

Faster, better, safer?

*Studies of safety, workload and performance in
naval high-speed ship navigation*

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Scientific environment

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Abbreviations

AR	Autoregressive
DnV	Det Norske Veritas
ECDIS	Electronic Chart Display and Information System
EEG	Electroencephalography
EOG	Electrooculography
FBP	Fast Patrol Boat
FIT	Fitness Impairment Test
G-force	Gravitational force
GNP	Gross National Product
GPS	Global Positioning System
HRA	Human Reliability Analysis
HRV	Heart Rate Variability
HSC	High Speed Craft
IBS	Integrated Bridge System
IMO	International Maritime Organisation
KSS	Karolinska Sleepiness Scale
LCS	Littoral Combat Ship
MAIB	Marine Accident Investigation Board (UK)
MART	Malleable Attention Resources Theory

MWL	Mental Workload
NASA-TLX	National Air and Space Administration Task Load Index
NATO	North Atlantic Treaty Organization
NMD	Norwegian Maritime Directorate
NRC	National Research Council
P&I	Protection and Indemnity (insurance)
PSF	Performance Shaping Factor
RNoN	Royal Norwegian Navy
RNoNA	Royal Norwegian Naval Academy
SC	Skin Conductance
SCN	Suprachiasmatic Nuclei
SD	Sleep Deprivation
SOFI	Swedish Occupational Fatigue Index
SPSS	Statistical Package for Social Sciences
STM	Short-term Memory
STSS	Short-term Sensory Store
TARGETS	Targeted Acceptable Responses to Generated Events or Tasks
UN	United Nations
USCG	United States Coast Guard
XTE	Cross-track Error

Abstract

Ship navigation in the Royal Norwegian Navy (RNoN) involves high demands on navigators, who are required to work under a number of dangers. Operations are carried out in poor weather and darkness, at day and night, in restricted waters, and at high speeds. Accidents are frequent, and sometimes serious. Currently, the RNoN is in the process of replacing its Hauk-class fast patrol boats with the new Skjold-class littoral combat ship. Fast patrol boats play an important role in Norway's coastal defence. Since this transition will involve a major change in manning levels and task characteristics, it is expected to have a considerable impact on the navigator's demands. The aims for this project were to a) examine the situation characteristics of past navigation accidents in the RNoN, and b) investigate the consequences of the Hauk-Skjold transition on workload and performance in navigation. This was accomplished through three individual studies.

The first study in this project examined the presence of *performance-shaping factors* in investigation reports following 35 navigation accidents in the Royal Norwegian Navy between 1990 and 2005. This was done to provide an overview of the situation characteristics present at the time of the accidents, related to either the human, task, system or environment. Performance-shaping factors (PSFs) are defined as any factors which influence the likelihood of an error occurring. Factors related to task requirements and individual cognitive characteristics were shown to be most common, followed by operational characteristics of the system. Eight PSF clusters were found, indicating a pattern in accident circumstances. It was shown that accidents almost always have a high number of different factors influencing accident risk.

The second study examined mental workload and performance in simulated high-speed ship navigation. Two navigation methods were compared; these were based on electronic chart display and information system (ECDIS) and a conventional system using paper charts. Twenty naval cadets navigated in high-fidelity simulators through 50 nautical mile-courses with varying levels of difficulty. Results showed

that ECDIS navigation significantly improved course-keeping performance, and reduced the total amount of communication on the bridge. No differences were observed in subjective workload between the two groups. Heart rate variability and skin conductance measurements did indicate higher sympathetic activation in conventional navigation, but the differences between groups were not statistically significant.

The third and final study in this project investigated how workload and performance in high-speed ship navigation was affected by sleep deprivation, using two different navigation methods. In two separate weeks, five navigators sailed through ten 55-minute routes in high-fidelity simulators, while undergoing 60 hours total sleep deprivation. Navigation performance was measured in addition to subjective and psychophysiological indices of workload and sleepiness. Results showed that navigation performance again was significantly better in the electronic-chart condition, but was largely unaffected by sleep deprivation in both conditions. At the same time, there was significant interaction between speed, sleep deprivation and navigation method, indicating that navigators using electronic charts reduced their speed proportionally more under periods of high sleepiness. Secondary task performance was significantly reduced by sleep deprivation, but was equally affected in both conditions. Mental workload was significantly higher in the electronic-chart condition, as indicated by subjective ratings and heart rate variability. No significant differences in sleepiness were found between navigation methods, but electroencephalographic recordings indicated a higher incidence of sleep episodes in the electronic-chart condition after 52 hours of sleep deprivation. This possible risk may have been influenced by significantly lower overall arousal (indicated by lower sympathetic activation) in the electronic-chart condition.

List of publications

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Contents

SCIENTIFIC ENVIRONMENT	2
ACKNOWLEDGEMENTS	3
ABBREVIATIONS	5
ABSTRACT	7
LIST OF PUBLICATIONS	9
CONTENTS	10
1. INTRODUCTION	13
1.1 THE SEA, SEAFARING AND THE NAVY	13
1.1.1 <i>Accidents at sea and maritime safety</i>	15
1.1.2 <i>Major causes behind accidents at sea</i>	17
1.2 DEVELOPMENTS IN TECHNOLOGY AND CREWS	18
1.2.1 <i>High-speed craft</i>	18
1.2.2 <i>Navigation methods</i>	22
1.2.3 <i>Manning</i>	27
1.3 AUTOMATION.....	29
1.3.1 <i>Problems with automation</i>	29
1.3.2 <i>Function allocation and levels of automation</i>	31
1.4 HUMAN ERROR.....	33
1.5 COGNITIVE WORKLOAD AND PERFORMANCE.....	35
1.5.1 <i>Basic elements of cognitive processing</i>	35
1.5.2 <i>Cognitive workload and performance</i>	37
1.6 SLEEP, SLEEPINESS AND SLEEP DEPRIVATION	41
1.6.1 <i>Sleep</i>	41

1.6.2	<i>Sleepiness, fatigue and safety</i>	42
1.6.3	<i>Sleep and cognitive performance</i>	43
1.6.4	<i>Sleep and applied task performance</i>	43
1.7	RATIONALE AND AIMS.....	45
2.	MATERIALS AND METHODS	48
2.1	STUDY SAMPLES.....	48
2.1.1	<i>Sample of Paper I</i>	48
2.1.2	<i>Sample of Paper II</i>	48
2.1.3	<i>Sample of Paper III</i>	48
2.2	STUDY DESIGN	49
2.2.1	<i>Study design of Paper I: Accident review</i>	49
2.2.2	<i>Study design of Paper II: Navigation under normal conditions</i>	50
2.2.3	<i>Study design of Paper III: Navigation under sleep deprivation</i>	51
2.3	MEASUREMENTS USED IN PAPERS II AND III.....	52
2.3.1	<i>Navigation performance measures</i>	52
2.3.2	<i>Psychophysiological measures</i>	54
2.3.3	<i>Subjective measures</i>	56
2.4	STATISTICAL ANALYSES.....	57
2.4.1	<i>Statistical analyses used in Paper I</i>	57
2.4.2	<i>Statistical analyses used in Papers II and III</i>	57
2.4.3	<i>Research ethics</i>	58
3.	SUMMARY OF RESULTS	59
3.1	PAPER I.....	59
3.2	PAPER II.....	59

3.3	PAPER III.....	60
4.	DISCUSSION.....	61
4.1	METHODOLOGICAL DISCUSSION.....	61
4.1.1	<i>Paper I.....</i>	<i>61</i>
4.1.2	<i>Papers II and III.....</i>	<i>64</i>
4.2	GENERAL DISCUSSION	69
4.2.1	<i>Characteristics of naval ship accidents.....</i>	<i>69</i>
4.2.2	<i>Influence of navigation method on navigation performance.....</i>	<i>71</i>
4.2.3	<i>Influence of navigation method on navigator workload and sleepiness.....</i>	<i>73</i>
5.	CONCLUSIONS.....	76
	REFERENCES.....	79

1. Introduction

1.1 The sea, seafaring and the navy

Most people live on land, work on land, and generally direct their attention towards what happens on land. Our awareness of the sea rarely extends beyond what we might see on the horizon. It is therefore easy to forget that our world is an ocean world, with water covering three quarters of the planet. It is also easy to forget that our lives on land depend on the sea, and the ships that sail on it. The shoes we wear, the oranges we eat, and the cars we drive – all have one thing in common, and that is that they were brought to us over water. More than 90% of the world's trade is transported by ship, totalling around 27 thousand billion tonne-miles in 2004. These goods are moved by approximately 50 000 international merchant ships, which are manned by more than a million seafarers (BIMCO et al. 2009). Without these slow-moving giants, global trade would quickly grind to a halt.

The sea always has, and will in the foreseeable future continue to play a vital role in the Norwegian economy. Norway is a small country surrounded by water, which has an economy dependent on exporting commodities such as fish and paper, as well as importing most foods and consumer products – mostly by ship. Furthermore, more than a quarter of Norway's gross national product (GNP) is generated from offshore oil and gas production (Statistics Norway 2007).

Shipping in itself is also a sizeable industry, accounting for around 9% of GNP (Nærings- og handelsdepartementet 2004). Since around 1800, Norway has developed into one of the world's major maritime nations, with Norwegians currently controlling approximately 10% of the total shipping tonnage in the world. Except for Greece, no other European country has benefited as vastly from shipping for its economic development. While the number of Norwegian mariners has fallen considerably in the past 30 years, Norway is still the 5th largest shipping nation in the

world, employing approximately 16100 Norwegian and 41300 foreign mariners (Norwegian Shipowner's Association 2008).

Despite its financial and social importance, the ocean is an unruly space. Disruptions to sea trade can have a profound effect on the global economy. This has for example been witnessed during recent cases of piracy off the coast of Africa, where ships carrying weapons and oil have been held ransom for millions of dollars, leading ship owners to divert their ships to long detours rather than pass through the Suez Canal. The role of the navy has therefore been extended from its traditional role of invasion defence to “policing” the sea, including response to piracy, terrorist attacks and smuggling (Shultz, Pfaltzgraff & Pfaltzgraff 2000).

Protecting ships from piracy is only one of the roles performed by the Royal Norwegian Navy. Norway has a long tradition as a seafaring nation, and the Navy is an important part of its national defence (Engdal & Mo 2006). The Norwegian navy history dates back to the Viking period from around 700AD, and was formally established in its current form after the Constitution was declared in 1814. Following the end of the Cold War, the Norwegian armed forces were reduced, including the Navy. Personnel was cut by around 30%, and its tasks were directed more towards international missions led by the North Atlantic Treaty Organization (NATO) and the United Nations (UN). In the period since 2002, the Navy has also changed towards being more mobile and less land-based (Engdal & Mo 2006). Nationally, its main tasks are defined as to maintain a presence along the coast and protect the country from hostile forces. Internationally, its main role is to carry out mutual defence tasks, protect against terrorism, perform peace-keeping missions, and support humanitarian operations along with its allies (Royal Norwegian Navy 2003).

The overall role of Norway's navy today is therefore to ensure stability and maritime security on the seas. Maritime security can be defined as “the security from terrorism, piracy and similar threats, as well as effective interdiction of all illegal activities at sea such as pollution of the maritime environment; illegal exploitation of sea resources; illegal immigrations; smuggling drugs, persons, weapons and other

matters that can be used for terrorist activities” (Jones 2006). However, a necessary precondition for the navy’s ability to ensure maritime security is its own maritime safety, which can be defined as “the safety of life and property at sea, and the safety of the marine environment from pollution by ships” (Urbanski, Morgas, & Kopacz 2008). This, and the role of human factors in maritime safety, is the primary topic for this thesis. While seafaring is characterized by a combination of demand characteristics such as high workload, tough environmental conditions, and long work periods, little human factors research has been carried out within this domain (Hetherington, Flin, & Mearns 2006).

1.1.1 Accidents at sea and maritime safety

The ultimate goal of maritime safety is to avoid accidents, and most important to the prevention of accidents is avoiding death and injury to humans. The definition of an accident is, at its minimum, “an unintended and untoward event” (Perrow 1999). However, the term is usually reserved for events of a more serious nature, whereas minor events are typically referred to as “incidents”. This term is often used interchangeably with the term “near miss”. In this thesis, the definition of an “incident” is based on Van der Schaaf’s definition of a “near miss”:

Any situation which has clearly significant and potentially serious (safety related) consequences

(van der Schaaf, Lucas, & Hale 1991, p.5).

The term “accident” may have different meanings depending on the context. In the perspective of maritime transportation, however, an accident is defined by the British Marine Accident Investigation Board (MAIB) as:

An undesired event that results in personal injury, damage or loss. Accidents include loss of life or major injury to any person on board, or when a person is lost from a vessel; the actual or presumed loss of a vessel, her abandonment or material damage

to her; collision or grounding, disablement, and also material damage caused by a vessel. (MAIB 2009).

While this definition also includes accidents such as fires and occupational injuries such as trips and falls, these are beyond the scope of this thesis. The main focus is instead on *navigation accidents*, which I have defined as:

Any collision, grounding or other contact damage sustained as a result of the controlled movement of a vessel.

Preventing accidents at sea is important, since they pose a considerable threat to the safety of people and the environment. Disasters such as the sinking of the Titanic (1912) and Estonia (1994) have had a startling death toll, and caused public outrage around the world. Oil spills following ship accidents such as the Amoco Cadiz (1978), Exxon Valdez (1989), Erika (1999) and Prestige (2002) are among the worst environmental disasters on record. All have had enormous financial consequences as well, the most expensive still being the Exxon Valdez accident, with a total cost of almost \$9,5 billion (Arendz 2004).

