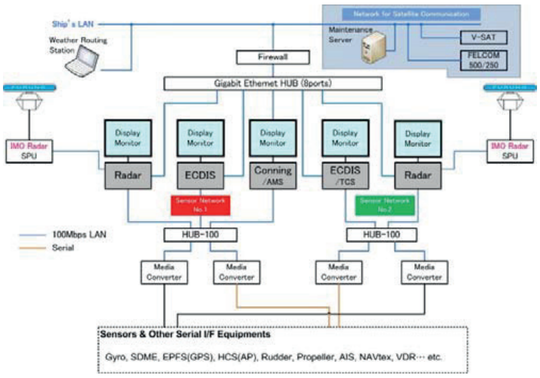

Figure 1. PSV Stril Luna Integrated Navigation System (courtesy of Rolls-Royce).

The INS can consist of several parts, but the most important navigation sensors for the navigator is:

- Electronic Position Fixing System (EPFS) (e.g. GNSS as GPS)
- Heading control system (HCS) (e.g. Gyro)
- Depth sensor (Echo Sounding System, ESS)
- Speed and distance measurement (SDME) sensor (e.g. Electromagnetic Log)

The INS also needs systems and sensors which can provide:

- Collision avoidance (e.g. Radar and AIS)
- Route planning and monitoring (e.g. ECDIS)
- Track Control System (TCS) (e.g. Autopilot)

These sensors and systems are interconnected in some type of network (e.g. NMEA2000, Ethernet, etc.).

The maritime bridge has become more and more digitalized the past years, and retrofitted and new ship bridges are equipped with several MFDs. These MFDs can present

1. Electronic Chart Display and Information System (ECDIS) application, which most commonly consist of an Electronic Navigation Chart (ENC) with navigation sensors integrated.
2. Radio Detection and Ranging (RADAR) application, which is a terrestrial navigation system using radio waves to determine range, angle or velocity of objects.
3. Conning application, which aim is to make key information available for efficient monitoring. Conning information gather all relevant sensor information and navigation data at a glance, and aims to improve accessibility for the navigator.

1.2 *E-navigation*

The International Maritime Organization (IMO) is currently working on an initiative called E-navigation.

The purpose of E-navigation is to improve electronic information exchange to:

- Enhance berth-to-berth navigation
- Provide simplification to improve safety, security and environment
- Facilitate and increase efficiency of maritime trade and transport.

With this in mind, e-navigation aims to minimize navigational errors, incidents and accidents through the transmission and display of positional and navigational information in electronic formats (Weintrit, 2011).

The last decades have seen huge developments in technology within navigation and communication systems. Although ships now carry Global Satellite Navigation Systems (GNSS) and have reliable Electronic Chart Display and Information Systems (ECDIS), their use on board is not fully integrated and harmonized with other existing systems and those of other ships and ashore. The work with Integrated Navigation System Performance Standard and with e-Navigation will enhance this integration and harmonization.

Currently some yards are looking at open system architecture for holistic and user-friendly integration of multi supplier bridge systems to e-navigation, such as the Vard (Fincantieri) Open Bridge (Tennfjord, 2016).

1.3 *Limitations and earlier work with the data set*

The current data set is collected in daylight in good visual conditions (Hareide and Ostnes, 2016a). The data set and its` analyses is described in detail in earlier work. An analysis of the use of simulators has been discussed (Hareide and Ostnes, 2016a), together with the use of eye tracking data when assessing human machine interface (Hareide et al., 2016), and a maritime usability study with the use of eye tracking data (Hareide and Ostnes, 2016b).

2 BACKGROUND

2.1 *Control strategies in the maritime domain*

With the introduction of more sensor and technology to the ship bridges, the degree of automation has increased. There is an ongoing discussion of how much knowledge and skills, and of what type, the modern ship navigator needs when it comes to the use of INS (Torskiy and Topalov, 2013). However, the craftsmanship of navigation has stayed the same during the past hundreds of years, and the methods of earlier days without digital displays still applies (Norris, 2015).

The Royal Norwegian Navy Navigation Competence Centre (RNoNNCC) has teached and trained navigators to the Royal Norwegian Navy (RNoN) for 200 years, and even though the syllabus has changed significantly, the basic methodology has stayed the same. Navigation starts with proper planning. With a good plan in hand, it is easier to conduct a safe passage. In conducting a passage, it is important that the navigator has a methodology to be used during the voyage. The methodology developed by the RNoNNCC has parallels to the DYNAV methodology (Forsman et al., 2011), but is an extended version. The methodology is shown in Figure 2.

Note that the four phases of navigation are utilized after a thorough planning process (as described in

SOLAS) has been conducted, and is the methodology that the navigator is using during the watch. The methodology fits on any type of vessels, but the process is more demanding in confined water and with higher speed. This is also similar to the OODA-loop (Richards, 2004), which is a decision-making strategy with the reoccurring cycle of observe-orient-decide-act.

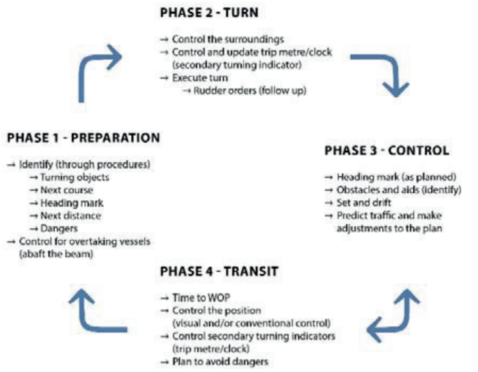

Figure 2. The Four Phases of Navigation

Phase 1 consists of the preparation before a turn is initiated. In this phase it is important to gather and highlight all relevant information to successfully conduct the turning phase.

Phase 2 is the critical turning phase for the vessel, where the vessel alters course. In this phase it is imperative that the navigators` focus is on the conning and surroundings of the ships, to make sure the turn is executed correctly.

Phase 3 consist of the control phase after an alteration of the course. Immediately after the turn, the navigator collects information to establish whether or not the ship is in the predicted (and correct) position. This phase also consists of the reoccurring cycle of predicting the set and drift, and also predicting the surrounding traffic pattern.

Phase 4 is the transit phase, where the vessel is transiting between two wheel over points (WOP). In this phase it is important that the navigator continuously monitors the position of the vessel, both by visual and conventional control methods (Hareide, 2013). Phase 3 and 4 is an iterative process until the next planned WOP is reached and the phases of navigation starts over again.

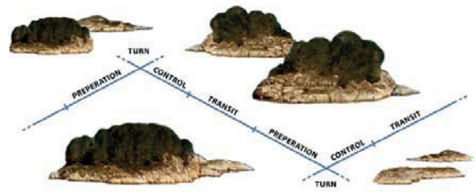

Figure 3. Overview of the Four Phases in Maritime Navigation.

The shift from paper charts to electronic charts was made to enhance the safety of operations. After years of experience, it is clear that the introduction of ECDIS also increases complexity (Wingrove, 2016). This complexity can be shown with a figure that outlines the navigational and human factors which implies when conducting electronic navigation.

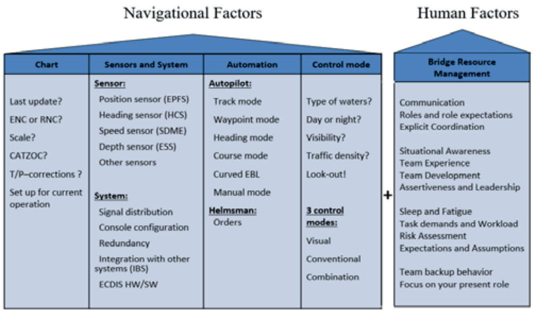

Figure 4. Safe and Efficient Electronic Navigation

As shown in Figure 4 above, an important part related to the conduct of the passage is the weather and visual conditions. If the visual conditions are poor, one must use conventional methods (e.g. use of radar) for controlling the passage.

The Figure also shows the importance of system awareness as a navigator. Situational awareness consists of three components; spatial awareness, system awareness and task awareness. System awareness is needed to keep the navigator informed about actions that have been taken by the sensors and systems (automated processes), and it is imperative for the navigator to know what state the system is in (automation). Compared with Figure 4, Sensor/System and automation is important to maintain a desirable System Awareness for the navigator (Wickens, 2002).

Combining Figure 1 and Figure 4 illustrates the importance of and amount of knowledge needed about the navigational factors for the navigator.

2.2 *Control methods in aviation*

Fitts et al. (1949) conducted a series of investigations in order to gather information about the pilots` eye movements during instrument approaches. This research subsequently resulted and formed the basis for the classic "T" arrangement of instruments around the attitude indicator, as shown in Figure 5.

The attitude indicator is in the top center, airspeed indicator top left, altimeter top right and heading indicator under the attitude indicator. The other two, turn-coordinator and vertical-speed indicator, are usually found under the airspeed and altimeter. These instruments are essential for the control of the flight.

When conducting a flight in aviation, there are two sets of rules for the aviator to understand. This is the Visual Flight Rules (VFR) and the Instrument Flight Rules (IFR). In general terms, the IFR means flying "in the cloud" and the pilot only navigates by using the instruments in the cockpit which requires a IFR flight plan and an instrument rating.

Figure 5. Basic T-arrangement (ASB, 2016).

The instrument scan reflects the information needed for the pilot (Brown et al., 2002). There are several studies which collects Eye Tracking data in order to analyze which instruments and AOI the pilot most commonly uses (van de Merwe et al., 2012, Haslbeck et al., 2012, Yu et al., 2016), also when it comes to visual scanning of the cockpit and the outside surroundings of the aircraft (Colvin et al., 2005). When in VFR the most important area for the pilot to observe is the outside, and the pilot should have to look away from the outside for the minimum period of time (RIN General Aviation Navigation Group, 2016).

Integrity is the measure of the trust that can be placed in the correctness of the received information supplied by a (integrated) navigation system, quantified by horizontal- and vertical alert limits (HAL and VAL) (Groves, 2013). The demand for integrity in the system design in aviation is high. In the Flight Management System (FMS), integrity of the sensor is monitored. The aviator reacts on an integrity breach warned by the FMS, and initiate an (emergency) procedure if so occurs.

2.2.1 *Scan pattern*

Scan pattern is a known terminology when it comes to aviation (FAA, 2016, p. 552). It is stated that of the bodies senses, vision is the most important for a safe flight. One of the important areas for efficient use of vision is the technique of scanning when in flight. The Scan (AOPA, 2009) is a technique used to optimize the vision for collision avoidance. It states that there are no "one size fits all" technique, but recommends a timesharing technique, such as block scan, to efficiently search for threats in the surroundings. This technique divides the horizon into blocks, each spanning 10 to 15 degrees. It is important that the eye fixates at the center of each block, because the eye needs one to two seconds to adjust, before they can focus. Focusing on each point allows the eye to detect any potential conflicts within the foveal field, as well as object in the peripheral area between the center of each block scan.

In aviation there are two primary block system scans, side-to-side scanning method and front-to side scanning method. The side-to-side scanning method starts at the left of the area and make a methodical sweep to the right, pausing in each clock of viewing to focus the eye. At the end of the scan, the pilot return to the panel. The front-to-side scanning method starts at the center of the visual field and moves to the left, focusing in each block then swing quickly back to the center block after reaching the last block on the left and repeat the performance to the right (AOPA, 2009). This is shown in Figure 6.

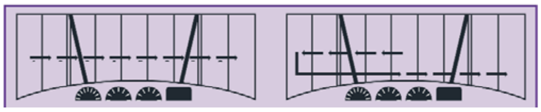

Figure 6. Block System Scan (AOPA, 2009)

When constructing a scan pattern, one should keep in mind that a scan tends to be most concentrated toward the center region of the visual field, avoiding the edges of a display (Wickens et al., 2015). The scan pattern and HMI should thus be design to adhere to this.

In the literature review there are not any findings of scan pattern related to the use of a maritime integrated navigation system.

2.2.2 *Link Analysis*

Link Analysis is a data-analysis technique which can be used to evaluate connections between points or nodes. Link analysis is used when it comes to handling information overload. When a user is confronted with a vast amount of information and data, data analysis techniques are required to make an efficient and effective use of the data. By utilizing a heuristic-based tool one can distill rules from knowledge using structured data such as eye tracking data. A scan pattern analysis for the maritime navigator based on eye tracking data consists of a link analysis. This could contribute to a more efficient and effective use of the data collected by the navigator from the INS and the surroundings of the ship.

