CAMBRIDGE
UNIVERSITY PRESS

RESEARCH ARTICLE

Navigators' views of a collision avoidance decision support system for maritime navigation

Katie Aylward,[1]* Reto Weber,[1] Monica Lundh,[1] Scott N. MacKinnon,[1] and Joakim Dahlman[2]

[1] Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg, Sweden
[2] Swedish National Road and Transport Research Institute (VTI), Gothenburg, Sweden.
*Corresponding author: E-mail: katie.aylward@chalmers.se

Abstract

Maritime navigation is a complex task involving the acquisition, analysis, and interpretation of information using seamanship, professional knowledge, and technology. As the maritime industry transitions towards maritime autonomous surface ships (MASS), there is an increasing gap between the operator and the technology. This paper explores a collision avoidance decision support system for navigation from the navigator's perspective. The system, developed by Wärtsilä, is called Advanced Intelligent Manoeuvring (AIM) and can generate suggestions for course or speed alterations based on data from surrounding traffic. Nineteen Swedish navigators completed three ship traffic scenarios with and without decision support. Qualitative data were collected using interviews and analysed with thematic analysis. The results show that the participants perceive the decision support system as an advisory tool to visualise how traffic situations could unfold, a task currently difficult for most navigators. This paper discusses the present and near future of maritime navigation, highlighting the benefits of automation, while remaining vigilant about the potential dangers.

1. Introduction

The fourth industrial revolution (I4.0) is arguably the most complex and disruptive of the industrial revolutions and will challenge almost every aspect of society (Schwab, 2017). I4.0 is characterised by cyber physical systems, the internet of things, connectivity, and interoperability among systems, people and the environment to foster real-time decision making (Schwab, 2017; Aiello et al., 2020). Maritime transport represents approximately 80–90% of international world trade, which makes it an integral part of I4.0 (ICS, 2020; Sepehri et al., 2021). The maritime ecosystem can be referred to as Shipping 4.0, an all-encompassing concept, referring to the transformation of the shipping industry throughout I4.0 (Aiello et al., 2020). This paper focuses on the safe navigation of ships during this transition. In relation to navigation systems, while the proliferation of technology to support maritime systems is becoming ubiquitous, the integration and use of such technology is still at the earliest stages.

The International Maritime Organization (IMO) has recently finished a five-year regulatory scoping exercise regarding the safety, security and potential environmental impacts of maritime autonomous surface ships (MASS) (IMO, 2021). The IMO has defined MASS as a ship which, to a varying degree, can operate independent of human interaction. IMO has organised the degrees of autonomy into four categories (IMO, 2017, 2021). MASS Degree 1 includes the highest level of human interaction and is defined as a 'ship with automated processes and decision support: seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control' (IMO, 2018, 2021). Degrees 2 and 3 each incorporate higher levels of automation and less human interaction, until Degree 4, which is a fully

autonomous ship that can make decisions and determine actions by itself. This paper focuses on MASS Degree 1, in which seafarers are in control of the ship as the primary decision makers but have access to some automated systems, including a decision support system for navigation.

1.1. Background

There exists a conflict between the push towards autonomy and the pull by maritime industry stakeholders. The autonomy agenda has been driven largely by technology developers, and projected economic gains. In 2018, the Nautilus Federation collected data from almost 1,000 maritime professionals across a dozen countries asking about critical issues surrounding the advancement of autonomous vessels. The results revealed that 84% of maritime professionals consider automation to be a threat to seafaring jobs, and 85% believe that unmanned remotely controlled ships pose a threat to safety at sea (Nautilus, 2018). Yet today, most research initiatives prioritise projects which hypothesise a future with remote operations similar to the MUNIN concept (Man et al., 2015), or full autonomy, leading to substantial research gains towards the development of collision avoidance algorithms (Woerner, 2016; Woerner et al., 2016; Zhang and Furusho, 2016; Ramos et al., 2018; Abilio Ramos et al., 2019; Perera and Batalden, 2019; Woerner et al., 2019; Ramos et al., 2020). These works have attempted to evaluate quantitatively and to implement the subjective nature of the International Regulations for Preventing Collisions at Sea (COLREGs) (IMO, 1972) through various approaches including optimisation methods, reinforcement learning, fuzzy-logic, neural networks, and Bayesian networks (Woerner et al., 2019; Porres et al., 2021). As machine learning and more advanced neural networks are developed, the potential for collision avoidance systems should be further advanced. However, while human operators remain in control of the ship there are many challenging research and practical implementation problems which remain unresolved. Even in human-centred research, there is an underlying assumption that these difficult problems, including incorporating seafarer experience and seamanship into artificial intelligence, can be resolved (Abilio Ramos et al., 2019; Ramos et al., 2020; Porathe, 2021). While it is necessary to investigate the future of MASS Degrees 2–4, the only way to get there safely is through a systematic socio-technical approach. Caution must be exercised surrounding assumptions about future maritime systems to ensure that the important roles of the human operator are prioritised and remain an integral part of the system. MASS Degree 1, which includes decision support systems for navigation, is the next systematic step towards smarter ships. While humans remain in control of the ship, human-automation interactions should be further studied.