Globally, the frequency of serious shipping accidents has declined considerably over the past few decades. According to Det Norske Veritas (DnV), the accident frequency is about half today of what it was in the late 1980s (Richardsen 2007). This improvement has especially been attributed to improved hull designs, as well as a major purge of inferior ships. However, some types of accidents at sea appear to be increasing again, particularly navigation accidents. There was been a global increase in this type of accidents in the period 2002-2007; these constituted approximately 60% of insurance claims in 2007 (Richardsen 2007). The number of navigation accidents in Norwegian waters has also increased steadily, particularly groundings. There was a 43% increase in groundings from 2005 to 2007, where a peak of 107 groundings was reached (Norwegian Maritime Directorate 2007). It is noteworthy that an accident trend similar to merchant shipping has been observed in recreational vessels in Norway. The number of fires and explosions have dropped, but

have been matched by a strong rise in the number of groundings, with a 40% increase from 2006 to 2007 (Avisa Nordland 2008).

Fortunately, navigation accidents today do not frequently lead to loss of life. In the period 2002-2007, 21 persons died in navigation accidents in Norway, of whom 19 were killed in a single accident (the grounding of the M/S Rocknes) (NMD, 2007). Global data on fatalities in maritime accidents is scarce, but has been estimated by the Institute of London Underwriters (now the Institute of Underwriters Associations) to average 688 deaths worldwide per year for the period 1988-1995 (Li 2001).

1.1.2 Major causes behind accidents at sea

Accidents can have a wide range of causes depending on their nature. Accident statistics in shipping are often compiled by insurance companies, which are equally concerned about damage to the ship's cargo as the vessel itself. Accidents may also occur during tasks or in places unrelated to sailing, such as when a galley fire burns down the whole ship. Accidents other than navigation accidents are considered beyond the scope of this thesis, and will not be discussed at length.

Navigation accident causes are usually divided into three main categories: External causes, technical causes, and human causes. "External causes" usually represent weather conditions, but may also include currents or ship motion. "Technical causes" denote equipment failures, and "human causes" relate to the operators of the vessel. Equipment may fail because of human causes during the ship's building, of course, but this is not reflected in the statistics.

According to the NMD (Gåseidnes 2008), the direct causes behind behind groundings in Norwegian waters were external in 20% of the cases, and technical in 19%. Human-related causes (typically referred to as "human error") account for the largest portion of navigation accidents in both Norwegian and foreign waters, however. The NMD classified 71% of the direct causes behind groundings in the period 2002-2007 under the category "human" (the three total more than 100%, since the NMD sometimes classifies more than one direct cause for an accident) (Gåseidnes

2008). United States Coast Guard statistics have shown that between 75% and 96% of major accidents at sea are caused by “human factors”. Similarly, the UK P&I Club (a maritime insurance consortium) found “human factors” to account for 62% of its major claims over a 15-year period. These were reported to have an estimated annual cost of \$541 million (The Nautical Institute, 2003).

1.2 Developments in technology and crews

Both civilian and military seafaring has undergone significant changes in the past three decades, particularly with regard to technological advances and reductions in manning levels (Anderson, Malone, & Baker 1998; Committee on the Effect of Smaller Crews on Maritime Safety 1990). While statistics show that overall accident rate during this period has gone down, it has been suggested that not all of these developments have benefited safety (Anderson et al. 1997; Lutzhoft & Dekker 2002)

1.2.1 High-speed craft

In the past 60 years, there has been an increase in the use of high-speed ships (or craft) in both civilian and military operations. A high-speed craft (HSC) is technically defined by the International Maritime Organisation (IMO) as “a vessel with maximum speed in meters/second, equal to or exceeding $3,7 \sqrt{V}$, where V = the volume of displacement corresponding to the design waterline in cubic meters” (Kjerstad 2004). Functionally, a HSC can be described as having a combination of light construction, combined with manoeuvrability under high speeds (Bjørkli et al. 2007). HSC technology rapidly evolved in the 1950s and 1960s, both in terms of hull designs and propulsion systems. A number of different HSC constructions exist, including single-hull ships, hovercraft, hydrofoils, surface-effect ships, and catamarans (Tupper 2005). Norway was early to begin with high-speed passenger ferry operations, more than ten years prior to the first regular US operation in the San Francisco bay. The shipowners Det Stavangerske Dampskibsselskab and Sandnæs Dampskibs-aktieselskab (SDA) opened a hydrofoil service in 1960, between the

cities of Stavanger and Bergen. Today, high-speed passenger ferries are in widespread use in Norway, and continue to play an important role in providing fast communications in rural coastal areas (Utenriksdepartementet 1994).

In the Royal Norwegian Navy (RNoN), HSC (as defined by the IMO) have been in use for more than 100 years. The Rap torpedo boat was commissioned in 1872, and had a maximum speed of 14,5 knots. The first “true” HSC came with introduction of the fast patrol boats (FPBs, also known as “motor torpedo boats”) which were commissioned after World War II. Today, the FPBs primary tasks in peace-time are to uphold national presence along the inshore coastline of Norway and “maintain national sovereignty”. In some situations, FPBs may also participate in operations led by civilian authorities, e.g. by participating in search-and-rescue operations. In recent years, they have also participated in international peace-keeping missions in the Mediterranean Sea.

The first Nasty-class prototype FPB was developed in the late 1950s, and had a maximum speed of 45 knots. These vessels had an open bridge design, a single-hull construction, and were powered by diesel engines. Although later FPB models were built with enclosed bridges, their basic construction, manning and navigation method remained essentially unchanged for the next 40 years. The last of the single-hull FPBs to be commissioned by the RNoN were the Hauk-class FPBs (fig. 1), which have been in service from 1977 until present (Thomassen 1995).

Figure 1. The Hauk-class FPB. Photo taken by Cato Bjørkli.



The Hauk-class FPBs are currently in the process of being replaced by the new Skjold-class ships (fig. 2). While the Skjold-class will be performing the same functions as the Hauk-class FPBs, these vessels are categorized as a “littoral combat ship”, or LCS. The technical features of the Skjold-class LCS, compared to those of the Hauk-class, are presented in table 1.

Table 1. Technical characteristics of the Hauk-class FPB (Thomassen 1995) and Skjold-class LCS (Sjøforsvaret 2008).

	Hauk-class	Skjold-class
Length	36,53m	47,5m
Beam	6,2m	16,5
Hull type	Monohull	Surface-effect ship (air cushion catamaran)
Depth	1,65m	0,8m on air cushion; 2,5m without air cushion
Displacement	150t	273t
Maximum speed	32 knots	60 knots
Crew size	25	16

The Skjold-class LCS represents a major change from the Hauk-class FPB and its predecessors. Functionally, it is nearly twice as fast, and much more maneuverable, due to its air cushion and water jet propulsion system. Furthermore, it has a reduced crew size. While there are five members of the navigation crew on the Hauk-class, the two navigators on Skjold use an electronic navigation system, which is integrated with the ship's autopilot manoeuvring system (Sjøforsvaret 2008).

Figure 2. Prototype of the Skjold-class LCS. Photo by Bjarte Knappen Røed.



From the beginning, both civilian and military HSC have been under scrutiny for their safety. The consequences of a grounding or collision with a HSC are comparable to that of an airplane crash, and one author has compared this type of navigation to “a continuous [airplane] landing phase in poor visibility” (Kjerstad 2002). Although there have only been a handful of major HSC accidents worldwide, some of these have had dreadful consequences, including the loss of 17 lives in the *Sleipner* grounding (Justis- og politidepartementet 2000). These have caused concern about the safety of HSC navigation.

1.2.2 Navigation methods

Origins of navigation

While the construction and performance capabilities of ships have made considerable progress in recent years, significant changes have also been made in how they are navigated. In the context of transportation, navigation can be defined as “the science of getting ships, aircraft, or spacecraft from place to place; especially: the method of determining position, course, and distance travelled” (Merriam-Webster Online Dictionary 2009). The etymology of the term navigate stems from the Latin words *navis* ("ship") and *agere* ("to move") (Bowditch 1995).

Seafaring is as old as modern humanity, and has been present in some form throughout the Holocene age. The earliest archaeological evidence of nautical equipment is around 9500 years old, and indirect evidence suggests that open sea crossings occurred between Greek islands up to 11000 years ago (Bednarik 1997). The first navigation techniques were mainly based on experience and intuition, combined with observations of the sky, planetary objects, wind, waves, currents, sealife, landmarks and seamarks (Frake 1985). The oldest known navigation tool is the sounding lead, used to measure depth (Frake 1985), and the first compasses were invented in the 11th century (Lane 1963). Many of the same tools and features of navigation can be found today, and celestial navigation (based on planetary objects) was taught at naval academies and nautical universities until only a few years ago.

The navigation task has always been cognitively challenging, requiring intricate knowledge of mathematical, astronomical, and geographical principles. The navigation proficiency of medieval sailors has been used to prove that the cognitive abilities of humans in the Middle Ages were well developed (Frake 1985).

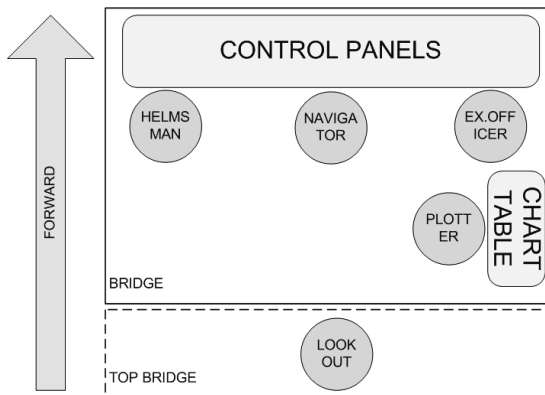
Methods used in FPB navigation

Conventional FPB navigation

The Hawk-class FPB is mainly navigated using conventional navigation methods. In general terms, “conventional” FPB navigation encompasses two techniques; optical

navigation in clear weather, and radar navigation in reduced visibility. In both techniques, the ship is navigated by a team of five crew members, consisting of two navigators and three conscripts. The location of these are shown in a schematic illustration of the Hawk bridge in fig. 3.

Figure 3. Schematic representation of the Hawk bridge and bridge crew members.



An executive officer monitors a navigator, who obtains route information from paper charts read by the plotter. The navigator uses this route information together with external visual observations to control the progress of the ship. Further position verification is done by using a stopwatch, since the navigator knows the elapsed distance of the vessel since the last known position when travelling at a fixed speed. The task of external observation is supported by a lookout, who verbally communicates information about ships, navigation objects or other features in the surrounding geography. The directional manoeuvring of the ship is ordered by the navigator, and executed by the helmsman using a wheel.

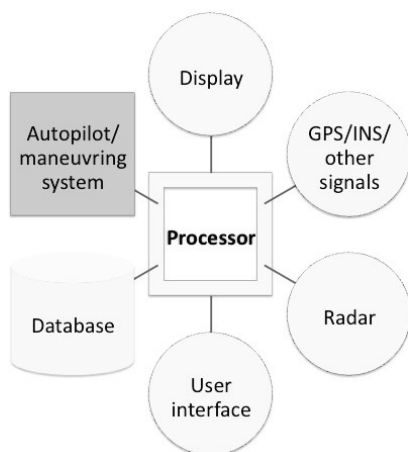
The navigation method used aboard the Hawk-class FPB is a team-dependent, dynamic task, which is carried out under severe time pressure. The individual roles in the navigation team are highly specialized and well-defined, with a clear command

hierarchy: One observes the outside environment, one reads the chart, and one compiles information regarding the ship's position, direction, and speed (Røed 2007). The navigation method used here is a very traditional method, which has been used in naval ship navigation for decades (Hutchins 1995). Thus, the Hauk-class navigation method has been refined and practiced by the RNoN since the first FPBs were acquired.

ECDIS-based FPB navigation

Navigation based on electronic charts is radically different from conventional navigation. An electronic chart display and information system, abbreviated ECDIS, typically consists of a navigation system input (e.g. from the Global Positioning System, or GPS), a computer and an information screen. Usually, the ECDIS system is also connected to an autopilot, which together constitutes an integrated bridge system, or IBS (although an IBS may encompass other auxiliary systems as well, the term will be used interchangeably with ECDIS in this thesis). Fig.4 shows a schematic representation of the components in an ECDIS/IBS system.

Figure 4. Schematic representation of an ECDIS/IBS system (Modified after Kite-Powell & Gaines 1995).

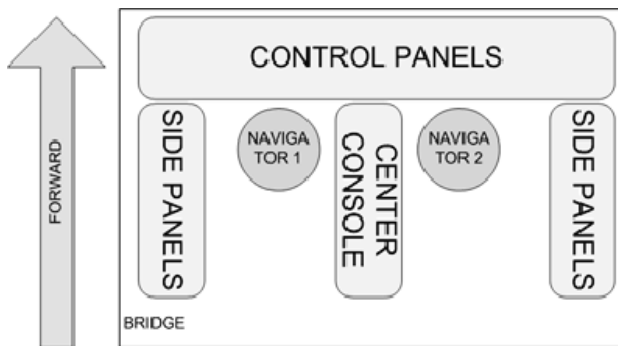


IMO defines this system as follows:

“An integrated bridge system (IBS) is defined as a combination of systems which are interconnected in order to allow centralized access to sensor information or command/control from workstations, with the aim of increasing safe and efficient ship’s management by suitably qualified personnel”.

The Skjold-class LCS is operated through the use of an IBS. Here, the system allows routes to be pre-programmed, and modified or entered as the ship progresses. The ship is directionally maneuvered by one of the two navigators using either direct manual control with a joystick, auto-pilot control (where turn information is manually entered into the system, but executed by the computer) or track-pilot control (where the ship automatically follows a pre-programmed route). While both navigators have access to identical navigation display information, one of them will support and monitor the other, who performs the navigation task. The bridge layout of the Skjold-class LCS is shown in fig. 5.