2.3 *Eye Tracking*

Eye movements collection in aviation have been a topic of interest for over 60 years (Glaholt, 2014). The collected information has been used as a window onto operator`s processing of information, and has resulted in a whole range of application.

With the use of Eye Tracking Technology, it is possible to collect and analyze data regarding the eye`s movement. In the simplest terms, eye tracking is a measurement of the eye`s movement. By analyzing this data, one of the products is to identify the search pattern of the subject (Holmqvist et al., 2011).

2.3.1 *Eye Tracking data set*

The data set to conduct this analysis is collected on board the Royal Norwegian Navy Corvettes (Figure 7). The Corvettes are the world's fastest combat ship, capable of speeds exceeding 60 knots. It has an INS from Kongsberg Defense Agency (KDA).

Figure 7. Skjold-class Corvette

The total amount of recorded eye tracking data is nearly 3 hours, and the data set is further outlined in earlier work (Hareide and Ostnes, 2016a, Hareide et al., 2016).

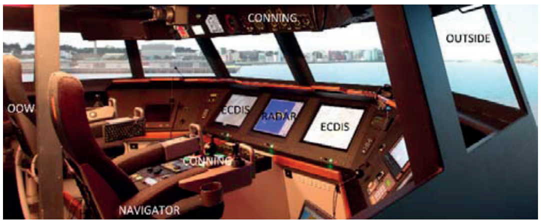

Figure 8. Areas of Interest

The Areas of Interest (AOIs) were defined as:

- *Outside* (AOIO): Consists of the surroundings of the ships, and are defined by the boundaries of the windows at the ships bridge.
- *ECDIS* (AOIE): The Electronic Chart Display and Information System (ECDIS) which is presented on the MFD in front of the navigator. AOIE also consists of the Route Monitor window (AOIM) which is in the lower right corner of the ECDIS software
- *Radar* (AOIR): The radar application, presented on the center MFD on the ships bridge.
- *Conning* (AOIC): Consisting of the displays, consoles and autopilot related to the propulsion and steering of the ship.
- *White Space* (AOIW): The other areas than those defined by the AOIs.

2.3.2 *Eye Tracking metrics*

To identify the search pattern of the navigator, both raw eye tracking data and attention maps could be used.

Fixation is defined as the state when the eye remains still over a period of time on a specific point (Holmqvist et al., 2011). Fixation time can thus be used as an indicator to analyze how efficient the navigators scanning technique is.

A saccade is defined as the rapid eye movement between fixations (ibid.). The amount of saccade could reveal if there are improvements in the scanning technique of the navigator.

The dwell time is defined as the total amount of time spent in the specific AOI, as shown in Figure 8. Dwell time can be used to identify if the navigators spend too much time in a (given) AOI.

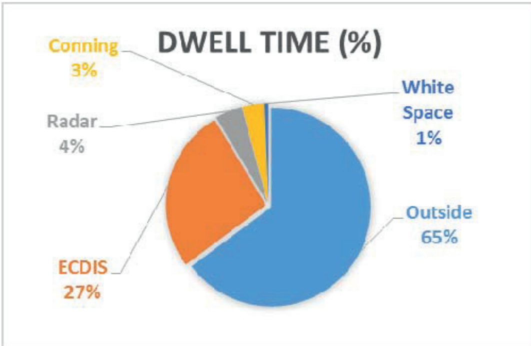

Figure 9. Dwell time in dataset

Attention maps such as a scan path presentation will visualize the scanning technique for the navigator. A scan path is also known as a scan pattern, and originates from the work of Noton and Stark (1971) which defined the term as the fairly abstract concept of a fixed path that is characteristic to a specific participant and his or hers viewing pattern. Today, a scan pattern is defined as the route of oculomotor events through space within a certain timespan (Holmqvist et al., 2011), and is shown in Figure 9.

A fixation in Figure 9 is shown as a circle, and the size of the circle reflects the fixation time. The lines between the circles reflects the saccades.

It is also interesting to look at time-sharing visualization, with the use of sequence charts (figure 11), in order to better understand and analyze where the navigator focus his/her attention.

The sequence chart is a good visualization technique when it comes to analyzing how much time, and how long, the navigator looks at different AOIs.

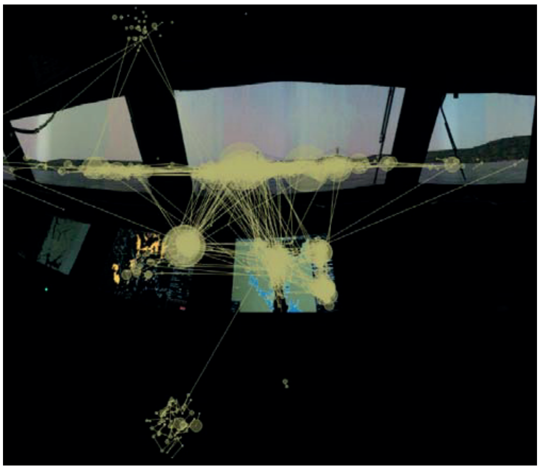

Figure 10. Scan Pattern

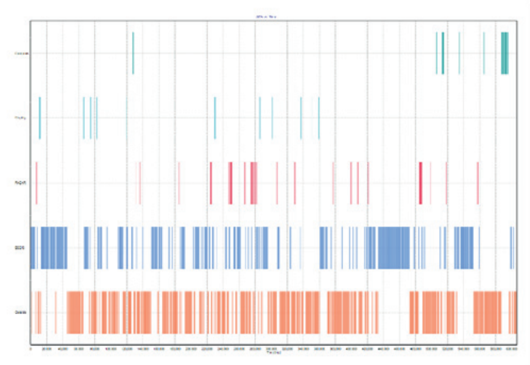

Figure 11. Sequence Chart

One could further analyze the eye tracking data for look-backs and backtracks, which is outline in an article on the use of eye tracking data for maritime usability studies (Hareide and Ostnes, 2016b). When establishing a recommended scan pattern for the maritime navigator, it is of interest to reveal if there are any design issues in any of the essential equipment for the navigator. The information should be accessible, and in the right context of use provide effectiveness and efficiency for the navigator (ISO, 2010).

Eye Tracking data is used to compare a novice and experienced navigator (Forsman et al., 2012), and has also been used to study the effect of stress at the maritime bridge during a passage (Pedrotti, 2014). Eye tracking metrics showed a good potential in both evaluating novices vs experienced boat drivers, and in analyzing the effects of stress at the maritime bridge. Van Westrenen (1999) examined Rotterdam Pilots to establish the dwell time in different AOIs, with the aim of quantifying the amount of time the pilot spends looking out the window. His study shows that the pilots spends 90% of the time looking out the window, checking the surroundings of the ship.

2.3.3 *Analysis of Eye Tracking data*

In the collected data set, the navigators` dwell time is presented in Figure 8. It is identified in earlier work that flaws in HMI steals attention from the navigator, and by adjusting this, more attention can be allocated to the surroundings of the ship (AOIo). In industry quality it has been developed models to predict the amount of time for detection. There is a concurrence between the search time available and the probability of detection (Wickens et al., 2015, p. 78). For the navigator this implies that the amount of time searching the surroundings should be as high as possible.

When looking at the scan pattern collected in the existing data set, AOI outside, ECDIS and radar stands out as important in the scan pattern for the maritime navigator (Figure 9).

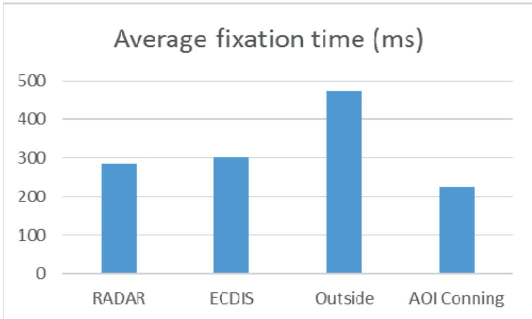

Figure 12. Average fixation time (ms) in AOIs

The average fixation time in AOIo reflects the importance of giving the eye time to actually look for objects in the surroundings, which is also reflected in scanning theory from aviation.

3 UTILIZING THE INTEGRATED NAVIGATION SYSTEM

In order to better exploit the integrated navigations system in conducting a passage, a need has been identified to develop an efficient visual scan pattern for the maritime high speed craft navigator. Link analysis theory can be applied in order to make an efficient and effective use of the collected eye tracking data.

3.1 *Recommended scan pattern*

The primary Area of Interest for the maritime navigator is the surroundings (AOI Outside, AOIO) of the ship (Norris, 2010). When conducting a passage, the navigator continuously cross-checks the information collected from the integrated navigation system. Dependent on weather and area, RADAR or ECDIS will be the second most important tool for the navigator. During nighttime or bad visibility, RADAR is an important navigation aid. When visibility is good, visual scanning supplemented with ECDIS will be the primary navigation aid for the navigator. Monitoring the conning information, with the rudder angles and trust, is important for the safe conduct of the passage.

The methodology of navigation (Figure 2) is the foundation of the recommended search pattern. This methodology implies which information that must be extracted from the INS during a passage:

During Phase 1 (preparation), information must be gathered from the ECDIS. This information should be easy accessible (Hareide et al., 2016) for the navigator, which again results in a short time sequence for the navigator to collect this information, which will be reflected in the sequence chart in Figure 11.

In Phase 2, the attention of the Navigator must be briefly at the conning to see rudder response, and mainly at the surroundings of the vessel (AOI_O) in order to continuously control that the vessel is heading in the right (planned) direction. The secondary turning indicators should have an HMI which supports this (Hareide and Ostnes, 2016b).

Phase 3 starts immediately after the vessel has turned to its` new course. Based on the information collected in Phase 1, the navigator controls the heading mark and course. Based on the analysis of the Eye Tracking data, it could be necessary with a look-back. A look-back can constitute a failure of memory (Gilchrist and Harvey, 2000), and could imply in Phase 3 if the information collected in Phase 1 is forgotten (human error/limitation or poor HMI). It is also a limitation of how much information from Phase 1 the navigator can memorize and use in Phase 3.

Phase 4 is often the longest phase of the voyage, as it consists of the time between turning points. Dependent on the environment, this will vary. In littoral waters and in high speeds, the transit phase can be very short (60 knots (111km/h), 1 nautical mile (NM) = 1 minute). In contradiction, on a journey in 20 knots (37 km/t) between Bergen and Aberdeen (310 NM), the transit phase can be more than 12 hours.

In the transit phase, the navigator controls the position, and continuously adjust the plan. The amount of controls is also dependent on the environment, and on the error and biases in the sensors used in the integrated navigation system. If the errors and biases is known to be high (e.g. terrestrial positioning), the position must be controlled often. If the errors/bias are low (e.g. GNSS as primary positioning), the control can be at increasing intervals.

The foundation in the Four Phases of Navigation must be aligned with a "Maritime Scan", based on The Scan from aviation (AOPA, 2009, FAA, 2016).

Based on the Collision Regulations (ColReg), a vessel has to give way for a vessel on their starboard side (IMO, 1972). Based on this fact, the Maritime Scan should be based on a Front-to-Side scanning method, with reference to Figure 6. The Maritime Scan should start from the center, move to the right (starboard) side, back to the center, continue to the left (port) side and return to the center (Figure 13, The Maritime Scan). The amount of side scan should be based on collision theory (Grepne-Takle, 2010, p. 26).

$$\alpha_O > \lambda \sin^{-1} \frac{V_T}{V_O} \tag{1}$$

If the own ship travels at 30 knots (V_O), and you assume that all other vessels (targets) travel at not more than 6 knots (V_T), the search width must be more than 23,1 degrees (α_O) to each side. This is with a safety margin (λ) of two used in Equation 1. This implies that the high speed craft navigator must scan an area with a width of >46.2 degrees (α_O*2). When deciding the width of the visual scan, Equation 1 could be used.

It is important to stress that the eye needs to fixate at the center of each block, because the eye needs one to two seconds to adjust, before they can focus. Thus the navigator must "rest" the eye in each block. As in aviation, 10 degrees' blocks are recommended.

Between each Scan, the navigator must control the sensor data in the INS. The Maritime Scan consist thus of two subparts, the scan in the surroundings of the ship (outside) which is based on collision theory, and the instrument scan to gain system awareness of the INS.