Work is underway to develop collision avoidance algorithms that can be used for onboard decision support systems and eventually unmanned vessels, however, there are fewer research efforts studying decision support from the operator's perspective. Few collision avoidance decision support systems have been developed and tested on end-users over the last decade. Two examples are NAVDEC, or navigation decision supporting system, the first of its type, originally proposed in 2012, and Multi-ARPA (MARPA) (Pietrzykowski and Wołejsza, 2016; Ożoga and Montewka, 2018). NAVDEC plans manoeuvres for the navigator that comply with COLREGs and is based on predefined distances and times (to closest approach to vessel traffic) while MARPA provides the navigator with information on safe headings and operates based on an algorithm which designates direct hazards for own ship with a proposed set of manoeuvres in a traffic situation. Both studies demonstrated the potential of decision support systems for navigation while highlighting the challenges of writing accurate algorithms given the challenging operational environment of ships (Ożoga and Montewka, 2018). Although promising, there has been little research or development on either NAVDEC or MARPA in recent years (http://navdec.com/en/). The Sea Traffic Management (STM) project developed decision support functions for both navigation and navigational assistance. These functions provide additional information about surrounding traffic and allow information exchange between ships to enable operators to make more informed decisions based on real-time information. The results from the STM project indicate that, although several of the STM services were useful, they caused changes to existing work practices which could impact communication structures, workload, and situational awareness (Aylward et al., 2020a,

2020b). This work highlighted the need for an increased research focus on the potential impacts of low-level automation within the maritime socio-technical system. These studies, in addition to a review of literature, have led to the identification of a major gap in research related to decision support for navigation activities and the potential influences it may have on work. Decision support systems should improve the safety of navigation; however, the reality is that any additional technology added onto the bridge can have unwanted or surprising consequences (Bainbridge, 1983). This technology can lead to over-reliance, misunderstandings, and even conflict between the human operator and automation (Endsley, 1995; Lee and See, 2004; Endsley, 2017).

1.2. Theoretical background

The complex interaction between human and technology is situated within the theoretical framework of human-automation interaction (HAI). There is an extensive body of HAI research within safety-critical industries including military operations, healthcare, aviation, nuclear, and transportation domains which can be used to study HAI in the maritime domain (Endsley, 1987; Jenkins et al., 2008; Hancock et al., 2013; Endsley, 2017). Theoretical contributions from the field of HAI including trust, reliance, workload, situation awareness, complacency, and user acceptance of automation lay the foundation for this work (Lee, 2008; Parasuraman et al., 2008; Parasuraman et al., 2000; Endsley, 2017). The four-level model of types and levels of automation (LOA) proposed by Parasuraman et al. (2000) is selected to describe the categorisation of automation discussed in this paper (Parasuraman et al., 2000). This model identifies the four levels of input functions as information acquisition, information analysis, decision selection and action implementation, and describes the human performance consequences associated with automating each input function. This model is unique amongst representations of LOA because various levels or degrees of automation can be applied to each input function level, and one system can have different LOA across all four dimensions. Levels 1 to 3 are applicable to the decision support system discussed throughout this paper and Level 4 is outside the scope of this work. Levels 1 to 3 are also associated with human information processing stages including sensing, monitoring and registering data as a pre-processing stage before perception and selective attention (Level 1); conscious perception, prediction and analysis of incoming data using working memory and inferential processes (Level 2); and this cognitive processing leads the user to select a decision based on decision alternatives (Level 3) (Parasuraman et al., 2000). This framework is useful to discuss the potential impacts of automation on human performance even at the introduction of 'lower' LOA.

1.3. Aim

The maritime industry lags behind its transportation counterparts and even though there have been major developments in onboard ship technology, the work practices and procedures reflect a more traditional workplace (Mallam et al., 2019b; MacKinnon and Lundh, 2019). To improve safety at sea, empirical evidence is needed to understand which aspects of navigation could and should be improved with increased adoption of automation. The aim of this paper is to explore how a decision support system could impact the safety of navigation and the role of the operator in routine ship traffic situations. The research question to be answered in this paper is:

> From the navigator's perspective, what are the benefits and potential challenges associated with a decision support collision avoidance system?