Figure 5. Schematic representation of the Skjold bridge and bridge crew members.



In the Skjold-class LCS, the plotter, lookout, and helmsman functions have all been eliminated, and have been replaced by technology. This technology allows a single navigator the possibility to sail the vessel alone. Therefore, the navigation method in this system can be said to be different from the Hauk-class method in that

it is not as team-dependent, is based on highly generalized task roles, and does not have the same clearness in command hierarchy. Furthermore, while navigating the Skjold-class LCS also happens under time pressure, the navigation task can be to a larger degree based on passive monitoring – especially when operating in “track pilot mode”. This navigation method is relatively new to the RNoN, and does not have an established practice to build on.

Research on conventional and ECDIS/IBS-based navigation and safety

Increased safety has been one of the main motivations for introducing ECDIS and other new navigation technology. Since statistics consistently showed “human error” to be the cause behind a majority of accidents, moving safety-critical functions from error-prone humans to more reliable machines was seen as sensible. According to Mills (2005), the main advantages of using integrated systems were (1) fewer screens and information sources, (2) high user involvement in making critical decisions, (3) automation of routine tasks not requiring significant decision making and (4) added training simplicity and cost-effectiveness, since training can be performed on PCs. As stated in the previous section, integrated bridge systems also allow significant manning reductions. One of the original aims for the first IBS prototypes was to allow a single navigator to operate any ship, large or small. The ability of a navigator to single-handedly operate e.g. a supertanker exists largely in the elimination of physical demands, especially due to the lowered demand for external visual observation (eliminating the need for a lookout) and manual wheelhandling (eliminating the helmsman) (Lee & Sanquist 2000). Furthermore, one study has shown that ECDIS systems reduce mental workload (Donderi et al. 2004), albeit in simulators, and under very controlled conditions.

However, since their arrival, ECDIS and integrated bridge systems have also been under scrutiny for having a possible negative effect on navigation safety, as well as being implicated in navigation accidents (Lutzhof & Dekker 2002). The introduction of electronic navigation aids implies automating significant parts of the navigation task, rather than just adding aids to conventional navigation method (such as radar). Lee and Sanquist (2000) argued that electronic navigation would reduce

workload, but at the same time introduce weaknesses that could reduce safety. Possible flaws that were identified included a false sense of precision, removal from the process of position finding, and an added number of low-level tasks (e.g. chart manipulations or finding the correct menu settings). Furthermore, Olsson and Jansson (2006) raised the issue that ECDIS systems can have complex user interfaces, which may be very different from system to system.

Many of the other general criticisms raised against ECDIS/IBS are shared with automation found in other transport systems and industries. A more general review of these issues will be presented in section 1.3.

1.2.3 Manning

A trend that has coincided with the introduction of IBS systems, is that manning levels on ships have become increasingly smaller. Typical merchant ships now have a crew of between eight and 16 persons, compared to about 45 crew members 40 years ago (Committee on the Effect of Smaller Crews on Maritime Safety 1990). A similar trend has been seen in naval ships, as well. The Hauk-class FPB has had a standard complement of 25 (twelve officers and 13 conscripts), whereas the Skjold-class LCS will have a crew of only 16 (nine officers, three enlisted sailors and four conscripts). This development is seen in nearly all new naval vessels; the US Navy's SS 21 submarines have crews 25% smaller than their predecessors (Anderson et al. 1997), and the DD21 destroyer was initially planned to have a complement of only 44 sailors – 144 less than the previous type (Anderson, Malone, & Baker 1998). There are signs that European nations, and perhaps Norway in particular, have been most aggressive in cutting crew sizes (Committee on the Effect of Smaller Crews on Maritime Safety 1990). The new RNoN Nansen-class frigates, for example, have complements with about 100 fewer crew members than comparable foreign frigates.

The motivation for minimizing crew sizes has primarily been financial, since personnel reductions allow significant savings in operating costs. Across the lifespan of a naval ship, manning costs are typically twice as high as the cost of the ship's construction (Baker et al. 2001). As an example, the total annual savings associated

with personnel reduction on a single DD21 destroyer was estimated at \$9,4m. Furthermore, the “lean manning” concept also permits smaller vessels, which can be faster, have less chance of being detected by radar, and have lower material costs. Finally, with smaller crews, fewer sailors are put at risk during combat (Anderson, Malone, & Baker 1998).

In order to make the “lean manning” approach viable, two main strategies have been used. First, tasks are consolidated, so single crew members are responsible for functions previously performed by multiple personnel. Second, a number of tasks have been automated (Baker et al. 2001). This is particularly the case in bridge operations, for example as in navigation based on ECDIS and integrated bridge systems. It is important to note that task consolidation and automation are deeply intertwined, since it is largely because of function elimination, task simplification and workload reduction from automation that allows crew members to perform several tasks at the same time (Baker et al. 2001). This approach has been employed in other areas of ship operation as well, including unmanned machine rooms and automated tools for deck operations.

A number of safety concerns have been raised following the introduction of minimum manning systems. In an early study by the NRC Committee on the Effect of Smaller Crews on Maritime Safety (Committee on the Effect of Smaller Crews on Maritime Safety 1990), the most important concerns were:

- a) fatigue, due to greater cognitive and physical demands on crew members;
- b) insufficient training, due to higher needs for technical competence and
- c) increased maintenance costs, due to lack of capacity for performing essential maintenance while in operation.

From the perspective of human factors in navigation, all of these are important issues to address. Perhaps the most important overall issues in a “lean manning” system, however, are how performance, workload and safety are affected by the use of automation to replace tasks previously performed by humans.

1.3 Automation

The issue of automation has been a major research theme in human factors over the past 60 years. Automation can be defined as “the execution by a machine agent (usually a computer) of a function that was previously carried out by a human” (Parasuraman & Riley 1997 p.231). Complex systems such as nuclear control rooms, airplane cockpits and ship bridges have become increasingly automated, where humans are thus being replaced by computers in performing a number of tasks (Bridger 2003). The shift towards automation has also been seen in the maritime industry, particularly with regard to navigation (Hetherington, Flin, & Mearns 2006).

1.3.1 Problems with automation

In the context of a control system, it could be said that the main purpose of automation is to replace inherently unreliable and slow humans with highly reliable machines, which can run at greater speed and consistency. As a consequence, the operators’ workload should be reduced, risk of error should be minimized, and system performance should be optimized (Bowers et al. 1998). However, it has become apparent that automation does not necessarily reduce the need for human operators; it only changes the nature of their work. In general terms, their role has moved from manual to supervisory control, i.e. not physically “doing” tasks, but to a larger degree monitoring the status of the system (Hollnagel 1998). Automation has therefore increased demands for complex intellectual tasks such as fault diagnosis, planning, and problem solving, which has in some cases made the operator task more difficult and error-prone than it originally was (Wei, Macwan, & Wieringa 1998). This has been termed “the ironies of automation” by Bainbridge (1983).

In addition to affecting the operators’ working environment and system performance, automation-related problems have been identified as a causal factor in major accidents in transport and industry, such as the grounding of the cruise ship *Royal Majesty* in 1995 (National Transportation Safety Board 1997). In a number of these accidents, investigations have found that operators have changed their behavior

as a result of automation, and used the system in ways totally unanticipated by system designers (Parasuraman 2000). For example, in aircraft cockpits with flight management computers, it has e.g. been found that pilots spend significantly less time looking outside than earlier (Damos, John, & Lyall 1999).

Research has identified a number of specific human performance problems associated with automation. These can be summarized under the following headlines (Parasuraman & Riley 1997):

- Lack of trust in automation

This problem usually arises as a consequence of automation that does not always work when it should, or “cry wolf” situations where e.g. alarms go off frequently, but do not usually indicate danger. In situations where the automation is necessary, operators may suffer from excessive workload because they are forced to continuously monitor that the system is functioning properly. Furthermore, in high alarm frequency-situations, they may ignore or sometimes even disable alarms, with potentially grave consequences if a “real” alarm situation should appear.

- Incorrect understanding of automation function

This is common in complex systems, where operators must employ a simplified “mental model” of how the automation functions. In some situations, this may cause the operator to misunderstand the state of the system, and e.g. not respond properly to abnormalities. A commonly cited reason for this is lack of feedback to the operator from the automation interface (Sarter & Woods 1997; Stanton & Young 1998).

- Overreliance on automation

This may be a problem where the automation is perceived as being more reliable than it actually is. The operator may give too much trust to information that is uncertain, or continue to rely on automation even when it is apparent that it is not functioning as it should. In a longer perspective, relying on automation may sometimes also lead to degraded operator skills in performing the core task. This may be especially problematic when operators are required to face novel situations, where automation is not able to handle a problem.

- Difficult working conditions as a result of automation

Research has frequently pointed out that humans are poor at monitoring tasks, which automated systems often require. Furthermore, when automation errors occur, they often require the operator to respond very quickly, causing sudden spikes in workload.

1.3.2 Function allocation and levels of automation

Although there are a number of problems associated with automation and human performance, it must also be said that automated systems have in many cases benefited working conditions as well. Automated flight aids have been reported to have had an overwhelmingly positive effect on aircraft accident rates (Matthews 2004). Automated aids may support operators in performing tasks where their information processing capacity is insufficient, the task is repetitive and boring, or requires high levels of precision. A central issue in human factors practice has therefore been allocation of function, i.e. deciding which task functions should be automated, and which should be left under manual control (Bridger 2003).

Originally, function allocation was performed by designating functions to either machines or humans by using lists or tables showing the respective strengths, such as Fitt's list (Fitts 1951). Today, this approach has been abandoned in favor of focusing on how humans and computers can complement and support each other (Hollnagel & Bye 2000). In most current systems, tasks are not carried out strictly by humans or strictly by computers, but rather by both, with varying degrees of responsibility. The distinction between manual and automated control is therefore no longer an "either/or" dichotomy. As a result, automation can differ widely in terms of type and complexity, which has implications for how it affects the operator's task. In order to classify the level of automation, Parasuraman, Sheridan and Wickens (2000) proposed the following model:

Table 2. Levels of automation of decision and action selection (Parasuraman, Sheridan, & Wickens 2000).

HIGH	9	The computer decides everything, acts autonomously, ignoring the human
	8	Informs the human only if it, the computer, decides to
	7	Informs the human only if asked, or
	6	Executes automatically, then necessarily informs the human, and
	5	Allows the human a restricted time to veto before automatic execution, or
	4	Executes that suggestion if the human approves, or
	3	Suggests one alternative
	2	Narrows the selection down to a few, or
	1	The computer offers a complete set of decision/action alternatives, or
LOW	0	The computer offers no assistance: humans must take all decisions and actions

The degree of automation has been shown to have importance for workload and human reliability, especially when switching between automation levels in high workload situations. Di Nocera et al. (2005) found that when workload was high in a set of simulated tasks, there was a high performance cost of switching between levels of automation. This cost of switching between automation levels was nearly universal, but was modulated by the type of task performed. In particular, performance was negatively affected when shifting from decision support (level 2) to

manual control (level 0) in a detection task. This indicates that in e.g. a monitoring task where automation has been adopted, the risk of performance breakdown following automation shut-down increases strongly.

The benefits of automation are not only dependent on the task being performed, but also by who will be using it. In a study on younger (mean = 21) and older (mean = 69) participants performing an airport luggage screening task, Wiegmann et al. (2006) found one of the automation aids benefited the younger group, but had no effect on the older participants. Automation benefits have also been found to be determined by self-confidence in using the system (Wiegmann 2002) as well as trust in the system's reliability (Lee & Moray 1994).

1.4 Human error

Statistics show that the majority of navigation accidents are attributed to what is commonly known as human error. The proportion of accidents claimed to be caused by human error varies, but is typically estimated in the range of 65-96% (Røed 2007 p.17). The consequences of these accidents can be huge, not only in terms of damage to the ship, but also for the responsible navigator personally, who may be charged with criminal misconduct. The idea of human error as a "cause" behind accidents has increasingly been challenged, however. An important reason for this is that humans generally do their best at the task they are assigned, since intentionally not doing so would endanger their own lives. Furthermore, accidents are usually a long chain of events, where the error is only one link in the chain, and usually is not the origin of it (Rasmussen 2003). In the "new view" of human error, it is therefore seen more as a symptom of problems with the system, thus being an effect rather than a cause (Dekker 2002). Operators may be faced with unreliable automation, excessive workload, poor user interfaces, long working hours and a number of other factors detrimental to human performance. It has therefore been stated that the actual error is not usually with the operator at the "sharp end", but rather with the system designers responsible for suboptimal working conditions (Endsley, Bolté, & Jones 2003).

Studies of human error have tended to focus on catastrophic accidents in process industry, nuclear industry, aviation, and to some degree other modes of transport. Shipping has to a lesser degree been the focus of accident studies, with the notable exceptions of the grounding of the Exxon Valdez (Grabowski & Roberts 1996) and the capsizing of the Herald of Free Enterprise (Reason 1990). While there are some similarities in accident and risk characteristics between industries (Williamson, Feyer, & Cairns 1996), recent studies have highlighted some of the factors that are typical to maritime transportation. Lützhöft (2004) found in her studies that ship navigation is based on what she calls “integration work”, requiring the effective integration of multiple persons and technology. She also showed that the adaptation of new technology – particularly when added on an incremental basis - created problems due to poor usability, lack of reliability, and haphazard training. Another important issue is the influence of the outside environment on the difficulty of the task, which may be strongly increased due to complex geography, changing weather or uncharted waters. The latter issue was addressed by Norros (2004), who proposed that uncertainty (e.g. from submerged rocks), dynamism (from high time pressure), and complexity (from were the three main factors contributing to the difficulty of navigation in littoral waters. Other factors adding to the difficulty of navigation include high speed (Kjerstad 2004) and unpredictable behavior from other ships (Hockey et al. 2003).