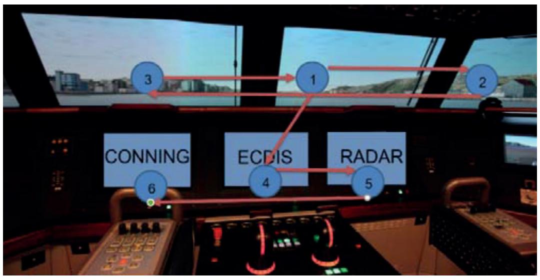

Figure 13: The Maritime Scan

The metrological conditions for conducting the passage is essential when it comes to the scanning pattern and the amount of attention to the Areas of Interest. As in aviation, the maritime has in general two categories. In good visual condition, Visual Sailing Mode (VSM) applies. When the visual conditions deteriorate, and increased use of conventional control (such as radar) is used, Conventional Sailing Mode (CSM) applies.

Table 1. Attention in AOIs in different metrological conditions.

Area of Interest	VSM	CSM
Outside (AOI_O)	80%	5%
ECDIS (AOI_E)	10%	15%
Radar (AOI_R)	7%	75%
Conning (AOI_C + (AOI_D)	3%	5%

The time distribution in AOI_O and AOI_E in VSSP is based on the benefits of better GUI and HMI together with a more efficient search pattern. This will provide more time for the navigator to control the surroundings (AOI_O) of the ships, compared with Figure 8. The amount of time spent focusing on the radar is slightly increased, due to the essential information with regards to collision avoidance which can be provided by the radar. The time distribution for collecting conning information is the same, due to the benefits of a better HMI and GUI by displaying this information in an MFD.

In CSM, the navigator must pay most attention to the Radar (AOI_R), as this is an important terrestrial navigation aid when conducting a passage during restricted metrological conditions. Note also that the ColRegs state that any vessel at all times should "maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision" (IMO, 1972). The navigator spends more time in the ECDIS (AOI_E) because of the increasing information requirement in restricted metrological conditions. The navigators need to withdraw essential information such as (but not restricted to) parallel indexes, safety indexes and radar turning indexes when in CSM. The time distribution increases for Conning information, due to the increased importance of the navigator checking the key information for the machinery status when not having any visual aid from landfall.

4 CONCLUSION

The efficient use of scan patterns has been known and used for other professions than the maritime. Defining a recommended scan pattern for the maritime navigator, in relation to different metrological conditions, can contribute to a more efficient interaction between the navigator and the INS. This will provide better situational awareness for the navigator, and thus provide a safer passage.

The Maritime Scan consist of two subparts, where the first consist of the outside scanning on the environment. The width of the scanning arc is based on collision theory, and by dividing this scan into blocks and conducting a front-to-side scan, a better situational awareness is expected. The second part consist of the sensor and system data in the navigations system. This data is integrated and presented in the three applications ECDIS, RADAR and Conning. The scan is conducted to increase system knowledge, and to identify if there are any errors or biases in the sensors or system. The amount of time in each of the subparts will vary with regards to the meteorological conditions, and a rule of thumb with regards to dwell time in the different areas of interest is presented in Table 1.

The use of the Maritime Scan will better utilize the spatial and system awareness for the maritime navigator, and as a consequence situational awareness will increase which will enhance safe navigation.

4.1 *Further work*

Collect a data set to verify the effect of the proposed Maritime Scan.

Collect a data set with navigation in poor visibility/nighttime (CSM) and compare the findings with the current data set (VSM).

Implement the findings in existing syllabus and taught courses at Royal Norwegian Naval Academy.

4.2 *Acknowledgement*

This work could not have been accomplished without the great support from:

- Royal Norwegian Navy Navigation Competence Center for financial support.
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Paper IV

Developing a High-Speed Craft Route Monitor Window

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Abstract. High-speed navigation in littoral waters is an advanced maritime operation. Reliable, timely and consistent data provided by the integrated navigation systems increases safe navigation. The workload of the navigator is high, together with the interaction between the navigator and the navigation system. Information from the graphical user interface in bridge displays must facilitate the demands for the high-speed navigator, and this article presents how eye tracking data was used to identify user requirements which in combination with a human-centred design process led to the development of an improved software application on essential navigation equipment.

Keywords: Navigation · High-speed · Eye tracking · GUI · HCD

1 Introduction

Conducting a safe high-speed passage in littoral waters is a demanding task. With increasing demands for efficiency, and increasing use of technology and Human Machine Interaction (HMI), the daily job for the navigator has changed. Good Situational Awareness (SA) for the navigator has been emphasized as a critical component to avoid navigation accidents [1], and thus there are several technological initiatives aimed to enhance the SA of the navigator.

The extensive use of technology on ship bridges has caused concern about poor system usability for human interaction. One concern relates to how new technology aiming to increase the safety of operation, actually ends up doing the opposite [2]. Involving the human element in the design of systems is therefore imperative to minimize the potential human error in the operation and to increase safe navigation.

Eye tracking technology is a tool that can inform the designer about operator behaviour. It can monitor the eye's movement, and the collected data can be analysed to identify what kind of equipment that is used and how much time the navigator addresses that specific equipment. Analysing the data further can identify equipment and interfaces that steal time from the navigator's main task, and consequently lowers the navigator's SA. This study gives an example of how collecting and analysing Eye tracking data in combination with a Human-Centred Design (HCD) process resulted in

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a new and more user friendly design of the High-Speed Craft (HSC) route monitor window.

2 Background

High speed navigation has evolved since the first Hydrofoils in the early 20th century, and in the 1990s with catamaran hulls. A HSC is defined as a craft capable of maximum speed, in knots (kn), equal to or exceeding [3]:

$$7.192\,x\,\nabla^{0,1667}$$

∇ = volume of displacement corresponding to the design waterline (m^3).

For the Skjold-class in Fig. 2, this implies:

$$7.192\,x\,641^{0,1667} = 21,1\,\text{kn}$$

Which concludes that the Skjold-class is a HSC, since the top speed is more than 21,1 kn.

The Norwegian coastline has been used to transport people for centuries, where the last decade has shown an increased need for even more efficient (faster) journeys. Norwegian yards and ship owners have a long tradition of building, utilizing and optimizing HSCs, most recently shown by the first hybrid HSC “Vision of the Fjords” [4]. Similarly, The Royal Norwegian Navy (RNoN) has a long tradition of operating HSCs, such as Fast Patrol Boats, to deter an enemy from attacking from the sea towards the coast. The challenging task of navigating a HSC in littoral waters has been emphasized, especially when it comes to the workload for the navigator [5]. The main difference between civilian and military maritime high-speed navigation, is that the civilian navigator usually sails established routes. The military navigator must be prepared to navigate in unknown and confined waters, often with poor or restricted data quality [6]. Littoral high speed navigation relies on a consistent methodology to achieve safe and efficient navigation [7], and the design of bridge equipment, layout and Graphical User Interfaces (GUI) must be in compliance with this methodology for successful interaction between the system and the navigator [8]. This underlines the importance of facilitating for systems that support the navigator in managing such demanding tasks.

2.1 e-Navigation

Todays’ ship bridges are equipped with a well of displays and electronic aids, such as the Electronic Chart Display and Information System (ECDIS). The International Maritime Organization (IMO) has defined the modern and future collection, integration, exchange, presentation and analysis of marine information on board as e-Navigation [9], where the ultimate goal of e-Navigation is to enhance safety and security at sea.

Several studies indicate the close and important relationship between the bridge equipment, the navigators' attention span and the bridge crews' use of available resources [10–13]. To improve harmonization and user friendly bridge design, one solution is the Integrated Navigation System (INS). The purpose of the INS is to "enhance the safety of navigation by providing integrated and augmented functions to avoid geographic, traffic and environmental hazards". Route monitoring is one such task performed by the INS, defined as "continuous surveillance of own ships position in relation to the pre-planned route and the waters" [14]. As such, modern HSCs utilize INS to provide more, and real time, information for the navigator when conducting the passage. Figure 1 shows an example of an INS.

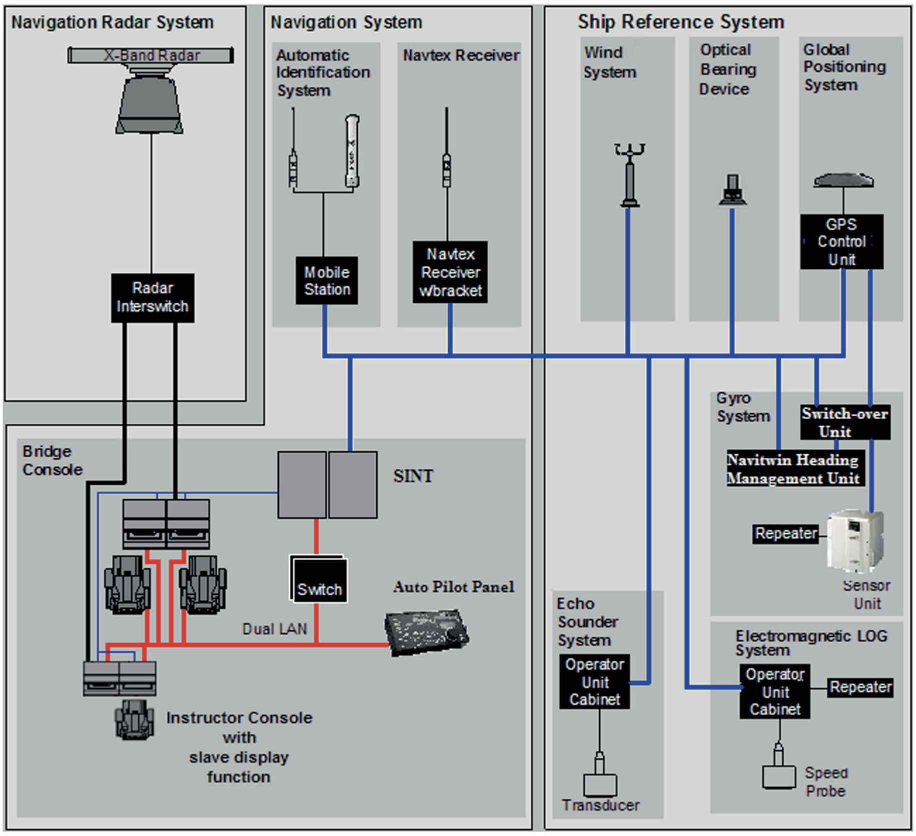

Fig. 1. Example of integrated navigation system (Courtesy of RNoN)

The INS layout in Fig. 1 outlines the complex structure of connecting multiple sensors to facilitate an integrated presentation of navigation information. The data collected is presented for the navigator on Multi-Function Displays (MFDs) in order to conduct navigational tasks.

There is an increased awareness of the need for efficient bridge design in high-speed operations [15]. The e-Navigation initiative has led to guidelines for HCD emphasizing the importance of including context and purpose in the design process [16]. The International Standardization Organization (ISO) has developed and released a standard for HCD for interactive systems. The standard identifies the importance of an iterative process that must include the end user to evaluate the ergonomics of human-system interaction [17]. This corresponds to other recommendations for designing HSCs based on a user perspective [18]. Reports from the maritime community identifies that several navigators find bridge systems difficult to access, and that they add noise and end up decreasing SA [10]. IMO will rectify some of these problems through its work on e-Navigation, expected to be finalized in 2019. Other initiatives are represented in the ongoing work with the Standard mode (S-mode) in ECDIS. S-mode is expected to contribute to standardisation and to provide detailed requirements for HMI and data presentation [19]. The work and initiatives within the e-Navigation scope underlines the present need for guidelines and standardisation for equipment placement and information presentation on a maritime bridge.

3 Data Collection Process

3.1 Eye Tracking

Eye Tracking is a method for collecting data of the eye's movement [20], and its use has expanded rapidly since the early 1970s. The original drive for eye tracking data was within research on the process of reading, but has later evolved to be used in the maritime industry as well [21, 22].

To improve design, eye tracking data can be analysed to better understand how the operator interacts with the systems [23, 24]. Eye tracking has been used to identify differences in the levels of experience between navigators [22], and to evaluate and improve maritime training [25, 26]. This article presents the development of a HSC route monitor window based on eye tracking data collected in the RNoN [27].

3.2 RNoN Eye Tracking Data Set

The data set is collected in field- and simulator studies using Eye Tracking Glasses (ETGs) [26], during daytime operations on board RNoN Corvettes and in similar conditions in the simulator. The Corvettes (Fig. 2) are capable of speeds exceeding 60 knots, and the navigation team consists of the Officer of the Watch and the Navigator. The navigation system on the Corvettes is delivered by Kongsberg Defence Agency (KDA), and the eye tracking data set was collected from the ECDIS and radar application from Kongsberg Maritime (KM). The ETGs were mounted on the navigator, who is the person responsible for conducting the passage.