A common methodology used to analyse human error is human reliability analysis (HRA), which encompasses a number of generic or industry-specific methods (Kirwan 1998). Some HRA methods are used prospectively to predict the risk of human error, whereas others are used retrospectively to analyze incidents (these are often referred to as “error taxonomies”). A typical feature for both approaches is that they analyze the nominal risk of error associated with a given task type (e.g. “monitoring” or “performing a skilled action”) in combination with situation characteristics known as “performance-shaping factors”. Performance-shaping factors, or PSFs, are defined as factors “which influence the likelihood of an error occurring” (Kirwan 1998). These include detrimental influences related to the

individual, system, task or environment. Therefore, factors such as “level of experience”, “signal-to-noise ratio”, “memory demand” and “visibility” are all considered PSFs. The basic concept of a PSF is that it may have a negative effect on human performance, but does not necessarily determine it (Hollnagel 1998). As a result, they may be considered both as cause or contributor in accident reviews (Kim & Jung 2003).

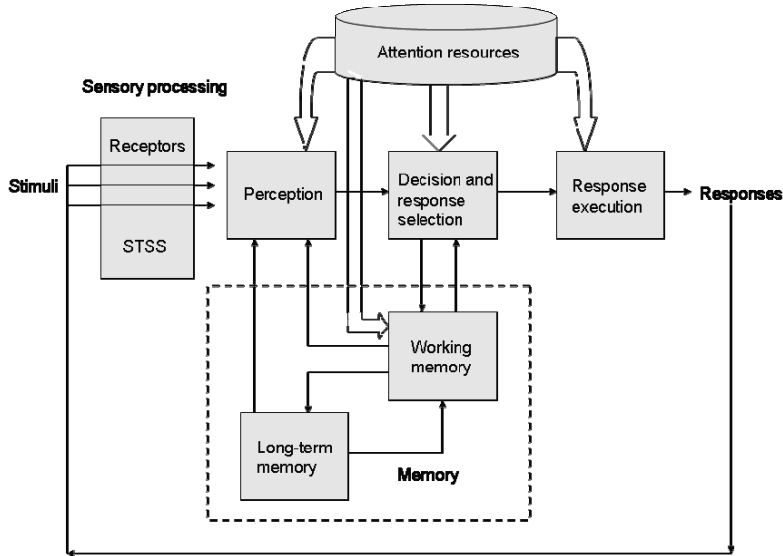
1.5 Cognitive workload and performance

Cognitive workload, performance and sleepiness are central topics in this project. In this thesis, the terms “cognitive” and “mental” will be used interchangeably, in the meaning of “relating to, being, or involving conscious intellectual activity” (Merriam-Webster Online Dictionary 2009). This section is not meant to provide a comprehensive account of these topics, as it will only focus on aspects directly related to the research questions in this project.

1.5.1 Basic elements of cognitive processing

In a socio-technical system, it is important to understand how information is communicated, understood, and acted upon in both humans and machines. However, while machines are fairly simple to take apart and explain, the same cannot be said for humans. Several models for human information processing have been developed. These have evolved over the course of the last 60 years, and there is still not one universally accepted model for the cognitive function of the human brain (Matthews et al. 2006). Models are abstractions, and their practical applicability can be debated. The model used here is based on the Information processing model (fig. 6), which was proposed by Wickens (2002).

Figure 6. Model for information processing. From Wickens (2002).



Wickens' model is a general illustration of human information processing.

Information is detected as sensory stimuli by various organs, such as the eyes and ears. The perceptual process converts the stimuli into a neural output representing for example color or sound frequency, and preserve them in short-term sensory stores (STSS). The information from the STSS is further processed by the central nervous system, and the stimulus is categorized and interpreted through the process of perception. At this stage, the information is processed both in terms of physical features and semantical categorization. In addition to bottom-up categorization of information, there are also top-down influences on this categorization, in the sense that e.g. prior experience and context affect the evaluation of the stimulus. Irrelevant information is quickly discarded, and never reaches conscious awareness.

Information considered important, however, is coded and "tagged" with associated details, before being saved in the working memory store. This memory store, often called short-term memory (STM), has a capacity limited only to a few information items. The information contained in the STM is also used in cognitive processing, while deciding on an appropriate response to the stimulus. Some of the information

that passes through the STM is transferred to the long-term memory storage, and can be retrieved later.

Wickens' model has several flaws; it does not take into account motivation or context, and its structure neglects important aspects of voluntary control. However, it does provide a model for how the human information system may be structured, as well as incorporating the concept of attentional resources. This concept is central to this thesis. In figure 6, the element of attentional resources is depicted as a fluid storage tank. The speed and accuracy of all information processing is dependent on energetic supplies from these attentional resources, which are often referred to as a "resource pool". Again, these attentional resources must be considered as an abstract concept, since there is much debate around whether there are one or many different "resource pools". What is clear, however, is that humans have a limited cognitive capacity. Nearly everyone has experienced feeling mentally tired, not capable of keeping up with a task, or feeling that a task is too difficult. These experiences are examples of situations where cognitive workload is higher than the attentional resources available, which is reflected in cognitive task performance.

1.5.2 Cognitive workload and performance

Over time, demands at work in the industrialized world have increasingly moved from being physical to being cognitive. As a result, mental workload has become more important in many occupations, especially where humans perform safety-critical tasks. Mental workload (MWL) can be defined as "the amount of cognitive resources being expended at a given point of time" (O'Brien & Charlton 2002 p.98). The concept of MWL is central to individual human performance and reliability, especially within complex systems. Humans have limited information processing capacities, and are therefore only able to attend to a limited number of inputs at once (Bridger 2003 p. 336). While early studies indicated that humans had a relatively fixed short-term memory capacity of 7 ± 2 "chunks" of information (Miller 1956), later research on attentional resource theories showed that human information processing was not necessarily fixed, but could also depend on fluctuating availability

of resources – sometimes referred to as “energization” (Norman & Bobrow 1975). As a result, cognitive performance could be expected to drop as a result of internal factors such as fatigue, or external factors such as the number of multiple tasks.

MWL is especially seen as important in assessing the effects of new task features, interfaces or automation systems (Pickup et al. 2005). The main goals for optimizing the level of MWL for operators has been to reduce human errors, improve systems safety, increase productivity and reach operator satisfaction (Moray 1988). However, a recurring problem with the concept of MWL, is that it does not appear to have a unified definition. There are a number of different definitions, which in most cases are connected to different methods for measuring MWL (Xie & Salvendy 2000). It is also sometimes used interchangeably with, or overlaps with the concepts of ‘stress’, ‘strain’, ‘activation’ and ‘arousal’.

Compensatory control theory

Contrary to what might be expected, increased workload, fatigue and other stressors do not always lead to decreased task performance. An explanation for this was provided through the compensatory control theory, a framework introduced by Hockey (Hockey 1997). This theory builds on resource theory (such as Wickens’), but adds to it the element of “cognitive energetics”. This concept suggests that performance is not only determined by a limited resource pool, but also by the “mobilisation of energy”, or effort. Thus, a person may be able to uphold task performance during high workload by increasing his or her mental effort to the point where the current goals are maintained. In the event of the person not reaching the desired goals, stability can be reached by lowering the performance goals.

Compensatory control theory rests on three basic assumptions. These are that 1) behavior must generally be goal-directed, 2) control of goal states is usually a self-regulatory process, and 3) regulatory activity has a cost to other parts of the system. The latter assumption forms the basis for how performance decrements under stress can be measured. While primary task performance is “protected” by increased effort, a physiological cost can usually be observed, as well as reduced secondary task

performance. Both increased physiological cost and decreased secondary performance have been shown in experimental studies, where e.g. sleep deprivation has been used as a model stressor (Hockey, Wastell, & Sauer 1998). An additional type of performance cost that has been observed are after-effects in the form of reduced performance after the main task is completed (Cox-Fuenzalida 2007).

The main strength of the compensatory control model is that it shows how regulation of effort is to some degree controlled by the individual, rather than purely being a feature of the task or environmental conditions. However, it is important to note its limitations. First, current task motivation plays a large role in determining how much additional effort can be expended. Second, other individual factors such as personality may affect when individuals choose to stop increasing their effort and begin to alter their strategy or reduce their performance goals. Finally, it is important to note that the compensatory control model can only predict performance under normal-to-high workload tasks, and therefore does not account for performance decrements in low-workload situations.

Vigilance and sustained attention

Sustained attention over long periods of time is typically referred to as “vigilance”. Vigilance as a research field came into existence during World War II, where the British military was interested in operators’ ability to continuously monitor radar and sonar screens (Bridger 2003). Current research on vigilance is closely tied to issues concerning automation, since automated systems often require operators to monitor for failures over long periods (Parasuraman et al. 1996). Accidents in transport systems such as railways have also been shown to frequently involve issues with sustained attention, where signals have been missed. Experimental research has shown that humans are generally quite bad at this type of task; detection errors (failures to detect signals) typically exceed 20% after only half an hour (Matthews et al. 2006). This drop in attention performance is typically referred to as the “vigilance decrement” (Mackworth 1964). Reasons for the vigilance decrement include boredom, distractions and sleepiness (Bridger 2003). However, this view has recently been challenged, as it has been shown that vigilance tasks have been shown to carry a

high mental workload, and place a considerable mental burden on operators (Grier et al. 2003). Performance decrements have been shown to be especially high when signals have low salience, are infrequent, have a short duration, and the operator has no feedback regarding his or her performance (Lanzetta et al. 1987). Vigilance tasks are also especially prone to negative effects from sleep deprivation (Durmer & Dinges 2005). While experimental research has consistently shown a vigilance decrement, these findings have been difficult to reproduce in real-life settings. Laboratory studies have tended to measure vigilance in tasks that are overly monotonous, only involve a single operator, and have had failure rates that have been artificially high (Molloy & Parasuraman 1996). Applied vigilance tasks are often more complex, have a higher level of intrinsic motivation, and often performed by teams (Bridger 2003).

Mental underload and malleable attention

Most theories of attention and mental workload have focused on situations involving normal to high demands, including Wickens' multiple resource model and Hockey's compensatory control theory. As a result, their predictive validity is mainly relevant to performance decrements caused by excessively high resource demands. However, few of them are able to explain situations where operators are subjected to excessively low resource demands. This is unfortunate, since extremes in mental workload at both the high and low end of the scale has been shown to impede performance (Wilson & Rajan 1995). Automated systems can sometimes involve long periods where the operator is not actively involved in task performance, resulting in low mental workload. This has been shown to be a problem in e.g. automobile drivers using driver support systems (such as adaptive cruise control), where drivers' attentional capacity was reduced as a consequence of being "out-of-the-loop" in regulating speed (Young & Stanton 2002a).

A model for performance effects from mental underload has been proposed under the Malleable Attentional Resources Theory (MART) by Young and Stanton (2002b). According to MART, attention capacity may shrink in underload situations, as a direct result of lack of effort and arousal. The person's cognitive resource pool is

therefore not constant in every task situation (as stated by e.g. Wickens' model), but will temporarily diminish in a low-workload situation from lack of demand.

Therefore, the attentional capacity of the operator would be expected to increase with rising task demands, up to the point where mental capacity is at its maximum, and performance begins to drop. Problems in low-workload situations could be especially be expected where there is a sudden spike in demands, since the operator would then have lower mental capacity to respond with. This model for performance is very similar to other cognitive resource theories, except that it shows attentional capacity as demand-variant rather than constant (Young & Stanton 2002b).

1.6 Sleep, sleepiness and sleep deprivation

1.6.1 Sleep

Sleep is a fundamental biological need in human beings. The role of sleep is still not fully understood (Sejnowski & Destexhe 2000), nor is there consensus about exactly how much sleep a human needs to function optimally (Ferrara & De Gennaro 2001). However, there is agreement that insufficient sleep can impair health (Harma 2006), cognitive performance (Durmer & Dinges 2005) and daytime function (Martin et al. 1997). This has been shown to have consequences for safety, as well.

Sleep is regulated by two factors; one homeostatic and one circadian (from Latin: circa=about, dias= day) (Ursin 1996). The homeostatic factor implies that sleep need is accumulated during wakefulness and reduced during sleep. The circadian factor is independent from the homeostatic factor and has a period of about 24 hours (Borbely et al. 1989). The circadian rhythm is controlled by the suprachiasmatic nuclei (SCN) in the hypothalamus, which has an endogenous rhythm with a length that is somewhat longer than 24 hrs (Czeisler et al. 1999). However, this endogenous rhythm is normally adjusted by external stimuli such as light, so that it adheres to a 24 hour rhythm (Czeisler et al. 1989). The contribution to wakefulness from the circadian rhythm reaches a minimum in the early morning and a maximum in the

evening (Dijk & Czeisler 1995). In addition to impact sleep, the circadian rhythm also has impact on cognitive and other biological processes. Cognitive performance is poorer during a persons biological night time compared to the biological day time (Folkard & Tucker 2003), and circadian variations in several metabolic, hormonal and immunological processes have been found (Foster & Kreitzman 2004). Biological adaptation to night work is possible by changing the circadian rhythm. However, this process takes several days and is seldom complete (Czeisler et al. 1989).