The field study was conducted when navigating in littoral waters in the northern parts of Norway. The simulator study was conducted in the Skjold-class bridge simulator at RNoN Navigation Competence Centres' (NCC) Navigation Simulator (NavSim), in a similar area as the field study. Eight navigators from the RNoN attended the trials, with an navigation experience spanning from two to six years, with both male and female participants [26]. The data was collected with the SensoMotoric

Fig. 2. Royal Norwegian Navy Corvette, Skjold-class (Courtesy of RNoN)

Instruments second generation ETGs and the Tobii Pro Glasses 2 [27], and analysed in the supplied and recommended software (BeGaze and the Tobi Pro Glasses Analyzer). 2 h and 57 min of eye tracking data has been processed and analysed in this study.

Eye tracking data in this type of study is unique, but it has still got its' weaknesses. The field data set and the simulator data set are not identical, but the area of operation is similar. There are also differences in the environment when collecting data in a field study versus a simulator study. The light and weather conditions are a challenge, both with regards to the data collection, and also concerning differences in the field study- and the simulator data set. The total amount of participants is eight, of both sexes, and they have a span in experience. The amount of military HSC navigators are limited, and it is difficult to introduce more participants to the data set. The difference between the conduct of the passage concerning sexes is not elaborated. Two different types of ETGs were used in order to collect more experience on different types of ETGs. However, this also hampers the resemblance of the data set. The analysing process of the data is semi-automatic, and is a time consuming task. As a rule of thumb 10 min of data takes 60 min to analyse. There is an uncertainty introduced in the manual task of the analysis due to the ambiguity of the data, and a 10% loss of data is also expected due to weaknesses in the ETG design. Collecting eye tracking data is the easy part and analysing is the challenging part [20].

When analysing eye tracking data, there are several eye tracking metrics and visualization techniques that can be used and applied to better understand the data [28]. One should note that some of the eye tracking data can be notorious ambiguous events. One example is backtracks, which is the specific relationship between two subsequent saccades where the second goes in the opposite direction of the first [20]. In order to conduct a more thorough analysis of the eye tracking data, it is recommended to use Subject Matter Experts (SMEs), to better understand the meaning of the data.

4 Route Monitor Window

The route monitor window is an important tool for the navigator, and results from the eye tracking data showed a high frequency of use during operation. Figure 3 shows the GUI as it is presented in Kongsberg ECDIS version 3.4.

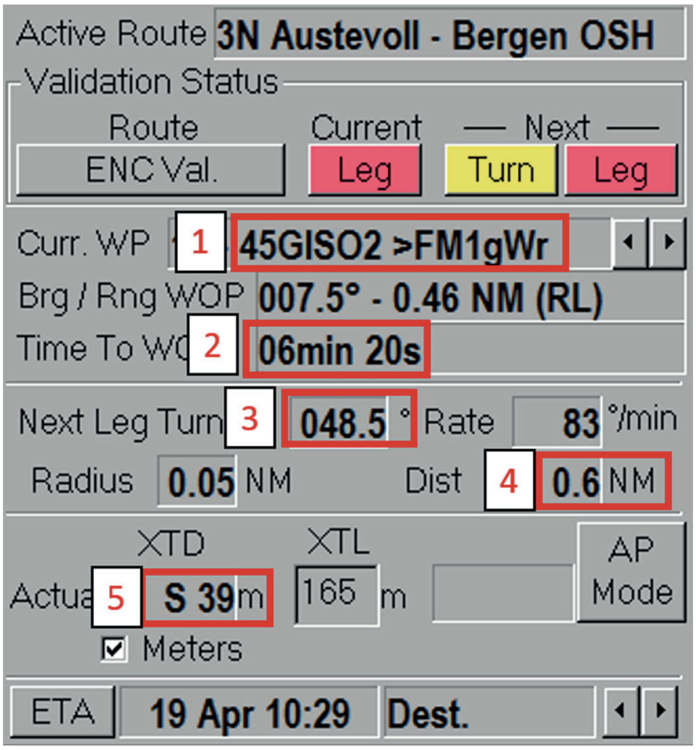

Fig. 3. GUI route monitor window

The route monitor dialog is used to display information about the selected route and to monitor the ships progress along it. The window consists of information about the route and its validation status, together with the current position of the ship and the upcoming information regarding the planned route. It also provides a button to enter the Autopilot (AP) mode, and information about Estimated Time of Arrival (ETA) to the final destination.

Information vital for high-speed navigation is highlighted by red boxes in Fig. 3, consisting of:

1. Information about turning object and next heading mark.
2. Time to Wheel Over Point (when the turn of the ship is to be conducted).
3. The course on the next leg.
4. The distance of the next leg.
5. Cross Track Deviation (XTD) which provides information about the ships actual position compared to the planned route.

The route monitor window is found in the lower right corner of the ECDIS application, and is presented as a KM standard size dialog window as shown in Fig. 4.

Fig. 4. Route monitor window seen from the perspective of the navigator

The distance from the navigator to the route monitor window is approximately 2 metres, and the size of the route monitor window is small, dependent on the size of the MFD. The navigators expressed concern about the accessibility of the information in the route monitor window. To investigate this concern, the scan pattern of the navigator was visualized through analysis of the collected eye tracking data (Fig. 5).

The circles in Fig. 5 represent fixation and the lines represent saccades. Fixation is defined as the state when the eye is remaining still over a defined period on a specific point, and fixation time is defined as how long the eye lingers on a specific fixation. The size of the circle indicates the time period of fixation; the bigger the circle, the longer the fixation. A saccade is defined as the rapid eye motion between two fixations, understood as movement from one fixation to another [20]. When analysing the eye

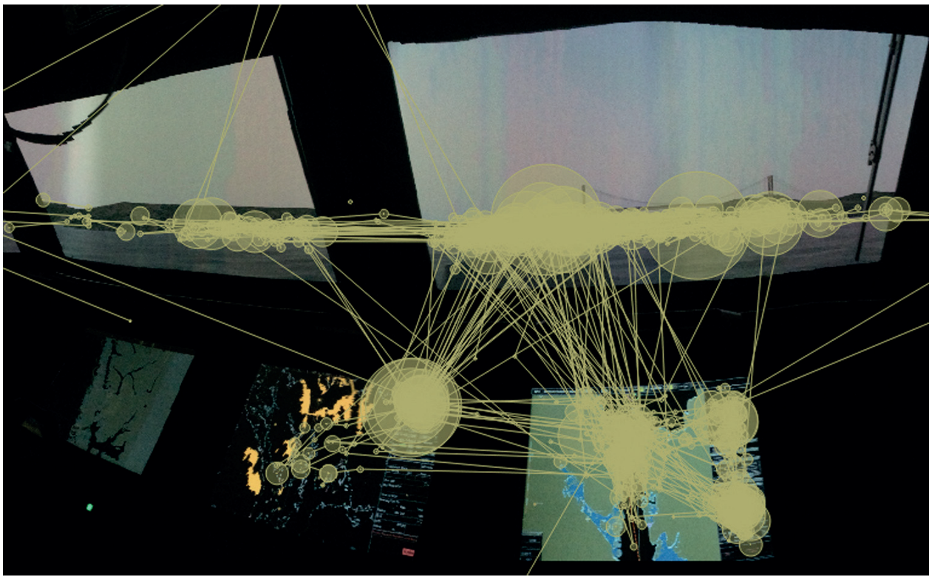

Fig. 5. Scan pattern of the navigator

tracking data together with the visualization techniques, it is identified that the route monitor window GUI is taking too much of the navigators' attention, and thus a HCD process of optimizing this GUI is initiated. This process is laid down in earlier work [28]. The results from the study was combined with RNoN standard operating procedures (SOPs) to manufacture a new HSC route monitor window that is better aligned to the HSC navigator's need.

4.1 Developing a High-Speed Craft Route Monitor Window

In close cooperation with SMEs and the supplier, an iterative process in accordance with IMO's guidelines for software quality assurance and HCD for e-Navigation [16] was started (Fig. 6).

The process is as follows:

1. Identification of challenge in design and HMI [27].
2. Create workgroup with SMEs and supplier to start the iterative HCD process of changing the GUI [16].
    - i. Activity 1: Understand and specify the context of use.
    - ii. Activity 2: Identify the user requirements.
    - iii. Activity 3: Produce and/or develop design solutions to meet user requirements.
    - iv. Activity 4: Evaluate the design against usability criteria;
        - i. Test the new software in a 1:1 simulator [26].
    - v. Activity 5: Maintain operational usability.

This method is illustrated in Fig. 6.

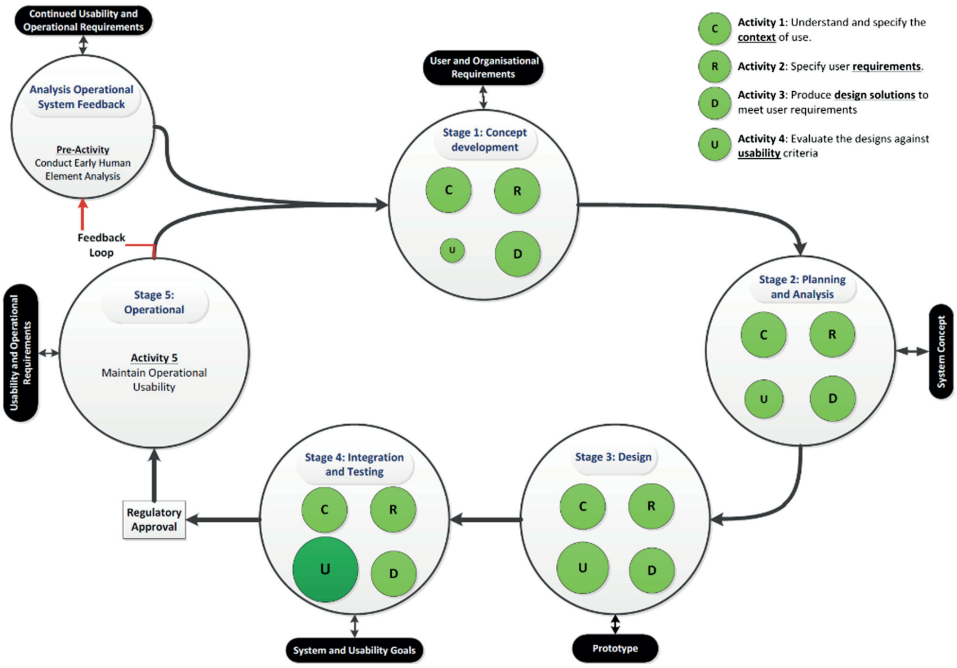

Fig. 6. Overview of HCD process for e-navigation systems (16)

The use of SMEs in a workgroup were essential for all activities leading up to the proposed design, and will be vital for trials and evaluations of the final design.

Activity 1 and 2 resulted in several design suggestions for activity 3, leading up to the conceptual content design of the route monitor window shown in Fig. 7. The supplier followed up the conceptual design with proposing a solution that fits the layout of the existing MFD (Fig. 8). The final proposal from the supplier will be tested later against usability criteria in activity 4.

Activity 1. When identifying the user requirements, it is important to start with the context of use. The context of use is to perform navigation on board a HSC in littoral waters, with the use of modern electronic navigational equipment such as the INS. It involves operations in narrow and open waters and in all types of weather and sea states, and ship movements and vibrations is expected to be high. The ship must also operate in demanding arctic waters, with no daylight during wintertime, which also drives the need for suitable night palettes in the GUI. In addition to this, the navigators' night vision is essential when conducting the advanced operation of maritime warfighting. Thus, the need for minimum light pollution from the MFDs is crucial.

This context suggests a need for frequent use of the route monitor window, a suggestion identified in a recent maritime usability study [23].

Activity 2. Level of accessibility of information provided in the route monitor window becomes a crucial design parameter. The GUI design must focus on user suitability while at the same time be coherent with RNoN SOPs. The SOPs in this context are the

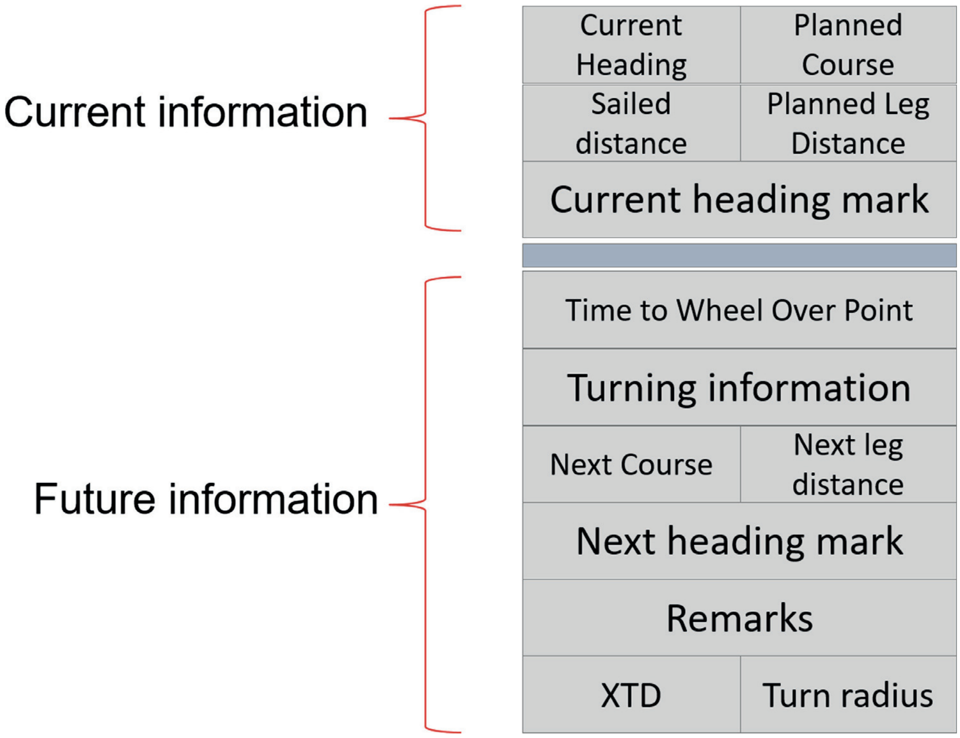

Fig. 7. Conceptual content of HSC route monitor window

rules and regulations for conducting a safe passage, which in the RNoN are known as the phases of navigation, with coinciding voice procedures [7].

The phases of navigation are in place to ensure that the navigator is aware and appreciative of the current and future environment to maximize the capabilities of the HSC. Figure 7 shows the results of Activity 2; a conceptual design of the new route monitor window for presenting the navigator with need-to-know information of the current and future route.

Activity 3. Human engineering design criteria are essential for successful design and solutions for high speed navigation [15, 18]. The conceptual content (Fig. 7) aims to ensure maritime SA for the navigator, and the goal for activity three is to balance user requirements with supplier and bridge equipment capabilities and constraints.

One such constraint is the size of the window, which limits the amount of information available for stacking. The window size is regulated by the design of the Kongsberg K-Bridge INS [29] and must be taken into consideration when designing a new GUI. Optimization of the new HSC route monitor window was made through suitable trade-offs between the supplier design criteria and the end user requirements.

Guidelines and requirements for HCD of display information systems were used to optimize system performance with consideration of inherent human capabilities and limitations as part of the total design trade-off space [30]. Specific considerations were given to the information architecture, including; the amount of information, density and presentation, text format and pattern coding, information grouping and label orientation.

Current information is presented on top (i.e. “what am I doing now”?) followed by future information (i.e. “what should I do next”?) on the bottom. Related information is grouped in sequences, limited by what kind of information that is necessary and sufficient to maintain maritime SA. This allows the navigators’ scan pattern to flow from top-to-bottom and left-to-right with data presented in a readily usable form [30], avoiding critical data from being obscured by pagination or scrolling.

The coding used in turning - and heading mark information is in accordance with the RNoN SOPs [31].

Based on inputs from RNoN working groups, Activity 3 resulted in a preliminary suggestion for the new GUI from the supplier (KDA), shown in Fig. 8.

Activity 4. The final design suggestion from the supplier will be tested at RNoN NCC NavSim (expected early April 2017). The testing will be performed by RNoN HSC navigators and human factors specialists to ensure that operator interaction requirements are met. Once the design is proven to maintain operational usability for achieving required performance for HSC navigation, the new HSC route monitor window will be implemented in the fleet to foster design standardization.

Fig. 8. HSC route monitor window suggestion from supplier

5 Conclusion

Today and in the future, there will be comprehensive interaction between humans and systems. This article has explained the process of refining and operationalizing a specific HSC route monitor window. Eye tracking data is an efficient Method to identify the level of user interaction with bridge systems, and can be utilized to aid the development of an improved software application. The guidelines for HCD activity 1–5 worked as an iterative process with a particular focus on combining operator requirements with system and human capabilities and limitations. The process resulted in an optimized design of a route monitor window specifically tailored to HSC navigation that will be thoroughly tested for user suitability. The final implementation of the product on-board RNoN ships is expected to minimize the potential human error in the operation and to increase safe navigation.

5.1 Future Work

Test and collect eye tracking data set of the new SW GUI in RNoN NCC NavSim. Implement the improved GUI in the RNoN (activity 5 in the HCD process).

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Paper V

Validation of a Maritime Usability Study with Eye Tracking Data

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Abstract. The main objective of the navigation system on board a High Speed Craft (HSC) is contributing to safe operation, which is supported by a high degree of situation awareness for the navigator. On the modern HSC bridge, an increasing amount of displays and support systems has been introduced, with computers being networked and integrated information presented on Multi-Function Displays (MFDs). Eye tracking data in human-computer interaction is a valuable tool to identify challenges with design and user interfaces, and to better understand the workload of the subject. This paper presents and analyse two eye tracking data sets collected to validate a mid-life update of a HSC navigation system, and outlines the challenges when collecting eye tracking data in an operational environment. Data collection with Eye Tracking Glasses (ETGs) is proven to be a valuable tool, but the quantitative data needs to be supported by qualitative data to be unambiguous.

Keywords: Maritime · High speed · Navigation · Eye tracking data
Eye tracking glasses · Navigation system

1 Introduction

High speed navigation in littoral waters is a challenging task. Both civilian and military High Speed Crafts (HSC) are operating in speeds above 20 knots (37 km/h) and some exceeding 60 knots, making the safe and efficient conduct of the passage crucial.

To support the navigation process, the bridge is equipped with MFDs to facilitate the information management in the navigation system for the navigation team [1]. The navigation system is integrated and networked together, and information is typically presented and integrated on a MFD on the Electronic Chart Display and Information System (ECDIS), radar application and application with information about the ship propulsion and technical systems (conning). The Situation Awareness (SA) of the navigator is crucial in order to facilitate for the safe and efficient navigation, and the navigation system aims to support a higher degree of SA [2].

Several studies have highlighted the challenge with information overload for the navigation team [3–8], and raises the question whether a bridge design and layout supports the safe and efficient navigation of the vessel.

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To better understand the task of navigation and what the navigator is addressing during a passage, eye tracking data can be collected and analysed. ETGs can provide sufficient freedom of mobility for the test participants, and has shown good potential in better understanding the task of the (HSC) navigator [9, 10].

Eye tracking data can be collected by using ETGs, and the use of ETGs has shown good potential in maritime usability studies [11–13]. Previous studies highlighted design and Graphical User Interface (GUI) issues on board the Skjold-class Corvette (Fig. 1) bridge navigation system [9, 11, 14], and these were corrected in a mid-life update [15]. This paper presents a pre- and post-mid-life update eye tracking data set collected to validate and support the findings in the pre mid-life update study.

The research question in the article is if eye tracking data collected from ETGs can be used to validate a design-review of a maritime HSC bridge.

1.1 Decision Making in High Speed Navigation

HSC navigation is most commonly conducted in a navigation team, consisting of two persons, the Officer of the Watch (OOW) and the Navigator, which share the tasks given to achieve safe and efficient navigation. Dependent on the confinement of the waters, weather and speed, the navigation team workload is high [16]. Safe navigation means that no incidents or accidents occur, while efficient navigation means that the speed potential of the vessel is utilized [17].

Figure 1 shows the Royal Norwegian Navy Corvettes, with speeds exceeding 60 knots (110 km/h or 70 mph).

Fig. 1. Skjold-class Corvette

The conduct of a safe passage with a HSC is a complex task, conducted in a sociotechnical system as a navigation team [18]. To support safe and efficient navigation, the navigation team uses a methodology to aid the decision making process and increase the SA, known as the phases of navigation [1] or Dynamic Navigation (DYNAV) [19, 20]. The conduct of safe and efficient planning is shown in Fig. 2, and is an iterative process.

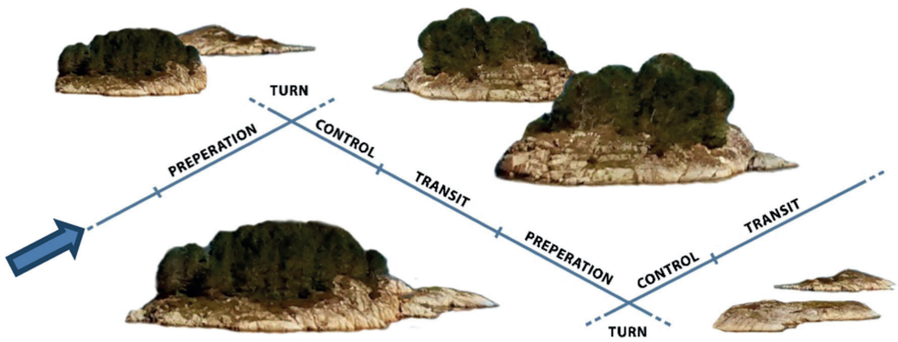

Fig. 2. Iterative process of (littoral high speed) navigation

In littoral waters there are multiple obstacles for navigation, making high speed navigation challenging. Each leg will vary in length, but as an example, a leg of one nautical mile (1 nm = 1852 m), will take 1 min to complete in 60 knots. In demanding waters, consecutive legs are often less than 0.5 nm in distance, making the decision process before the next leg less than 30 s.

In each phase of navigation, the navigator has a mental checklist to follow, and it is important that the navigators prioritize in order to have time to finish one phase before the next one starts, in order to maintain a high degree of SA. The navigator's SA consist of spatial-, task- and system awareness [6, 21], and the complexity of these factors affect the navigator's workload as shown in Fig. 3. Note that the bottom line in Fig. 3 is meant as examples, and is not complete.

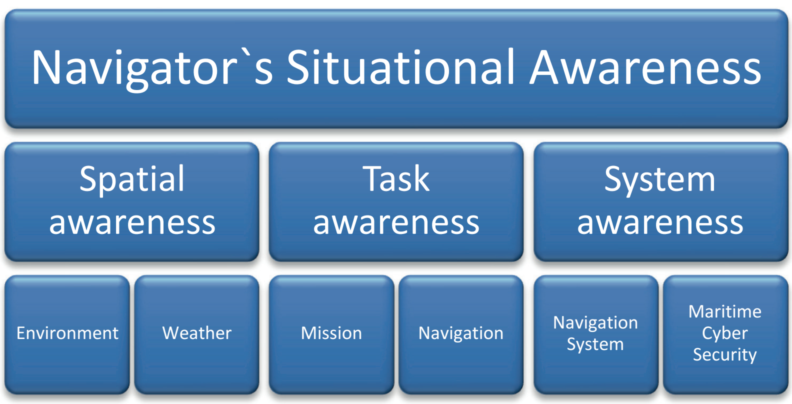

Fig. 3. Navigator's SA [21]

As navigation is conducted in a team, the communication skills is important to create and maintain a shared mental model in the navigation team, and the communication is mainly conducted in accordance with standard operating procedures. The integrated navigation information on the displays provide some of the basis of the navigation team shared mental model, however this information collection is non-verbal and could thus be interpreted differently by the operators [16].

1.2 Vulnerabilities in an Integrated Navigation System

Navigation systems on a modern HSC are networked, and the navigation sensors are integrated. The integrated information is presented on one or several MFDs, as shown in Fig. 4.