1.6.2 Sleepiness, fatigue and safety

Inadequate or disturbed sleep has been shown to constitute a major safety hazard, and increases the risk of human error-related accidents (Dinges 1995). Lack of sleep and operator fatigue has been cited as causal factors in major catastrophes in transport, the military and nuclear industry, including the grounding of the Exxon Valdez in 1989 and the Three Mile Island accident in 1979 (Mitler et al. 1988). Sleepiness and fatigue should be considered separate conditions, since *sleepiness* is defined as “the tendency or drive to fall asleep” (Carskadon & Dement 1982), whereas *fatigue* is a more general condition, defined as “a feeling of weariness, tiredness, or lack of energy” (Medline Plus Medical Encyclopedia 2009). It has been estimated that between 7% and 30% of fatal road traffic accidents are related to operator sleepiness (Philip et al. 2005; Sagberg 1999), and the number of accidents in industry have been shown to increase during the night shift (Folkard & Tucker 2003). Extended wakefulness and long shifts have been shown to have a major impact on serious medical errors by physicians (Landrigan et al. 2004). Sleepiness and fatigue appears to play an important role in shipping accidents, as well. In a sample of accidents from 1994 to 2004, about a third of the groundings investigated by the Marine Accident Investigation Branch (MAIB) involved sleepy officers alone on the bridge (Marine Accident Investigation Branch 2004). In Norwegian waters, 30% of the “direct human causes” behind groundings in the period 1998-june 2008 were “falling asleep on watch”, according to data from the Norwegian Maritime Directorate (Gåseidnes 2008).

1.6.3 Sleep and cognitive performance

Except for actually falling asleep on the job, the safety risk from impaired or reduced sleep is mainly a result of decreased mental capacity. As a comparative measure, sleep disturbances and sleep limitations have been shown to have effects similar to alcohol, with 24 hours of continuous wakefulness roughly equalling a blood alcohol concentration of 0,10% (Dawson & Reid 1997;Roehrs et al. 2003). It has been established that mental performance is strongly influenced by altered sleep/wake patterns (Åkerstedt 2007), as well as both partial and total sleep deprivation (Durmer & Dinges 2005; Pilcher & Huffcutt 1996).

Research has shown that mental performance impairment under reduced sleep has a strong neurophysiological basis. The brain areas that are most affected by sleep deprivation include the frontal lobes and prefrontal cortex, the thalamus, and the hippocampus (Boonstra et al. 2007). There is growing evidence that the prefrontal cortex is particularly vulnerable to sleep deprivation effects, possibly due to a higher need for homeostatic sleep in this area (Finelli, Borbely, & Achermann 2001). The prefrontal cortex has been shown to play an important role in executive cognitive functions, which can be defined as higher-level, goal-directed behavior (Muzur, Pace-Schott, & Hobson 2002). Consequently, sleep deprivation has been shown to have a strong negative influence on executive functions in general (Nilsson et al. 2005), as well as specific functions such as decision making (Harrison & Horne 2000) and task shifting ability (Heuer et al. 2004). An additional problem is that sleep-deprived subjects often lose the ability to effectively judge their own level of performance (Dorrian et al. 2003).

1.6.4 Sleep and applied task performance

Although a large number of studies have reported negative performance effects in laboratory settings, primary task performance in applied, complex tasks has in some cases demonstrated robustness against the effects of sleep deprivation. Anesthesiologists have shown unimpaired clinical performance after 25 hours of

wakefulness (Howard et al. 2003), and researchers have failed to show clear operational performance effects from sleep deprivation on thermal power plant operation (Gillberg et al. 2003) or simulated laparoscopic surgery (Uchal et al. 2005). Also, while some studies on flight under sleep deprivation have found a significant performance degradation (Caldwell et al. 2004), other simulator experiments have shown that military pilots can maintain performance well after 24 hours of sleep deprivation (Chelette et al. 1998), and reasonably well (i.e. not crash) after 40 hours (Caldwell & Leduc 1998).

Factors moderating the influence of sleep deprivation on performance

A number of factors may influence the effect sleep deprivation has on performance. The first is the nature of the task, since certain task characteristics seem to either augment or mitigate sleep deprivation effects on performance. Specific factors such as motivation, attention demand, task duration, monotony, feedback and multiple-task performance have been shown to influence sensitivity to sleep deprivation (Matthews et al. 2000) pp 207-224. This is evident in that for example impaired driving performance has been strongly and consistently associated with sleep deprivation (Philip et al. 2005) which has also been identified as a cause behind a large proportion of road vehicle accidents (Horne & Reyner 1999; Sagberg 1999). Thus, accident risk under sleep deprivation in applied tasks can be expected to be equally a result of the nature of the task as the psychophysiological development of sleepiness alone. Sustained primary task performance under sleep deprivation has also been explained by Hockey (1997) as being a result of “compensatory control”, or increased effort as a result of increased task demands. Caldwell and Ramspott (Caldwell 1998) state that high task complexity may offset the effects of sleep deprivation by increasing motivation, but could also increase sensitivity if associated with even higher task demands. In addition to intrinsic task characteristics, performance under sleep deprivation is affected by personal characteristics and individual coping strategies. It has been established that there are trait-like interindividual differences in susceptibility to sleep deprivation effects, with differences in subjective sleepiness,

cognitive processing capability and behavioural alertness (Van Dongen et al. 2004a). However, a biological basis for these differences has not yet been found.

The most common individual coping strategy under sleep deprivation is caffeine consumption, usually in the form of coffee, tea or soft drinks. Normal caffeine has in some studies shown a limited mitigating effect on a number of performance measures under sleep deprivation, including reaction time, decision making and attention (Snel, Lorist, & Tiegens 2004). A positive effect of caffeine has also been found in applied tasks performed under sleep deprivation, such as marksmanship (Lieberman et al. 2000) and automobile driving (Reyner & Horne 2000). Healthy individuals subjected to 62 hours of continuous sleep deprivation have also shown dose-related changes in sleepiness when given varying quantities of caffeine (Kamimori et al. 2000), but with insignificant changes when given the smallest dose (150mg, or 2.1mg/kg). The lack of effect in this group was interpreted as a result of tolerance effects, which are common in regular caffeine users. Withdrawal effects in regular caffeine users normally appear within 12-24 hours, and usually subside within three-five days (Griffiths et al. 1990). In a recent review of caffeine withdrawal effects, the symptoms and signs considered valid included headache, fatigue, decreased energy, decreased alertness, drowsiness-sleepiness, decreased contentedness, depressed mood, difficulty concentrating, irritability, and fogginess (Juliano & Griffiths 2004).

1.7 Rationale and aims

This thesis was carried out to gain knowledge concerning safety in high-speed ship navigation. A high proportion of shipping accidents have human-related causes, in civilian as well as military vessels. Excluding war or other conflict situations, naval high-speed ships do not play a major part in most people's lives. Only a small number of crew members are exposed to the risks involved, and their operations usually take place far away from the general public. In spite of this, interest in human factors in fast patrol boat navigation has been considerable lately; the topic has been addressed

in at least four recent PhD theses in Norway (Røed 2007, Bjørkli 2007, Bjelland 2008, Ødegård 2008). Much of this interest has stemmed from the complexity of the FPB as a sociotechnical system. It has people who work in teams, performing tasks which involve considerable tacit and formal knowledge, simple and advanced technology, considerable time pressure, as well as possibly severe consequences from errors. These are all central issues in the science of human factors, and have been extensively addressed in the aforementioned theses, although mainly from a theoretical perspective. The present thesis separates itself from its predecessors in that it has not only focused on prior FPB navigation methods (as seen in the *Hauk*-class FPB), but has also examined the consequences of the transition to a new navigation method, which is currently in use in the new *Skjold*-class LCS. Furthermore, a quantitative approach has been employed in each of the studies.

Naval high-speed ship navigation is a particularly risk-exposed situation, because of the tasks that are performed, the environment it is carried out in, and the potentially catastrophic consequences of failure. Furthermore, there are developments taking place in navigation technology and manning which are suspected to affect safety and human performance. This assumption is based on a limited amount of research on naval navigation accidents. Furthermore, there appears to be a scarcity of controlled research on navigation methods in ship navigation, and existing research has generally lacked objective measures of performance and workload. Finally, the changes in task characteristics associated with electronic chart-based navigation appeared to potentially increase the risk of performance decrements under sleep deprivation. Sleep deprivation is common in naval operations, and has been shown to be an important causal factor in a number of shipping accidents. On the basis of this, the following aims were formulated:

The **main aim** for this thesis was to examine human factors which may affect safety in naval high-speed ship navigation.

The specific aims included were:

- 1) To examine situation characteristics in a sample of navigation accidents in the RNoN in the period 1997-2005 [Paper I].
- 2) To evaluate differences between conventional, paper-chart based methods to electronic chart-based navigation in task performance and cognitive workload under neutral task conditions [Paper II].
- 3) To evaluate differences between conventional, paper-chart based methods to electronic chart-based navigation in task performance and cognitive workload under sleep deprivation [Paper III].

2. Materials and methods

2.1 Study samples

2.1.1 Sample of Paper I

In Paper I, the study sample consisted of all available accident investigation reports following navigation accidents in the RNoN in the period 1990-2005. This time period was chosen on the basis of availability; reports from before 1990 were generally not archived, and reports between 1990 and 1997 had mostly been lost - except for one accident, all of the reports were from between 1997 and 2005. The total number of accident reports was 35, of which 24 were full accident investigation reports and 11 were self-reported incident reports. Most ($n=33$) of the accidents were groundings.

2.1.2 Sample of Paper II

In Paper II, the study sample consisted of 20 cadets (17 male, 3 female) at the Royal Norwegian Naval Academy (RNoNA), who were recruited by invitation. All but one of the cadets were in their third and final year as cadets; at the completion of their training they would be licensed navigators. The cadets were recruited on the basis of having approximately the same level of experience with paper chart- and ECDIS-based navigation. Their actual ship navigation experience ranged from 10 to 275 hours (mean = 76,3, SD = 79,3) and their simulator navigation experience ranged from 3 to 37 hours (mean = 14, SD = 4,8).

2.1.3 Sample of Paper III

In Paper III, two separate study weeks were planned. The total study sample consisted of 13 FPB navigators. The participants were recruited by invitation from the RNoN 22nd and Skjold FPB squadrons. All of the participants were male, and had an average of 23 months experience as FPB navigators (range 1-76, SD 22.1).

Since a number of the participants dropped out of the study between study weeks (due to a mission deployment), only five of them participated in both study weeks.

2.2 Study design

2.2.1 Study design of Paper I: Accident review

In order to gain an overview of the situational factors characterizing navigation accidents in the RNoN, a sample of recent major navigation accident investigation reports were analyzed. All available accident reports were obtained from various archives. Two types of situational factors were determined; 1) environmental factors (such as weather, visibility and time) and 2) performance-shaping factors (PSFs). The definition of a PSF is “a factor which influences the likelihood of an error occurring” (Kirwan 1998). PSFs are used as part of most types of human reliability assessment (HRA), on the basis that each individual PSF can have a negative effect on human task performance, without necessarily being the direct cause behind accidents. As there exist a large number of HRA methods, the PSFs used in this study were extracted from a total of 18 different HRA analysis methods and taxonomies. These were derived from a paper by Kim and Jung (2003), who followed the same approach in creating an accident taxonomy for nuclear emergency situations. Out of a total of 220 PSFs, 109 were found to be applicable to navigation accidents based on relevance, concordance with available data, and minimal overlap with other PSFs.

The accident investigation reports were not fully standardized with regard to investigation procedures or reporting, and were occasionally prone to competency bias from the investigators. Therefore, the study design used two main approaches to reduce bias and increase validity. First, the PSFs were scored individually by two separate reviewers, using a dichotomous scoring method (i.e. the PSF was present/not present). In cases where there was a discrepancy between the two reviewers' assessments, a final data set was reached through consensus. Second, only factual information from the accident investigation reports was used for the analysis. Thus,

conclusions and subjective assessments from the reports were not taken into consideration in the analysis.

2.2.2 Study design of Paper II: Navigation under normal conditions

A controlled simulator study was carried out in order to evaluate the effect of navigation method on workload and performance. Two methods were compared; one based on paper charts with a five-person team (two navigators and three conscripts), the other based on electronic charts with a two-person team (two navigators). In addition to navigation method, navigation difficulty was varied across four levels within each navigation session and used as an independent variable in the statistical analysis. Since we only had access to each participant for one day - they were not allowed to miss their normal training for longer - the participants were randomly assigned to either the paper chart group or the electronic chart group. Furthermore, because FPB navigation is performed by working in pairs (by a navigator and navigation assistant), the participants were assigned to only one of these two roles based on their prior navigation experience. The study was performed for the purpose of research, and was not part of the cadets' normal training.

The experimental set-up was meant to have a high degree of task fidelity, so the simulator sessions were carried out so that they would represent real navigation exercises on Hawk- and Skjold-class FPBs. This included holding a realistic task briefing, and allowing the participants to plan the actual navigation courses themselves according to a general route provided to them. However, since we were only interested in comparing differences between the actual navigation methods, and not the two ship types, speed and hydrodynamic characteristics were kept the same between the two ship types. Furthermore, operating conditions were kept "neutral" by not adding any additional stressors such as sleep deprivation, inclement weather or equipment failures.

2.2.3 Study design of Paper III: Navigation under sleep deprivation

The third study was also designed as a controlled simulator study, which compared electronic chart- and paper chart-based FPB navigation. However, a full repeated-measures design was employed in this study, with all participants performing both navigation types and in both navigation roles. Furthermore, an added factor was introduced by subjecting the participants to approximately 60 hours of total sleep deprivation. This was carried out by having the participants perform two three-day experimental sessions, with ten navigation courses in each session. To avoid carry-over effects from sleep deprivation, a ten-week washout period was held between the experimental sessions. In order to maximise realism and avoid withdrawal effects, caffeine and tobacco consumption was allowed, limited to normal daily consumption (as determined from questionnaire information gathered at recruitment). To compensate for learning effects, a crossover design was employed, with half of the participants navigating with one of the two navigation methods in the first week, and switching these in the second week.