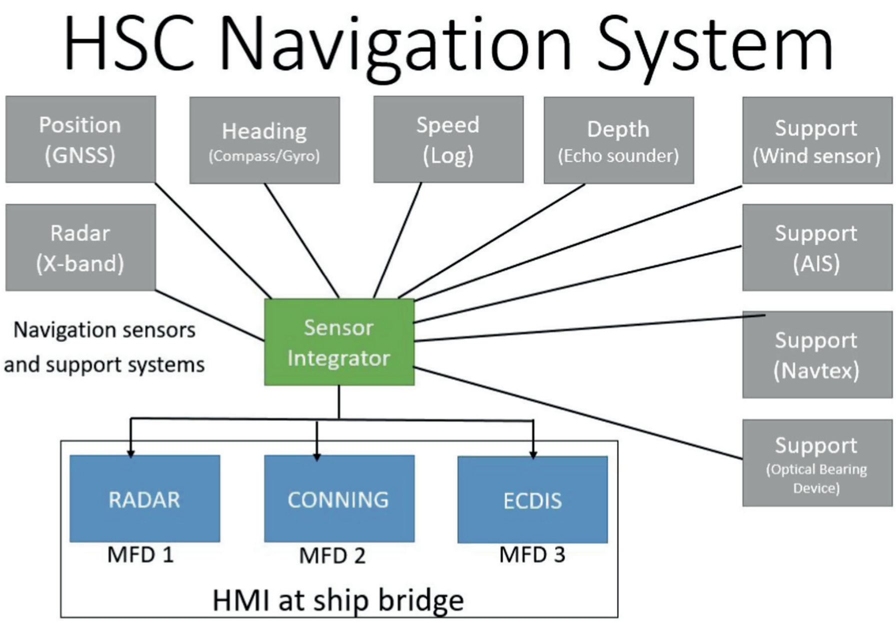

Fig. 4. Example of a HSC navigation system

The integration of navigation sensors in the navigation systems aims to contribute to improved SA for the navigator, and thus support the safe navigation of the vessel [2, 22–24]. This is partly conducted by presenting the near real-time position of the vessel on the ECDIS. The information from the position-, heading-, speed-, depth- and support sensors are integrated and presented on one of the MFDs on the ship bridge. The three main applications available for the navigation team is ECDIS, radar and conning.

The navigation system even on a relative small HSC vessel below 50 m is arguably a complex system in accordance to Redish [25], and there is a concern that the navigator does not hold a sufficient understanding of the navigation system they are operating [26–28], known as system awareness in Fig. 3. This could lead to misinterpretation of information from the navigation system presented on the MFD.

Signal interference on the signal from a Global Navigation Satellite System (GNSS), intentional or un-intentional, can lead to Hazardous Misleading Information presented to the navigator [29]. There are several examples of jamming and spoofing of GNSS-signals [30–33], and the navigator needs to be aware of the vulnerabilities in the computer system in use [21].

1.3 Eye Tracking

Eye Tracking is the process of measuring the eye activities [34]. This could be performed by measuring either the point of gaze (where one is looking) or the motion of an eye relative to the head. An eye tracker is a device that can measure eye position and eye movement. ETGs is constructed in order to study human behaviour in real-world environments [35].

During the past years, eye tracking in Human-Computer Interaction (HCI) and usability studies/research has been more frequently used [36–41]. There has also been research and suggested frameworks for the use of eye tracking measurements when conducting usability evaluation at a ship's bridge [42].

Eye Tracking data from ETGs has been used to improve usability of bridge design [13, 43, 44], and the Graphical User Interface (GUI) and bridge layout of a HSC has been examined with ETGs in an earlier study [14, 15]. ETGs has been used as a tool to measure the efficiency of a navigator when conducting a passage [10], and in maritime bridge simulator assessments [45]. Nielsen and Pernice [40] find that the use of eye tracking data will aid the designers and software developers to better understand what people see and don't see, and ETGs has shown to be a useful tool in a framework to improve SA in demanding maritime operation training [12].

2 Methodology

The work presented in this article builds on earlier studies conducted prior to a mid-life update of the Skjold-class Corvette navigation system [9, 11, 14]. ETGs were utilized to better understand the visual attention of the navigator, in order to identify, and if possible correct, flaws in design and/or GUI. Tobii Pro Glasses 2 was used for the two data collections, and pros and cons with the use and different types of ETGs is laid down in earlier work [11].

2.1 Subjects

The participants were personnel in active service, mean age of 29 years (Standard Deviation (SD): 4 years), and a total of 13 subjects participated in the test conducting 19 runs. It would be beneficial with a higher number of test objects, but the amount of relevant personnel is limited. The RNoN has six Skjold-class in service, with two navigation teams on each vessel, thus 54.2% of available personnel participated in the data collection.

When recruiting personnel to the data collection, several challenges with the availability of relevant personnel was identified. The workload on personnel in active duty is high, and the data collection was not characterized as operational service, and therefore not given a high priority. This lead to challenges with the amount of participants, cancellations and time-constraints when conducting the data collection.

2.2 Apparatus

The data collection was conducted in the Navigation Simulator (NavSim) at the Navigation Competence Center at the Royal Norwegian Naval Academy. Earlier work has argued that the Skjold-class simulator at the NavSim provides eye tracking data with quality equal to live data [9].

The navigation bridge of the Skjold-class is shown in Fig. 5, and to better organize the eye tracking data, Areas of Interest (AOIs) of the bridge was defined. AOIs defines important regions in the visual scene, and further allows events such as dwells, transitions and AOI hits to be defined [35]. The AOIs are shown in Fig. 5, and is in accordance with the visual areas most commonly used by the navigator on board a Skjold-class Corvette.

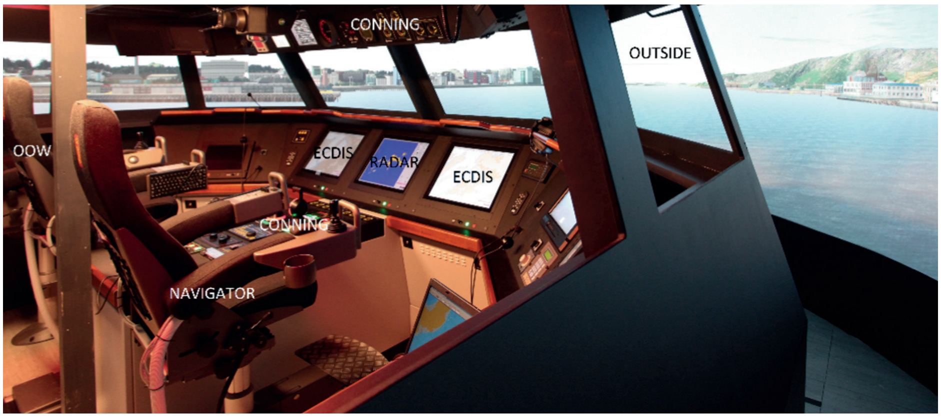

Fig. 5. Skjold-class bridge layout with primary AOIs

The AOIs were defined by using experience from earlier studies, together with a pre-study conducted with three persons in three runs. This resulted in four main AOIs, which are divided into 7 AOIs in total. The AOIs are:

1. Outside (AOI_O): The surroundings of the ships, and are defined by the boundaries of the windows on the ships bridge.
2. ECDIS (AOI_E): The ECDIS information is presented on the MFD in front of the navigator.
   a. AOI_E also consists of the Route Monitor window (AOI_M) as a part of the ECDIS application [15].

3. Radar (AOI_R): The radar information, presented on the centre MFD on the ships bridge in Fig. 5.
   a. AOI_R consist of the heading bearing (AOI_H) in the upper right corner of the radar application [11].
4. Conning (AOI_C): Consisting of information from the displays, consoles and autopilot related to the propulsion and steering of the ship.
   a. AOI_C consist of the consoles for manoeuvring (AOI_{CO}) and the speed log display (AOI_D) [11].
5. White Space (AOI_W): The other areas than those defined by the AOIs [46].
   a. Both data sets white space was marginal, and has been left out of the graphics, which indicates that most fixations were within a defined AOI.
      i. AOI_W pre-study data set: 0.22%
      ii. AOI_W first data set: 0.15%
      iii. AOI_W second data set: 0.26%

The navigations system (Sect. 1.2) consist of AOI ECDIS, Radar and Conning, and the eye tracking data analysis aims to provide a understanding of the use of these AOIs and thus an understanding of the system awareness which contributes to the Navigator's SA (Fig. 3).

2.3 Validation Procedure

The procedure and scenario for the pre- and post- data collection was identical. The scenario was set up in the simulator instructor software Polaris, and used in all the scenarios. The area of data collection is in Norwegian territorial waters, between Bergen and Floroe. The area, traffic, route and environmental conditions are identical in both the data collections throughout the 19 runs. The pre-planned route has a distance of 20.6 NM, and the average sailing time for each participant was 24.8 min (SD: 3.42 min). A total of 6 h and 12.4 min of eye tracking data has been analysed. The experience of the participant averages 1.9 years (SD: 1.75 years). The timeline for the project is shown in Fig. 6.

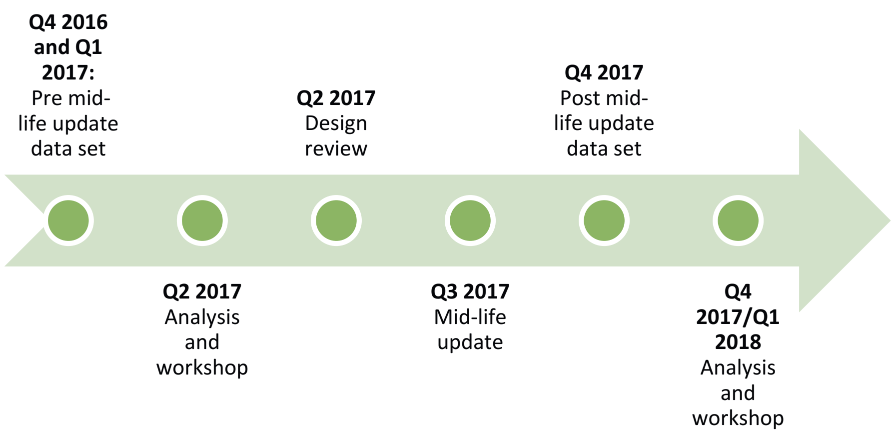

Fig. 6. Timeline process of validating HSC bridge design

The analysis was conducted in the manufacturers software, Tobii Pro Lab. Eye metrics data was captured, and further analysed in Microsoft Excel. In Excel sheets regarding fixations, duration, counts and events was analysed and visualized using diagrams (Figs. 9, 13 and 14). Visualization maps such as heat maps and scan paths were created in Tobii Pro Lab (Figs. 7, 8, 11 and 12). The visualizations maps provide a static overview of the visual attention of the navigator in the given period of time. The process of analysing and interpreting the eye tracking data can be challenging and time consuming, and a rule of thumb is one hour of analysis for every 10 min of eye tracking data.

2.3.1 Statistical Model

The statistical analysis has been conducted in four steps, where the statistical model is established and consist of a normality test, an F-test and a t-test to control if the values disprove the null hypothesis of similarity between the two eye tracking data collections within a significance level of 5%. The F-test is conducted to control the p-value for validation of similarity of the two collected data set. The t-test is conducted to control if the expectations values in the two collected data set are valid.

The generation of the analysis has been conducted in Microsoft Excel, by using the eye metrics data which is generated by the manufacturer software.

2.4 Technical Workshops

To better understand the Eye Tracking data and the analysis of it, workshops with Subject Matter Experts (SMEs) were conducted. This was facilitated through the creation of a Technical Group High Speed Navigation on the manufacturers equipment.

The working group consisted of SMEs, who are active navigators from the high speed navigation community in the RNoN. Representatives from the ECDIS manufacturer contributed together with HCI experts from the RNoN, which is supported by the call for more usability testing in complex systems [25].

The SMEs used the working group as a forum to express their opinions regarding the possibilities and the challenges with the existing navigation system. These opinions were correlated towards the presented eye tracking data and analysis, and discussed in the working group. System Problem Reports (SPR) and Engineering Change Proposals (ECPs) were produced where opinions from the SMEs and eye tracking data correlated. Amongst these were the three design issues described in Sect. 3.3, thus we investigated if eye tracking data collected from ETGs can be used to validate a design-review of a maritime HSC bridge.

The technical group conducted workshops both pre- and post-mid-life upgrade, and the feedback from the post mid-life update was correlated with the eye tracking data. The SMEs response to the revised design of the three main design issues was positive.

3 Results

3.1 Pre Mid-Life Update Data Set

The first data set consists of data from 10 participants, nine males and one female. Average age of participants 29 years (SD: 4 years). Average experience 1.6 years (SD: 1.6 years). The average time for conducting the passage was 24.5 min (SD: 3.9 min.

The first data set identified three main design issues, supported by earlier work [11]:

1. Poor availability of the presentation of heading bearing in radar GUI.
2. Challenges with the HCI with the distance measurement unit (Electromagnetic Log – speed log).
3. Sub-optimal GUI in route monitor window.

It is important to understand where the visual attention of the navigator is allocated during a passage. The visualization maps in the first data set is shown in Figs. 7 and 8.

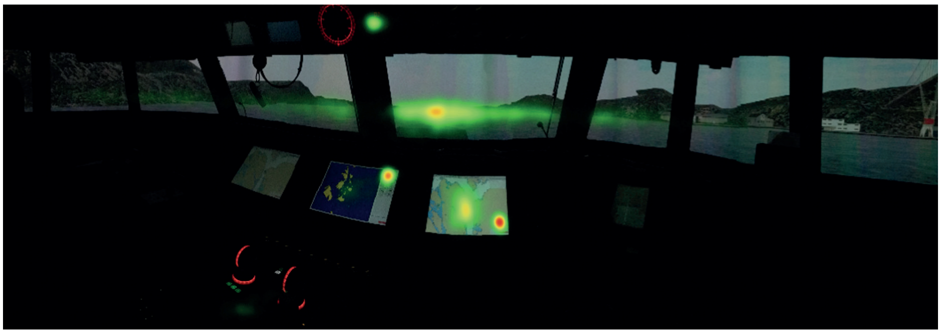

Fig. 7. Heat map from pre mid-life update data set

The heat map identifies the hot spots where the navigator addresses its' attention, and the three design issues is identified. Number 1 in the top right corner of the radar (centre MFD), number 2 in the top centre of the figure, where the speed log is placed. Design issue number 3 is the route monitor window in the lower right corner of the ECDIS GUI on the right side MFD (reference to Fig. 5).

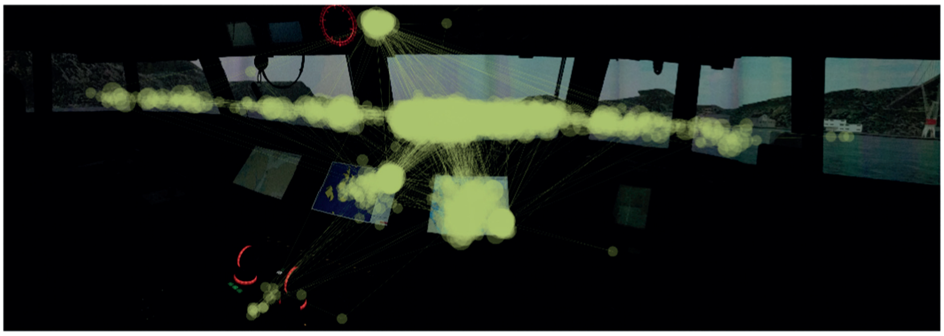

Fig. 8. Scan path from pre mid-life update data set

Analysing the scan path from the first data set, the three design issues are evident. Each fixation is represented by a circle, and the size of the circle represents the fixation time (larger circle, longer fixation).

The total time spent in an AOI can be an indication of the importance of the AOI. It could also indicate a design issue or high mental workload [35], and thus contribute to a decrease in SA for the navigator [40]. The total time spent in the AOI in the first data set is shown in Fig. 9.

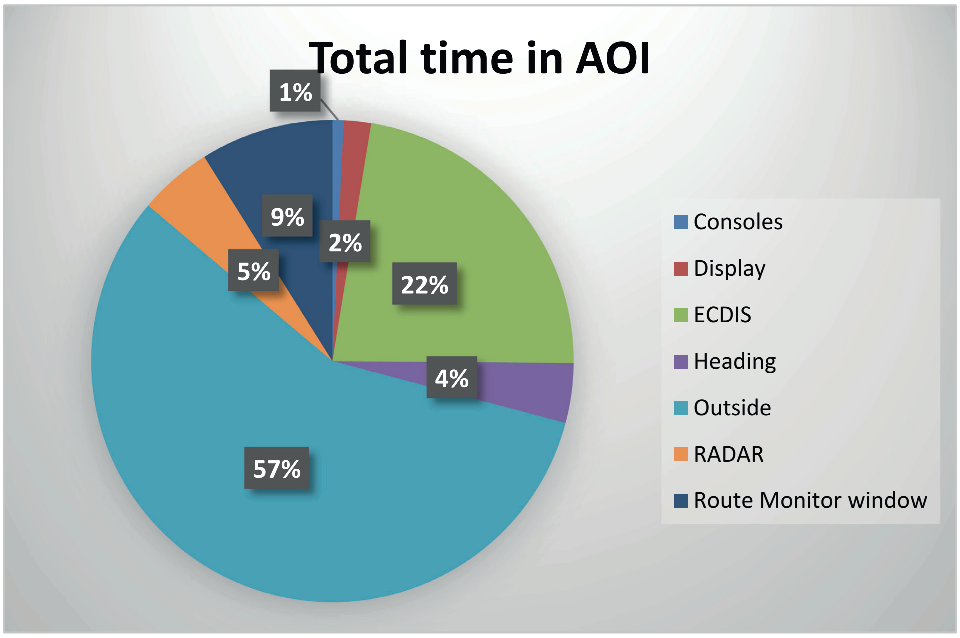

Fig. 9. Total time in AOI from first data set (pre mid-life update)

The pie chart provides valuable insight in the visual attention of the navigator [1], and the main objective is to provide more time for the navigator to control the surroundings to facilitate a higher SA (Fig. 3 – Spatial and Task Awareness). A suggestion of an optimal visual attention to AOI Outside is 80% in good visual condition conducting the passage in visual sailing mode [1], in order to support the navigators SA. The SD in AOI outside in the pre mid-life update data set is 8.3%.

3.2 Mid-Life Update Navigation System Skjold-Class Corvette

The three design issues were addressed during a design-review and mid-life update of the navigation system on board the Skjold-class Corvettes. The SPRs were discussed in the working group, and ECP developed for each of the design issues.

ECP for design issue 1 was moving the presentation from the top right corner of the radar GUI to a larger presentation in a new High Speed Craft Route Monitor (HSCRM) window. The final version of the HSCRM window is shown in Fig. 10, and the heading bearing is presented with large fonts in the upper left corner of the GUI (#1). The HSCRM window is to be placed in the centre-top left corner of the ECDIS application, this in order to have a short visual passage from the display to the outside (surroundings) of the vessel, and contribute to a higher degree of SA by supporting the spatial, task and system awareness [15].

Fig. 10. HSCRM window from design review [15]

ECP for design issue 2 suggest moving the reset button for the trip meter from the overhead panel of the speed log [14], to the arm rest panel located on the left armrest of the navigator's chair (reference to Fig. 5). This implies the physical movement of the reset button from the speed log panel to within arm's reach of the left hand of the navigator. The display of the trip meter is co-located with other relevant information in the HSCRM window, and is shown on the top second line in Fig. 10 (#2). This makes the speed log display excessive, and the navigator only needs to address the HSCRM window.

ECP for design issue 3, a new route monitor window design, is shown in Fig. 10 and has been elaborated in earlier work [15]. The aim of this change was to sort and present the information needed for the navigator to maintain a high degree of SA. The presentation of this information is in line with the standard operating procedures on HSC in the RNoN [47]. A challenge identified in the workshops is that the HSCRM window will probably lay hold of relative more time from the navigator's visual attention, due to the relative large amount of information co-located in this GUI.

3.3 Post Mid-Life Update Data Set, Validating Design Updates and Measuring Impact

The second data set consists of six participants, all male. Average age of participants 29 years (SD: 4 years). Average experience 2.3 years (SD: 1.8 years). The average time for conducting the passage was 25.3 min (SD: 1.9 min).

The purpose of the design review was to free time for the navigator to control the surroundings of the vessel (AOI Outside), and contribute to a better SA for the HSC navigator.

In order to evaluate the end-state, a final eye tracking data set was collected (Fig. 6). Figures 11 and 12 shows the visualization maps for the validation data set.

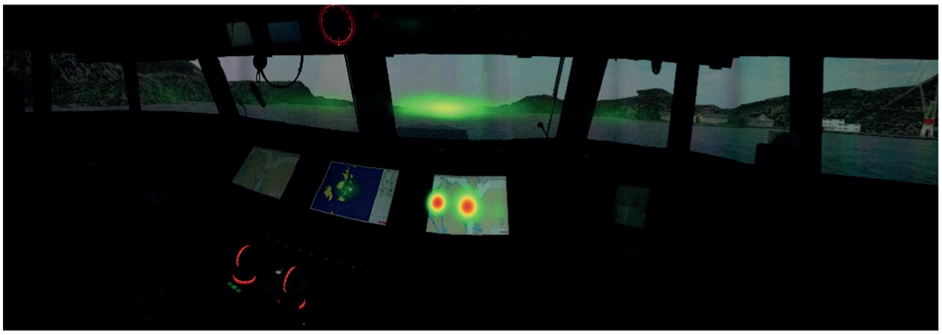

Fig. 11. Heat map second data set (validation)

When comparing the heat maps from the two data sets (Figs. 7 and 11), the heat map clearly identifies the three design flaws in Fig. 7, while these three areas are not present in Fig. 11. According to the heat map, more of the attention has been addressed to the ECDIS, Outside, Route monitor window and to the centre of the MFD with the radar application. There are fewer AOIs for the navigator to direct the visual attention towards, since AOI Heading, AOI Display and AOI Consoles is marginalized. This should in turn contribute to freeing time for the navigator to focus in more important AOIs, and contribute to increase the SA of the navigator. The eye tracking data visualization clearly indicates fewer AOIs in the new bridge design and GUI, more visual attention directed towards operational important information in AOI Outside, ECDIS and radar, which should contribute to safer operation.

Comparing the scan paths from the two data sets (Figs. 8 and 12), the second data set (Fig. 12) indicates a tidier scanning pattern, where fewer AOIs are visited. As shown with the heat map, less important AOIs such as AOI Heading, AOI Display and AOI Consoles are marginalized. This should contribute to a more efficient visual search for the navigator, and thus supporting an increase in the SA of the navigator. This finding supports the suggested Scan Pattern for the Maritime Navigator [1], which aims to streamline and optimize the visual search for the navigator. Note that the heat map in Fig. 11 shows inferior resolution inside the AOIs, compared to the scan path in Fig. 12. As an example the amount and placement of fixations inside AOI ECDIS becomes

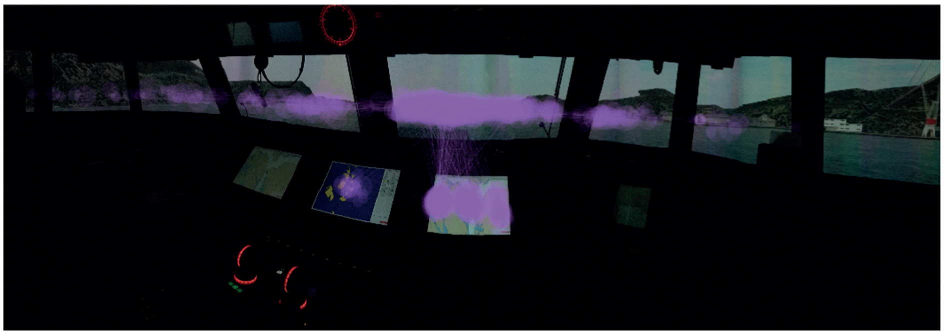

Fig. 12. Scan path second data set (validation)

more distinct in the scan path, than in the heat map. When analysing the heat map, be aware of the strength of the colour coding in the generation of the heat map can be adjusted in the manufacturer software [48], and is not uniquely. The increased resolution of the amount and placement of fixations in the scan path visualization, will support a better understanding of the eye tracking data.

The analysis of the eye tracking data from the post mid-life data set indicates that several of the AOIs have been marginalized in the mid-life update, shown in Fig. 13. AOI Console, Display, Heading and Radar has less than 1.5% of the total time. Since this was a passage conducted in daylight, it would be reasonable to suggest a vigorous increase in the attention to AOI radar during hours with reduced visibility or darkness. The total time in AOI for the second data set indicates an increase in the time spent addressing the ECDIS, and a retrogression in the accumulated visual attention in AOI Outside. One of the main objectives for the design review was to transfer more of the visual attention of the navigator to the actual surroundings of the vessel (AOI Outside).