Figure 7. Polaris simulator (Kongsberg Maritime AS, Horten, Norway) used in Papers II and III.



The navigation sessions were performed using five identical fixed-base, full-scale Polaris simulators (Kongsberg Maritime AS, Horten, Norway). Skjold- and Hauk-class FPB simulator models were used, with hydrodynamic and performance characteristics similar to the real vessels. All bridges had a generic layout, with a 270 degree view-field (180 degrees forward view, 90 degree aft). The ECDIS system was a SeaMap™ 10 (Kongsberg Maritime AS, Horten, Norway) with S57 (Primar, Stavanger, Norway) and CM-93 edition 3 charts (C-MAP AS, Egersund, Norway). The simulator was programmed to have 70% simulator noise, external light representing “dusk” (85% darkness) and 10% rain. “Dusk” conditions were those which were reported to be visually most similar to actual navigation, while allowing the use of optical navigation principles and being challenging.

2.3 Measurements used in Papers II and III

2.3.1 Navigation performance measures

Cross-track error

Cross-track error (XTE) was calculated as the deviation of the vessel relative to its planned course, and was used as the primary navigation performance variable in Paper II and III. XTE is one of the most common performance metrics in studies on navigation performance, and has been used in previous human factors studies on ship navigation (Donderi et al. 2004; Lohrenz 2003).

The XTE was defined as the perpendicular distance between the participants' planned route and the actual track from the simulator GPS receiver:

$$\text{XTE} = \text{ABS} [(YE-YS)(X2M)(Y2M)(XP-XS) - (XE-XS)(X2M)(Y2M)(YP-YS)] / \\ \text{SQRT} [(X2M(XE-XS))^2 + (Y2M(YE-YS))^2]$$

Where (XP, YP) = longitude (X) and latitude (Y) of the GPS point along the actual track,

(XS, YS) = longitude and latitude of the starting point of the planned route segment,

(XE, YE) = longitude and latitude of the ending point of the planned route segment,

X2M = constant to convert longitude into meters (for the average latitude of the course),

Y2M = constant to convert latitude into meters (which is independent of longitude).

In papers II and III, XTE was calculated manually using the simulator track log (sampled at a rate of 2Hz) and the planned route from the ECDIS. Turns were removed from the calculation, with a cutoff starting two cables (0.2 nautical miles, or 370.4 m) before and ending two cables after each turn. Mean XTE values were calculated for each participant for the period he acted as navigator in each simulator navigation session. The analyses were performed using Microsoft Excel (Paper II) and Java (Paper III).

Overshot turns

Sailing past the turning point at the end of each course leg is described as “overshooting”. FPBs should generally not overshoot turns, since this may involve loss of control, and risk of grounding or collision (Bjørkli et al. 2007). We registered

the number of overshoot turns in Paper III, as a supplement to measuring XTE. This was calculated as the ratio of overshoot turns to correct turns in each run, or “percentage of turns which were overshoot”.

Expert assessment

In Paper II, navigation performance was also evaluated by two navigation experts, using the Targeted Acceptable Responses to Generated Events or Tasks (TARGETS) method (Fowlkes et al. 1994). The method was used by separately evaluating task-generated and event-generated activities. Task-generated activities were defined as “observable safety-critical navigation tasks”, e.g. communicating observed navigation objects. The event-generated activities were defined as “responses to external objects”, which in this case was “safe passing of oncoming ships and stationary barges”. Unsafe passing was classified as a distance violation (passing too close) or a speed violation (not adjusting speed properly). The task-based activities were registered each time one was performed, while the event-based activities were registered as “acceptable” or “unacceptable” responses. The criteria for “acceptable” or “unacceptable” responses were defined by the navigation instructors prior to the study.

2.3.2 Psychophysiological measures

Skin conductance (SC)

As a measure of sympathetic activation, tonic SC levels were recorded during the simulator sessions described in Paper II using VU-AMS36 portable loggers (Vrije Universiteit Amsterdam, Department of Psychophysiology, Amsterdam, The Netherlands). This measure was used as an indicator of cognitive workload, since skin conductance level has reliably been found to change with workload variations (Collet et al. 2003). Analyses were carried out by subtracting the baseline values from the mean values for each leg of the simulator session, using proprietary AMSGRA software. Artifacts were identified using visual inspection, and removed manually.

Heart rate variability (HRV)

HRV was recorded as a measure of sympathetic-parasympathetic activation, which was used as both an indicator of cognitive workload (in Paper II and III) and of general arousal (in Paper III). There is ample evidence that frequency domain measures of HRV are reliable indicators of workload (Boucsein & Backs 2000) pp 12-14. In Paper II, R-R intervals were recorded during simulator sessions using VU-AMS36 portable loggers (Vrije Universiteit Amsterdam, Department of Psychophysiology, Amsterdam, The Netherlands). In Paper III, R-R intervals were recorded with ambulatory Embla A10 device (Medcare, Reykjavik, Iceland) while the participants were performing the navigator role, and with Polar S-810 heart rate monitor (Polar Electro Oy, Kempele, Finland) while performing the executive officer role. Signal artifacts were identified by visual inspection, and by using an automated detection method (Xu & Schuckers 2001). In Paper III, where possible, artifacts were corrected with an algorithm based on a method described by Berntson et al. (1990). Intervals that could not be corrected were removed.

Spectral analysis was performed in both papers using HRV Analysis Software for Windows v.1.1 (Niskanen et al. 2004) with a linear detrending method (Tarvainen, Ranta-Aho, & Karjalainen 2002). Analyses were carried out by measuring parasympathetic activation as high frequency-band power (0.15-0.4 Hz, in normalized units) and sympathetic activation as low-frequency band power (0.04-0.15 Hz, in normalized units), based on a fast Fourier transform of the R-R interval data. The LF/HF ratio was analyzed as measure of parasympathetic-sympathetic activity balance (Camm et al. 1996). Two sets of analyses were performed on the HRV data in Paper III: One using raw values from the simulator sessions, and another with resting baseline measurements subtracted from the simulator session measurement. Standing baseline measurements were subtracted from standing simulator tasks (during Hawk/paper-chart navigation) and sitting baseline measurements were subtracted from sitting simulator tasks (during Skjold/ECDIS navigation). The first analysis was performed to determine the absolute parasympathetic-sympathetic activity balance in the two navigation methods, while

the second was corrected for effects from body posture. In Paper II, only the corrected values were analyzed.

Electroencephalography (EEG) and electrooculography (EOG)

In Paper III, ambulatory EEG and EOG was used to measure sleep episodes during navigation, with an Embla A10 device (Medcare, Reykjavik, Iceland). EEG and EOG measurements were scored manually, using the vigilance scoring system described by Sallinen et al. (Sallinen et al. 2004). With this method, recordings were divided into 20-second epochs, and categorized in one of the following categories: 1) Wakefulness, 2) Drowsiness indicated by slow eye movements accompanied by theta activity of <5s period in EEG, 3) Microsleep indicated by theta activity for 5 to <10s in EEG, and 4) stage 1 sleep denoted by theta activity for at least a 10-s period in EEG. In the present study, the categories were dichotomized into “wake” (category 1) or “non-wake” (category 2-4) periods. The percentage of non-wake epochs in each simulator session was used as outcome variable for the statistical analysis.

Fitness Impairment Test (FIT)

A mobile Fitness Impairment Tester (FIT 2000-3, PMI Inc, Rockville, MD) was used in Paper III to measure four oculomotor indicators of sleepiness: Peak saccadic velocity, initial pupil diameter, pupil-constriction latency, and pupil-constriction amplitude (Rowland et al. 2005). The purpose of performing these tests was to examine if baseline and progressive sleepiness differed between study weeks, independent of which navigation method was being used.

2.3.3 Subjective measures

Subjective workload

In both studies, a computer-based version of the NASA-TLX index (Hart & Staveland 1988) was used to measure self-reported workload. The method was used because it discriminates between different dimensions of perceived workload, in addition to being validated. In Paper II, the subjects also rated the workload dimensions’ relative importance (weighting). Since unweighted values have been

shown to correlate strongly (0.97) with weighted values (Noyes & Bruneau 2007), only these were used in Paper III.

Subjective sleepiness

The Karolinska Sleepiness Scale was used as a subjective measure of sleepiness in Paper III. The KSS is a validated index of subjective sleepiness, which has been found to be strongly related to EEG and EOG measures (Gillberg, Kecklund, & Akerstedt 1994).

2.4 Statistical analyses

2.4.1 Statistical analyses used in Paper I

Cluster analysis

The PSF variables in Paper I were analyzed using binomial hierarchical cluster analysis (Everitt 1993). The purpose behind performing the cluster analysis was to evaluate the presence of patterns in accident circumstances. The method works by hierarchically categorizing variables according to their similarity, based on the number of matching, positive cases. The optimal number of clusters was determined by visually finding the largest distance between cluster levels in the hierarchy. The analyses in Paper I were performed using SPSS 12.0 software (SPSS, Inc. 2003).

2.4.2 Statistical analyses used in Papers II and III

T-tests

In both Paper II and III, background variables were compared using paired-samples *t*-tests; all variables were tested for the assumption of homogeneity of variance. These tests were mainly performed to verify that there were no significant differences in background characteristics between groups.

Mixed-model analysis of variance

In both Paper II and III, most other outcome variables were analyzed using linear mixed-model analysis of variance, using a restricted maximum likelihood function, as suggested by Van Dongen et al. (2004b), but using the AR(1) covariance method.

This method was chosen, since it allowed maximum use of repeated-measures data, as well as being robust against inter-individual variance. In order to model circadian rhythm effects in Paper III, a third-order polynomial time variable was added, denoted as time^3 .

In Paper II, navigation method as between-subjects factor, and course difficulty was used as within-subjects factor. In Paper III, navigation method was also used as between-subjects factor, but time and time^3 were used as within-subjects factors. The analyses in Papers II and III were carried out using SPSS 14.0 software (SPSS, Inc. 2006).

2.4.3 Research ethics

The accident reports analyzed in Paper I were kept locked in a safe location, and were returned to the RNoN after the completion of the study. All identifiable information for the ships and personnel involved was removed from the data set prior to the analysis. The studies described in Papers II and III both adhered to the Declaration of Helsinki. The participants were informed about the objectives and conditions of the study, and participation was voluntary. Informed written consent was obtained from all participants prior to beginning the studies. A physician was on call throughout both studies, in case of discomfort or adverse health reactions in any of the participants. The study protocols were approved by the Regional Committee for Medical Research Ethics, Western Norway, and the Norwegian Social Science Data Services. The participants were paid by the RNoN according to normal wage regulations for participating in both studies. After the completion of the project, raw data and result files have been stored in a secure, locked archive.

3. Summary of results

3.1 Paper I

Accident investigation reports following 35 RNoN navigation accidents in the period 1990-2005 were analyzed. More than half of the vessels involved were high-speed craft, 40% were fast patrol boats. Nearly all of the accidents (94%) were groundings that did not lead to personal injury. The accidents were evenly distributed between time of day, season and weather conditions. Few accidents (16%) occurred in reduced-visibility conditions. Around half of the accidents (54%) occurred during training exercises. A total of 109 performance-shaping factors (PSFs) were scored. The most commonly identified PSFs among these were “operator expectations”, “high perceptual demands”, “attention”, “anticipatory requirements”, and “lack of operator experience”. There was an average of 18 PSFs identified in each accident. The cluster analyses showed that the PSFs could be grouped into eight categories, where the largest of these were “demand-capability balance” and “work organization and distribution”.

3.2 Paper II

The study behind Paper II compared FPB navigation based on paper charts and ECDIS, with student navigators operating simulators under normal task conditions. Navigation performance (measured as cross-track error) was found to be significantly better in the ECDIS navigation teams compared to the paper-chart teams, with a mean XTE of 49m in the ECDIS groups and 104m in the paper-chart groups. There was no difference between the two teams in expert-evaluated performance, measured as correct responses to pre-planned navigation tasks. The total amount of navigation-related communication was significantly lower in the ECDIS teams, although the differences were largest for communication actions nonessential to ECDIS navigation. Subjective and psychophysiological measurements did not indicate any differences in mental workload between navigation methods. A tendency towards

higher mental workload in the paper-chart navigation condition was observed in the heart rate variability measurements, indicated by higher sympathetic activation. The overall subjective workload was determined to be low by participants in both navigation conditions.

3.3 Paper III

The study behind Paper III also compared navigation based on use of ECDIS and paper charts, but used sleep deprivation as an additional variable. Navigation performance was significantly better in the electronic-chart condition, but was not significantly affected by sleep deprivation in either navigation method. There was a significant interaction between speed, sleep deprivation and navigation method, indicating that navigators using ECDIS reduced their speed proportionally more during periods of high sleepiness. Secondary task performance was significantly reduced by sleep deprivation, but was equally affected in both conditions. Mental workload was significantly higher in the ECDIS condition, as indicated by subjective ratings and heart rate variability. No significant differences in subjective sleepiness were found between navigation methods, but electroencephalographic recordings pointed towards a higher incidence of microsleep episodes in the ECDIS condition after 52 hours of sleep deprivation.