4 Discussion

By comparing and analysing the visualization maps (Figs. 7, 8, 11 and 12), one could argue that the design changes conducted in the mid-life update has contributed to fewer areas for the navigator to focus on. Comparing the heat map (Figs. 7 and 11) indicates that the overhead displays, consoles and upper right corner in the radar (heading bearing) is removed as areas where the navigator focusses its' visual attention. Attention to these areas were identified as design flaws in the pre mid-life data set. The post mid-life update heat map (Fig. 11) indicates more visual attention to AOI ECDIS, and clearly indicates increased visual attention to the new HSCRM window located in the centre-left part of the AOI ECDIS as expected. The heat map also suggests more visual attention to the centre part of AOI radar, which shows an increased awareness from the navigator towards the operational valuable information provided from the radar (Fig. 3 – System awareness). By addressing attention to the centre of the radar, the navigator interprets the radar picture and evaluates and compares the surroundings of the vessel with a terrestrial mean. This will contribute to a higher degree of SA for the navigator, and thus supporting safe operation of the vessel.

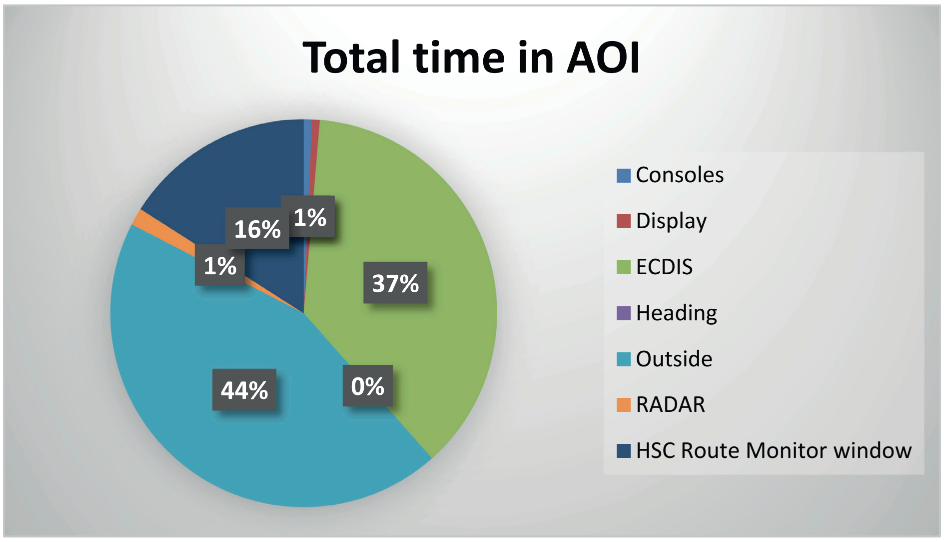

Fig. 13. Total average time in AOI post mid-life update data set

Analysing the scan path (Figs. 7 and 11), indicates a neater scan pattern for the navigator. The post mid-life update data set holds less scanning clutter, and this could contribute to a more efficient and less time consuming visual scan pattern for the navigator [1].

Total time in AOI (Figs. 9 and 13) shows an undesirable increase in the visual attention towards AOI ECDIS, and a decrease in the attention in AOI Outside. One could argue that an increase in attention towards AOI ECDIS will support increased SA (Fig. 3 - Task and System awareness) for the navigator as long as the chart is in focus, but the solution of the eye tracking data is not good enough to support the assumption that the visual attention is allocated to the chart alone. The design revisions aim was to support more attention towards AOI Outside, and the post mid-life update data set indicates the contrary. To better understand this finding, each of the participant's data set has been analysed, and there are discrepancies in the visual attention which are ambiguous and challenging to analyse.

When analysing the data individually, the difference from participant to participants becomes clear. If introducing experience and familiarization with the new design and software as a variable, it is a clear indication that the amount of time spent in AOI Outside is dependent on experience and familiarization. This is shown in Table 1.

When analysing the data from the participants in Table 1, the values gives an indication that the experience and familiarization time with the new SW, installed during the mid-life update, is a variable affecting the visual attention of the navigator. This is shown with participant 5 s time in AOI in Fig. 14, showing a high amount of attention towards AOI Outside, which is opposed to the accumulated visual attention in Fig. 13.

Table 1. Relation between experience and total time in AOI.

Participant	Total time in AOI outside (%)	Years of experience (years)	Time with new SW (months)
#1	43.52	1	2
#2	27.17	0.5	0
#3	46.24	4.5	0
#4	45.24	2.5	1
#5	68.49	5.5	4
#6	39.16	0.5	3

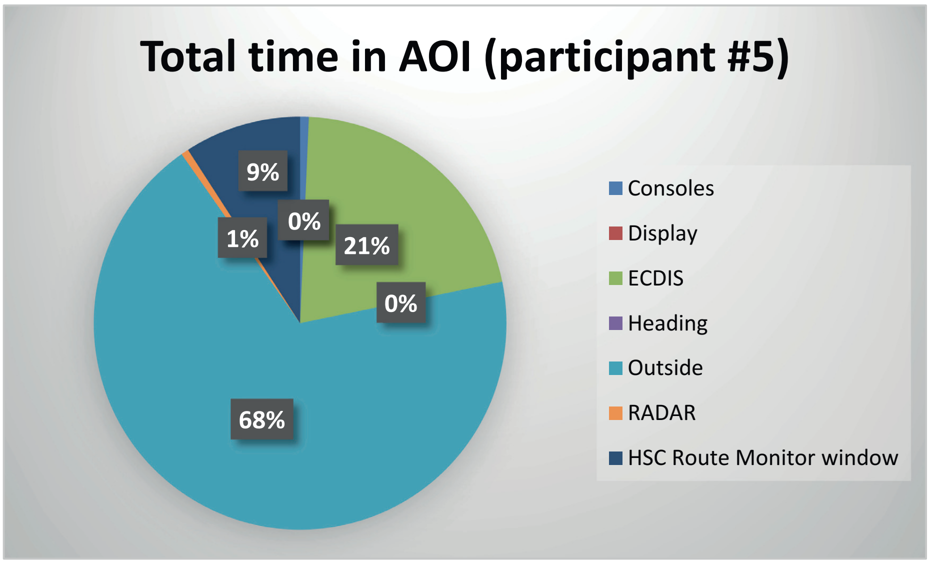

Fig. 14. Total time in AOI post mid-life update data set for participant #5

To better understand and analyse this finding, the most and least experienced participant of the subjects who participated in both data collections where analysed. This was the same persons in both data sets, and is shown in Tables 2 and 3.

Table 2. Comparison of the most experienced participant in the two data sets.

Data set/AOI (%)	Outside	ECDIS	Route monitor	Radar	Conning
Pre mid-life update	70%	14%	8%	3%	5%
Post mid-life update	68%	21%	9%	1%	1%

Table 3. Comparison of the least experienced participant in the two data sets.

Data set/AOI (%)	Outside	ECDIS	Route monitor	Radar	Conning
Pre mid-life update	47%	29%	10%	5%	9%
Post mid-life update	27%	49%	21%	1%	2%

Analysing Tables 2 and 3 can explain the deviation in the expected increase towards AOI Outside. Both experience and familiarization with equipment is known to be important variables when utilizing the navigation system [49]. Table 2 show how an experienced navigator with 4 months of familiarization on the new GUI shows good progression in utilizing the visual scan and direct the attention towards AOI Outside. Tables 3 indicates how an inexperienced navigator has challenges with operating unknown software, and must thus direct more attention towards the new design (the ECDIS and HSCRM window). Glover [50] presents the planning-control theory in visual representation, where he argues that human action is directed by a control system, while the perception is commanded by a planning system. This implies that a human (the navigator) take account for a wide variety of visual and cognitive information when conducting the planning of an action. This information is further integrated with memories of past experience, which could explain why experience is an important factor when using a system. This provides a link to how experience contributes to the navigator's SA.

Table 4 shows the higher SD in the post mid-life update. The SD could be a measure of the familiarity with the software and GUI. This is analysed as an indication of a higher familiarization with the software and GUI used in the pre mid-life update. All participants were familiar with the GUI in the pre mid-life update, since it had been in use for several years.

Table 4. Comparison of standard deviation in the two data sets

Data set/measure	Standard deviation in AOI outside
Pre mid-life update	8.3%
Post mid-life update	12.3%
Increase in % between pre- and post-mid-life update measures	48.2%

The importance of familiarization and experience is supported by earlier studies with eye tracking, and the findings in this study indicates the importance of both experience and familiarity with new software and design as factors [51–53]. It also indicates an important finding concerning operational use after post mid-life updates, which indicates that the low level of experience and low level of familiarization with new software decreases the visual attention towards AOI Outside. This could in turn contribute to a decrease in the SA of the navigator, and thus in the degree of safe operation. The importance of familiarization is thus supported and outlined by the findings in the two data sets [49].

The design of the method will contribute to less uncertainty when analysing pre- and post-mid-life updates of design. The pre mid-life update data set consist of 10 recordings and participants, while the post mid-life update data set consists of six recordings and participants. Five of the participants attended both data collections, and the two data sets where identical in conduct but not with regards to attendance of participants. With an increased amount and same number of participants in both data sets, the analysis will be less ambiguous. It would strengthen the data set if the same participants took part in both data collections, and the design of the two data sets should be identical to avoid sub-optimal analysis of data sets. The findings in the data set does not support the hypothesis that the two data sets are similar within a statistical significant level of 5%, partly due to the low number of participant (F-value 0.45, p-value = 0.14). To achieve a p-value of less than 5%, with the assumptions of the same values as in the current data set, the amount of participants must be almost four times higher. This would be very difficult and time consuming to achieve in an operational environment with personnel in active duty.

Collecting eye tracking data in an operational environment, such as the bridge simulator, is challenging [54], and the ETGs and the manufacturer software is not mature to meet the demands of the operational environment in this study. It is also evident that data collection with personnel in active duty is challenging and changes in plan on short notice must be expected. Research will not supersede operational demand.

When comparing the analysis of the eye tracking data with the information collected from the SMEs in the working group, there are sufficient indications of an improvement in the mid-life update bridge design to support a higher degree of SA for the navigator. The qualitative measurements from the workshops is emphasised as an important support for the quantitative measurements, due to the ambiguities in the eye tracking data due to immature technology (ETG robustness and manufacturer software) and sub-optimal method design.

5 Conclusion

ETGs has shown a potential to support identifying design and GUI challenges that contributes to a decrease in the SA of the navigator, and in validation of design changes of ship bridges. This study shows that the quantitative data needs support from qualitative data to be unambiguous. The use of eye tracking data such as visualization maps provides a simple and intuitive measure for identifying changes in visual search pattern after a design alteration, but the process of analysing the data is time consuming. The eye tracking data is useful as a basis for the design-review, and as evidence and support for the discussions and conclusions in the technical working group. However, eye tracking technology used to collect data in an operational environment with ETGs, is in this work assessed to be immature.

The collected data set shows the uncertainties related to eye tracking data when the amount of participants is relatively low, and the challenges concerned with few possible participants when conducting studies in a narrow domain.

The importance of experience and familiarization with new design is salient, and this study shows that the participants must be given ample time to familiarize themselves with the new design and software to conduct a better and less unambiguous analysis of the eye tracking data. This finding is also important for the operational domain, concerning familiarisation with new equipment before operational use.

The method and procedure when conducting the data collection are imperative with regards to the quality of the data collected. The cost and effort of collecting an eye tracking data set in an evaluation of a bridge design or software GUI, must be weighed towards the benefits, and the technology is at this time argued to be immature to collect eye tracking data from an operational environment.

If conducting maritime usability studies with data collected by ETGs, it is recommended to support the quantitative measurements with qualitative data for correlation and less ambiguity.

5.1 Further Work

Collect a new post mid-life update data set with optimal method design, in order to control the main objective of increased time in AOI Outside.

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Appendix A

Consent form

Please read and sign this form.

This study is about testing training methods in maritime simulators and gaining insight in the use of integrated navigation systems. During the study, your eye movements will be tracked by an eye-tracker. Eye tracker is easily wearable and removable like a safety goggle.

In this study:

- You will be asked to wear an eye-tracker
- You will be informed when recording is being conducted.

Participation in this research study is voluntary. All information will remain strictly confidential. The descriptions and findings will be used to form a research paper and in developing current technology. You can withdraw your consent to the experiment and stop participation at any time.

If you have any questions, please contact Odd Sveinung Hareide at (+479XXXXXXX).

I have read and understood the information on this form and had all of my questions answered

______________________________ _______________

Signature of the participant Date

______________________________ _____________

Signature of the person conducting the study Date