4. Discussion

4.1 Methodological discussion

4.1.1 Paper I

Materials

The results in Paper I were built on data from accident reports following navigation accidents in the RNoN. These were either based on internal investigation commissions (following accidents) or self-reports by commanding officers (following incidents). Both types of reports had some weaknesses, which are inherent to post-hoc accident studies. Most importantly, the reports were written in natural language, and often invoked terms such as “workload” and “error”. Since these terms are ambiguous, inconsistent and rarely defined, it could sometimes be difficult to interpret behind the reasoning and the conclusions drawn in the reports (Johnson 2000). This is a well-known problem in analyses of such reports. As a consequence, we attempted to base our analysis mainly on factual information in the reports, and to ignore the subjective evaluations expressed in the accident reports.

It was also apparent that there was some degree of competency bias in the reports, since they varied in detail and focus. The investigative process may have been influenced by the committee members’ competencies, concerns and experience, possibly causing differential misclassification (Drury 1995). This kind of difficulty is frequently encountered in archival accident studies (Kirkland et al. 2003). While this may have influenced the level of detail in the reports, it could also be that the precision and length of the reports were influenced by the severity of the accident. In the present study, this may have led to some skewing of the results according to ship type, since accidents with smaller vessels generally are less expensive, thus resulting in incident reports rather than more thorough accident investigation reports (accident cost is a primary criteria for instigating an accident investigation). The availability of the incident reports was no different than to investigation reports for the time period included, however, so there was no selection effect with regard to ship type. Every

effort was made to locate available reports from relevant archives, so although the total number of reports investigated was relatively low, the data set can be assumed to be nearly complete for the period 1997-2005. It is possible that the report from 1990 should have been omitted, but was included on the basis that there were no major differences in navigation equipment or procedures at the time of the accident compared to the later accidents.

Methods

The concept and use of PSFs is central to human reliability assessment (HRA). Yet, PSFs are employed differently in different methods and studies. While most HRA methods use PSFs to quantify risk of human error (Kirwan 1998), our approach was merely to identify the PSFs without quantifying their effect. Since it is a basic assumption that PSFs differ in their effect on human performance, this indicated that the detail level in this study was low in assessing the relative influence of each individual PSF. However, it is also assumed that there is a considerable range in the magnitude of effects of various PSFs, according to individual characteristics and the situation (Park & Jung 1996). This makes it difficult to precisely determine PSF effects without having direct access to the persons who were involved in the accident. This was not possible in the present study, since the personnel involved were unavailable.

Although we did not determine the effect of each PSF in an accident, we did assess a large number of PSFs on a dichotomous level (present/not present). PSFs relevant to ship navigation were drawn from a large number of HRA methods and taxonomies, since we did not find any one method entirely suitable for this context. This approach emphasized breadth over depth, since the overall goal of Paper I was to “describe the situational context in which naval navigation accidents have occurred”. While a number of previous accident studies have focused on specific issues, such as use of radio communications (De Voogt & Van Doorn 2006), errors of memory (Shorrock 2005) or errors of perception (Shorrock 2007), our study did not intend to limit itself to one topic, but extended its focus across the full range of factors known to influence human performance.

No attempt was made to identify causal factors, but rather situational factors, since “causal” and “contributory” factors are in practice impossible to separate (Dekker 2002). The threshold for scoring a PSF as “present” was therefore not very high. As a result, it is likely that many of the PSFs identified were not unique to the accident situation, but would also be present in most normal RNoN navigation situations. An example of this could be the PSF “level of experience” (found in 56% of the accidents), due to the fact that the navigator on a naval ship is almost always in a training role. However, we think this approach was the best suited to assess all possible factors of importance.

Paper I was an exploratory study, mainly intended as a baseline study of navigation accidents in the RNoN. Due to the sample size being relatively small, no inferential statistics could be carried out. However, since we had a high number and wide range of PSFs, we wished to examine if these were systematically connected in our data set. This was performed by using binomial hierarchical cluster analysis (Everitt 1993), which is a statistical method used to identify “clusters” of categorical variables. This method has been used in previous accident studies on shipping (Le Blanc, Hashemi, & Rucks 2001; LeBlanc & Rucks 1996), but with a focus directed more towards weather and other environmental conditions. Cluster analysis proved useful in identifying patterns in the PSFs in the data. We named the two most prevalent clusters “demand-capability balance” and “work organization and distribution”. However, illustrating a major weakness of cluster analysis, it is not clear whether the clusters can be generalized beyond the data set the analysis was performed on (Everitt 1993). This was not a major problem in this study however, since all accidents for the period 1997-2005 were included. Furthermore, the analysis does not show strength of association, so there was no way of knowing which PSFs were most strongly connected. An alternative to this would have been to factor-analyse the variables; this was not possible due to the size of the data set, unfortunately.

4.1.2 Papers II and III

Materials

The studies described in Papers II and III both involved skilled participants, using navigator cadets and experienced FPB navigators respectively. Since both groups were recruited from limited populations, the samples were small, and not entirely homogenous with regard to e.g. prior experience or sleep characteristics. Using a larger sample would have improved statistical power, but was not feasible due to availability of participants and simulator time. FPB navigation is a complex and demanding task, requiring extensive and specific training. An alternative of using e.g. civilian navigators would therefore not achieve the same validity. Other studies have used e.g. trained students (Hockey 2003), but have used a PC-based task with very low realism.

Using navigator cadets in one and experienced navigators in the other study was a deliberate choice, in order to achieve different goals. Since the cadets were trained, but equally inexperienced in using the two navigation methods, this reduced experience effects when comparing the two methods in Paper II. However, it has been shown that experienced and inexperienced operators are affected differently while performing tasks under high workload and fatigue (Lenne, Triggs, & Redman 1998), and utilize different strategies in executing them (Bellenkes, Wickens, & Kramer 1997; Parasuraman & Hancock 2001). Using experienced navigators in Paper III was therefore considered necessary to assess the navigation methods' sensitivity to sleep deprivation with adequate validity. It is a possible weakness that personality data were not gathered in either of the studies. Although this factor may have influenced e.g. susceptibility to sleep deprivation (Killgore et al. 2007), it was not expected to be a problem. The participants were selected to their positions in the RNoN partially on account of having good physical and mental health, and had been subjected to psychological tests on multiple previous occasions.

The simulators we used were advanced, and had to be run by experts throughout both simulator studies. Demand for simulator time was high, and had to

be planned a long time in advance. Performing the studies in these simulators with skilled participants was heavily resource-demanding, and also created some restrictions in the number of weeks we were able to perform measurements. This had a determining effect on our study design and sample size. A study based on e.g. a PC-based task with regular students would have allowed a larger number of study design options, but would have negatively influenced validity.

Methods

Papers II and III were both based on results from simulator studies. The study described in Paper II had a between-groups design, due to time restrictions. Although participants were balanced between groups according to experience, this design had considerable weaknesses with regard to statistical power, as well as not fully controlling for individual differences. This was improved upon in Paper III, where a counterbalanced repeated-measures design was employed. However, statistical power was still low, and might have caused type II-errors in our study. On the other hand, despite the low numbers, some significant results were found.

While the navigation simulators we used were advanced and had a high level of fidelity, simulators are always only an imitation of reality. Their ability to recreate actual operational conditions will therefore never be complete. A simulator system can be said to have three main components: a model, equipment, and a software application (Stanton 1996). In our studies, the model was a mathematical software representation of the two vessel types being navigated. In the study described in Paper II, the same model (of the Hauk-class FPB) was used in both study conditions, while different models were used for the two groups was used in Paper III. The model of the ship does not relate to its physical appearance, but instead comprises factors such the ship's propulsion and hydrodynamic qualities. While the models approximated the ships closely, the participants reported that the simulator behaved somewhat differently than a real FPB, especially during navigation at low speeds. The simulator bridge had a generic design, but was equipped with mostly the same navigation equipment as in the real vessels. Visually, the biggest shortcoming of the simulators was the representation navigation lights, which appeared almost the same

size regardless of distance. The simulators did not allow motion, but provided otherwise high physical fidelity. Finally, it should be pointed out that the simulators' primary application was navigation, and were thus well suited for our use.

We were not able to compare results from our simulator studies with field data, but studies evaluating simulator with real operations have been carried out in similar domains. Magnusson (2002) compared bomber pilots' physiological reactions with HRV during real and simulated missions, and found that HRV patterns closely approximated each other, although absolute levels differed between conditions. In a similar study by Veltman (2002) it was also found that HRV patterns were contiguous in simulated and real flight, while cortisol levels were not elevated in simulator flight. This led the authors to conclude that while mental effort was the same in both conditions, higher G-forces caused the increase in cortisol under actual flight. Finally, an important study was performed by Caldwell and Roberts (2000) comparing effects of 40 hours total sleep deprivation on performance in real and simulated helicopter flight, with or without a pharmacological stimulant (dextroamphetamine, or "Dexedrine"). Their results showed that pilots' performance decrements under sleep deprivation were considerably lower in real flight, where the pharmacological agent also showed comparatively less effect than in the simulator. This suggests that simulator tasks may be able to evoke comparable levels of workload as in real life, but are less stimulating. It seems likely that the motivation for exerting maximal performance is higher when sailing between real rocks compared to computer-generated ones.

One of the greatest challenges in simulator studies is finding appropriate performance measures. As a field, *human factors* distinguishes itself from e.g. experimental psychology by emphasizing the use of actual system performance parameters rather than standardized tests. In this project, this was done by measuring subjective measures of navigation performance with the TARGETS method (in Paper II) as well as objective measures such as overshooting (in Paper III) and cross-track error (in Paper II and III). The TARGETS method is based on using expert observers to quantify positive actions (or "behaviors") carried out by a team, which are pre-

defined for an operationally relevant task. The method has been used mainly in military contexts (Dwyer et al. 1997), but also in settings such as airplane operation (Brannick, Prince, & Salas 2005) and emergency management (Schaaftal, Johnston, & Oser 2001). This method has its strongest advantage in that it reduces subjectivity in expert-based assessment, since the expected behaviors (both positive and negative) have been pre-defined. Furthermore, the method is team-oriented. This is essential in the context of FPB navigation, where performance is not only a result of the individual navigator's efforts, but the collective effort of the entire team. Finally, the method has been shown to exhibit high interobserver reliability, which is a common problem in observational methods (Fowlkes et al. 1994). Our results showed that the greatest differences in team behaviors between the two methods were found in communication actions, such as "identify and communicate navigation landmarks" and "communicate next course and distance to turn". While these actions are critical to safe performance in conventional FPB navigation, it could be argued that they are not strictly necessary in ECDIS-based navigation. Others have even argued that communication may have a hidden "cost" that is detrimental to overall performance (Serfaty, Entin, & Johnston 1998). Therefore, it may have been a weakness in the use of the TARGETS method that it compared the two navigation methods on some variables that were of different criticality. Therefore, this measure was not included in the second simulator study (Paper III).

XTE was the only objective navigation performance measure used in Paper II, but was supplemented by recording overshoot turns in Paper III. While XTE has been used in some prior studies (Donderi et al. 2004), there has not been established a common measure of ship navigation performance. XTE alone is arguably insufficient as a measure of safety in ship navigation, especially where waters vary in size and ship traffic. A number of the accidents reviewed in Paper I involved manoeuvring errors made in turns, but rarely errors made during straight legs. Overshooting the turning point was therefore chosen as an additional performance measure, since this has previously been shown to involve loss of control, and risk of grounding or collision (Bjørkli et al. 2007). As evaluative measures, these measures could not stand alone, however, since they only reflected primary task performance. A

secondary observation task was therefore added to the study described in Paper III, in order to evaluate reserve performance capacity. Many studies (e.g. Sauer et al. 2002) using secondary tasks have examined these as performed on an individual basis, with tasks that are not entirely relevant, but are easily measurable (e.g. a temperature gauge that needs to be constantly regulated). Instead, this study used a team-based task, consisting of observing and recording external ships, with a high degree of realism. The disadvantage of this approach was that the measurement lacked specificity, since the performance of the individual navigator was not measured as much as the whole team. The advantage, however, was higher ecological validity, since FPB navigation in real life is indeed performed by teams, and not individuals. Furthermore, performance measures only reflect outcomes specific to the operational scenario used, but does not provide information about the demands of the actions leading to them (Fahrenberg & Wientjes 2000). For this reason, it was necessary to also assess factors such as workload and sleepiness.

Measurements of workload and sleepiness were performed using both subjective methods and psychophysiological methods. The “triangulated” approach of combining performance measures, subjective measures and psychophysiological recordings has been recommended by Wierwille and Eggemeier (1993), and has been used in a considerable number of simulator studies as far back as World War II, particularly in studies of automobile and aircraft operation (Boucsein & Backs 2000). Measuring both subjective and psychophysiological workload indices has a number of advantages. Subjective measures such as the NASA Task Load Index, the Swedish Occupational Fatigue Inventory and the Karolinska Sleepiness Scale reflect the operators’ feeling of workload, fatigue and sleepiness, and should therefore have high face validity. However, these methods are intrusive, and do not measure continuously. In demanding cognitive tasks such as FPB navigation, psychophysiological measures (such as the ones used in our study) have a strong advantage in that they do not require an overt response, and provide an objective, continuous measure of workload (Sirevaag et al. 1993). The methods used in the present study – skin conductance, heart rate variability and electroencephalography –

are advantageous in that they can be recorded using ambulatory measuring equipment, which is necessary in a task such as ship navigation. The biggest disadvantages of using these methods in such an uncontrolled environment, however, are recording artefacts and task-related measurement error. Skin conductance recordings from the fingers can in some cases be affected by pressure artefacts from performing manual tasks, or can be affected by changes in ambient temperature (Fahrenberg & Wientjes 2000). Neither of these were major problems in Paper II, but skin conductance was not used in Paper III because it was considered too uncomfortable over a long period of time for the participants. HRV can be affected by verbalization (Bernardi et al. 2000) and posture (Fortrat, Yamamoto, & Hughson 1997), both fairly uncontrollable in a realistic navigation setting. It is therefore apparent that the higher realism in our studies is to some degree accompanied by shortcomings in internal validity, due to the complexity of effects and presence of confounding variables.

4.2 General discussion

4.2.1 Characteristics of naval ship accidents

Naval ship navigation poses task demands that are quite different from those encountered in civilian transportation. Since the ships are usually training for or in combat situations, the threshold for what is considered safe is shifted upwards. This was clearly reflected in the results presented in Paper I. Groundings occurred in waters civilian ships probably would not enter, sailing at speeds civilian ships almost certainly would not be moving at. The largest cluster of PSFs identified was titled “demand-capability balance”, which characterized a large part of the problem: That navigators were required to perform tasks with high cognitive and perceptual demands, while having limited resources in the form of e.g. error margin and rest.

The sources of the task demands varied, however. Environmental factors such as poor weather and darkness did not appear to be a predominant characteristic of the accidents, which were evenly dispersed between night and day and between good and

poor visibility. This is a common finding in traffic research, and is usually attributed to the phenomenon of risk compensation – that an increase in safety from e.g. better visibility is counteracted by an increase in performance aims (i.e. for speed) (Wagenaar 1992). An environmental characteristic of greater importance to naval ship accidents in Norway was geography, or the difficulty of the waters that the ships sailed in. This could not be seen in background data from the accident reports, but was apparent in that nearly all accidents were groundings (94%). This is contrast to accident data from other parts of the world, where geography is not as much a challenge as heavy traffic, resulting in a higher proportion of collisions (Chauvin & Lardjane 2008).

Common to all ship navigation, however, is a high degree of uncertainty, dynamism and complexity (Norros 2004). This is reflected in the uncertainty of the waters and other ship traffic, the dynamism of the navigation task, and the complexity of the sociotechnical system on the bridge. Following uncertainty, the aspect of dynamism was also clearly shown in the accident situations analyzed in Paper I. The navigators frequently encountered unexpected situations, were not attentive to or did not perceive critical information, and were forced to make critical decisions with little available time. Factors such as predictability and available time separate much of naval ship navigation from civilian merchant ships, where movement usually is slower and monitoring constitutes a larger part of the task. Finally, there was the complexity of a multiple-person navigation team, often working aboard a complex technological bridge comprising a number of advanced navigation aids. Since human-machine interaction on ships first was recognized as a challenge in the early 1970s (Brigham 1972; Lazet & Walraven 1971), ships' performance and speed have increased together with the amount of technology on the bridge. This has had the consequence of adding to the amount of information that must be mentally integrated by the navigator (Lützhöft 2004), while increasing the potential consequences of an accident.

The findings from the accident study described in Paper I were partially used to guide the development of the studies performed in Papers II and III. Both prior

research (Hockey et al. 2003; Leung et al. 2006) and the findings in Paper I provided evidence for the role of both high workload and fatigue in accident situations.

However, while Paper I analyzed the characteristics navigation accidents in hindsight, the studies in Papers II and III focused on the effects of navigation characteristics of the future. It is interesting to note that while the accident data showed *high* cognitive workload to be a problem, the simulator studies indicated that *low* workload were a potentially larger problem with new navigation methods. Therefore, it seems likely that future studies of navigation accidents may show a somewhat different picture than that seen in the present study.

4.2.2 Influence of navigation method on navigation performance

Results showed that ECDIS improved navigation performance in both simulator studies. This was reflected in both higher precision and fewer overshoots, while secondary task performance was no worse affected than in the conventional navigation method. Among the possible explanations for this, there are two which seem likely, at two different sociotechnical levels. At the individual human-machine level, ECDIS simplifies the navigator's task of position-finding and route-keeping, by continuously presenting the ship's position and planned route on the display. This simplifies the cognitive mapping and decision-making processes described by Chen and Stanney (1999), but at the same time does not eliminate the navigator from these processes. Considering the range of automation levels presented by Parasuraman, Sheridan and Wickens (2000), ECDIS should be classified near the low end ("the computer offers a complete set of decision/action alternatives"). Therefore, it may appear that ECDIS offers many of the benefits of automation, while avoiding problems such as "keeping the operator out of the loop" described in studies of automation in other contexts (Parasuraman 2000). FPB navigation is characterized by variation and rapid change of work conditions, and is therefore in many ways different from supervisory systems found in e.g. process control (Bjørkli, Øvergård, Røed, & Hoff 2007). The findings from our study therefore indicate that the level of automation found in the ECDIS navigation method we used were appropriate for FPB navigation.

A second reason for why ECDIS improved performance might be found on the team level. Conventional FPB navigation is very dependent on precise and frequent communication, and therefore involves a high coordination cost for the navigators. This has been shown to impede performance in team tasks (Serfaty, Entin, & Johnston 1998). In a war situation, high team coordination requirements have been shown to add to the risk of performance breakdown (Wilson et al. 2007). Furthermore, the findings from Paper I showed that PSFs such as clearness in responsibility, [lack of] team cohesion and [lack of] team cooperation were present in a number of accident scenarios. Using ECDIS is likely to reduce the need for coordination, and eliminates the potential for error from the plotter and helmsman, which both could have serious consequences. These roles are normally filled by conscripts with limited experience, increasing the need for the navigators to verify their actions. At the same time, there are still two navigators present in the ECDIS method (as employed on the Skjold-class LCS), so the control function of a second person is maintained.

These findings should be interpreted with caution. First, a prerequisite for using ECDIS is that the system must be trusted by its users. It has been shown that a major problem in implementing technological navigation aids is that they are prone to failure when they are needed the most: In high-stress, difficult situations, and where the consequences of them failing are greatest (Lützhöft 2004). As a consequence, their perceived unreliability has led to lack of user acceptance among some navigators (Mills 2007). The role of trust is essential in any human use of automation, in that users must know when they can trust that the information they are presented is correct, and when it must be double-checked (Parasuraman & Riley 1997). Furthermore, automated systems in e.g. flight decks have been reported in both research and accident reports to sometimes give the operators “surprises” in the form of unwanted or unexpected actions (Sarter & Woods 1997). In the studies described in Papers II and III, the participants navigated in simulators, and could therefore assume that equipment failure would not affect them. Furthermore, the navigators in this study were not allowed to use ECDIS in track-pilot mode, i.e. where navigation

is fully automated (“the ship sails itself”). This is likely to have affected both performance and workload, and should be investigated in future research.

4.2.3 Influence of navigation method on navigator workload and sleepiness

The reason for examining the level of mental workload in the two navigation methods came from the results from Paper I, which identified an imbalance between navigator demands and resources as a problem. In Paper II, a significant difference in neither subjective nor psychophysiological indicators of MWL was found. This could be a result of the results being range-limited, in that the navigation task simply was not demanding enough to show a difference. In the second simulator study (Paper III), speed was differentiated between the two navigation methods, according to the sailing characteristics of the Hauk-class FPB and Skjold-class LCS. This study showed that ECDIS-based navigation involved significantly higher subjective and psychophysiological indicated workload, throughout the study.

The biggest question following this result is whether the heightened workload constitutes a problem. Excessively high workload has been repeatedly been shown to impair performance (Matthews et al. 2006 p.87-106), and low workload has been shown to reduce attentional capacity (Young & Stanton 2002b). So where on this scale can conventional and ECDIS-based FPB navigation be found? The navigation performance results do not suggest that workload levels experienced by navigators using either system were excessive. However, this statement is only valid for the task conditions used in this simulator study. In actual operations, there could be additional parallel tasks, which is likely to increase workload further (Wickens 2002). In addition, the effect of operating under war conditions is likely to have an additionally detrimental effect on performance (Lieberman et al. 2005), driving demands closer to the capacity limits of the navigators. The implications of this might be that future research should look at the ability of ECDIS teams to perform multiple tasks, with regards to factors such as time-sharing and selective attention. Finally, difficult weather was not a factor in the simulator studies. Off the coast of Norway, this can often place high demands on navigation.

Sleep deprivation did not significantly impede primary task performance in either navigation methods in Paper III. This finding was not consistent with our hypothesis, but does have empirical support in earlier research. Real-world tasks such as fighter jet flight (Chelette et al. 1998) and thermal power plant operation (Gillberg et al. 2003) have been shown to be performed without significant decrements in earlier studies. The latter study had a high degree of task realism in its study design, which may be an important reason for the lack of performance impairment can in our simulator experiment. The participants were asked to perform navigation tasks in the same manner as on a real FPB, with a realistic secondary task as well. Moreover, the tasks were performed by teams, and compensatory measures such as drinking coffee were allowed. As a consequence, the degree of experimental control was lower than in many other sleep studies, where tasks are usually studied on an individual basis, and caffeine intake is usually not permitted. With regard to this, it is important to note that the study in Paper III was not meant to be a study on the effects of sleep deprivation per se, but rather how navigation with the two navigation methods was influence by extended wakefulness. As long as caffeine intake was not different between study weeks, this factor does not invalidate the results for this objective. Validity would probably have been lower in a comparative study under operating conditions totally different from those found on actual ships.

Both the workload and sleepiness results should also be treated with caution. The participants did not navigate legs longer than 55 minutes, which is considerably shorter than typical operations. Time-on-task has been show to have a strong negative effect on subjective fatigue (Richter et al. 2005) as well as performance (Johnson 1982) under sleep deprivation, particularly when performing vigilance tasks. Furthermore, the routes were designed to be equally challenging throughout the study, with routes passing through moderate-to-difficult geographical areas. In a situation with routes of lower complexity (long passages), the two methods may to a larger degree have been different in susceptibility to sleep deprivation effects.

While our results did not show strong evidence for it, there were indications that low arousal and sleepiness could be a problem in ECDIS navigation. Although

the relative HRV values showed higher arousal (sympathetic activation) using ECDIS, the absolute values showed higher arousal under conventional navigation. Arousal has been correlated with sleepiness, and is linked to both posture (higher in standing than sitting) and speech (increased with conversation) (Bonnet & Arand 1999). This may be an important factor, since ECDIS navigation usually is performed sitting, and conventional navigation standing. Although results were not significant, this was supported by our finding that microsleep events were more frequent in the ECDIS condition.

5. Conclusions

The main finding from the first study in this project (Paper I) was that navigation accidents in the RNoN involve a large number of performance-shaping factors, which almost always coincide with a number of other PSFs. It can therefore be assumed that these accidents almost always are multifactorial in origin, and that distinguishing causal from contributing factors is of little value. The PSFs identified were mainly related to the cognitive characteristics of the crew members, and the sensory and cognitive requirements of the tasks performed. However, the background data indicated that factors such as weather and visibility were of less significance in accident situations. The main implication of this study was that it provided a more comprehensive understanding of the factors involved in navigation accidents. This understanding could be used to improve navigator training, for example when carrying out simulator exercises.

The second study (Paper II) showed that ECDIS-based navigation improved navigation performance compared to paper chart-based navigation, without any significant differences in subjective or psychophysiological indices of mental workload. In addition, ECDIS-based navigation was shown to reduce the total amount of communication on the bridge. It can thus be concluded that ECDIS is likely to improve navigation performance under normal operating conditions, but that it will also change the nature of the task considerably. The third study (Paper III) followed up these results by showing that the performance improvement from ECDIS was upheld under up to 60 hours sleep deprivation, in higher sailing speeds, and with experienced FPB navigators. However, this study also found an increase in subjective and psychophysiological indices of mental workload in ECDIS navigation under higher sailing speed, but with no difference in sleepiness or secondary task performance. The lack of difference in sensitivity to sleep deprivation should be interpreted with caution though, since the EEG recordings showed a higher, but statistically insignificant, increase in microsleep episodes in ECDIS navigation.

The main implication of the two simulator studies is that the use of ECDIS-based navigation in naval high-speed ship operations should be considered safe, with some precautions. It appears that a smaller navigation crew is able to safely perform the navigation task with ECDIS at higher speeds, without excessively increased workload or susceptibility to sleepiness-related performance defects. However, this study examined a task considerably narrower than that the overall tasks performed by crew members on an FBP or LCS. As the *Skjold*-class has been deployed and is being phased into active duty, the results from these studies should be followed up by field studies under actual operative conditions. These should have special focus on the occurrence of microsleep episodes, including measurements of the supporting navigator, which were not performed in our study.

Mental workload assessment has previously played a major role in the decision to downsize flight decks from three to two crewmembers (by eliminating the flight engineer's position) in new aircraft, such as the Boeing 757/767 (Ruggerio & Fadden, 1987) and the KC-135 (Rueb, Vidulich & Hassoun 1994). In the first instance, the Federal Aviation Authority's decision to allow reduced manning was directly supported by a workload assessment of the two-crew design to ensure that the demands of flight tasks did not exceed the capacities of the two-person crew (Parasuraman, Sheridan & Wickens 2008). Therefore, the relative lack of differences found in workload and performance between navigation methods should not be considered inconsequential. ECDIS is a powerful navigation tool, and showing that the crew reduction it permits does not lead to increased workload is an important observation. While using ECDIS may have prevented some of the accidents analyzed in Paper I, others may have taken place because of this technology. As in aviation, there are a number of other possible automation-related side effects, which have not been fully addressed by this thesis. These include issues such as "skill fade", problems over time with automation trust, and communication-related mishaps. Navigation accidents will still happen in naval high-speed ship operations, hopefully less often, but probably with different characteristics. Being one of the first studies to examine the human consequences of transition to ECDIS-based navigation, this

project should thus be considered a starting block rather than a finishing line for this area of research.

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