2. Materials and methods

2.1. Advanced Intelligent Manoeuvring (AIM)

The decision support system studied in this paper is called Advanced Intelligent Manoeuvring (AIM), developed by Wärtsilä, a manufacturer of innovative technologies and lifecycle solutions for the

Figure 1. *AIM user interface.*

marine and energy markets. This system provides suggestions for collision and grounding avoidance. To prevent collisions (or near misses) in traffic situations, navigators are bound to follow the International Regulations for Preventing Collisions at Sea (COLREGS) which are the 'rules of the road' for ships and other vessels at sea, i.e., making it clear as to which ship is the 'stand on' and 'give-way' ship and how to respond (IMO, 1972). To support the navigator in ascertaining if a risk of collision exists, ARPA (Automatic Radar Plotting Aid) and AIS (Automatic Identification System) are mainly used. ARPA is a radar with the capability to track and obtain information about plotted targets (TG) such as the closest point of approach (CPA) and the time to CPA (TCPA). ARPA includes a Trial Manoeuvre function where the effect of an own ship manoeuvre on all tracked TGs can be predicted in time. AIS is an automatic tracking system in which ships transmit information including name, position, size, course and speed to other AIS receivers and can be depicted on both the radar and the Electronic Chart and Information System (ECDIS). AIS is regarded as a useful source of information supplementary to that derived from other navigational systems and therefore is an important 'tool' in enhancing situation awareness (IMO, 2015). The ECDIS also has a 'look ahead' or 'watch vector' function to prevent groundings, which compares safety settings entered by the navigating officer and depth information from the electronic navigational chart, generating a warning when the ship may be in danger (IMO, 2019).

AIM is marketed as a smart addition to a standard ARPA and Trial Manoeuvre, covering all working cycles of operations, including situation monitoring, problem detection, suggesting a manoeuvre and monitoring execution of the manoeuvre based principally on mathematical calculations. The system assumes that the other ships keep their course and speed. AIM provides graphical solution(s) on how to solve the traffic situation by changing either course or speed with an additional possibility to 'play ahead', simulating and visualising a future manoeuvre on the ECDIS. The suggestions are displayed on the monitor based on the CPA/TCPA settings in AIM. The TCPA value will control the timing of the suggestion, meaning the higher the TCPA value, the earlier the suggestions are displayed. Suggestions may also change during the exercise, as AIM is constantly updating based on the traffic situation. The user interface is shown in Figure 1.

2.2. Simulator scenario development and test set-up

Subject matter experts were involved in creating, implementing and testing various traffic scenarios in a Wärtsilä NTPro 5000 Full Mission Bridge Simulator. The goal was to develop scenarios

that were realistic and somewhat challenging for both the participants and the AIM system. The scenarios were developed based on the following criteria: meeting, overtaking and crossing situations, neither open sea nor restricted waters, good visibility, calm weather conditions (i.e., no wind or current), manageable for one single officer on the bridge, and lasting for approximately 20–25 min. Based on the criteria, three scenarios were developed, all of which involved three vessels – Alpha, Bravo and Charlie – and were set in three different geographical areas: Anholt, Fehmarn and Halland.

The AIM station on the bridge of each of the ships was configured with the relevant data for each scenario. The data consisted of the dimensions of the ship, its deadweight and its minimum turning radius. The AIM station on each bridge was configured to display the ship's route and supplied with compass/gyro, log, GPS and AIS data. For technical reasons ARPA/Radar data could not be integrated in the AIM stations. However, as there was no wind or current in the simulation scenarios, AIS data was considered as being acceptable even though not compliant with the COLREGs. The route and corresponding safety settings for each ship and scenario were pre-planned using Wärtsilä's NaviPlanner and imported to the simulator software to enable the route exchange between the simulator software and the AIM stations. Realistic CPA/TCPA values were discussed and evaluated by the subject matter experts considering the exercise area, the ship type, the geography of the designated areas and the traffic density. According to these conditions, the following settings were chosen in all exercises: CPA 0.5 nautical miles and a TCPA of between 20 to 24 min. The simulator software was configured for one stand-alone workstation with the AIM software and monitor on each bridge close to the seat from which the test person was navigating the ship.

2.3. Participants

Participants were fully informed of the procedures and risks of the experiment and signed written informed consent forms prior to the start of the data collection. The participants satisfied one of the criteria: active or recently active masters, mates, officers, maritime pilots, or fourth-year Master Mariner students. In total, 19 participants were recruited, all of whom were of Swedish nationality and identified as male. The participants were distributed in age groups as: 18–24 years: six participants; 25–34 years: four participants; 35–44 years: two participants; 45–54 years: four participants, and 55–64 years: three participants. Seven participants were fourth-year Master Mariner students, three were employed as Officer of the Watch or Senior Officer, four identified as instructor or teacher at Chalmers University of Technology, one participant was not employed, and four participants identified as 'other' (two pilots, one director and one researcher). To determine their pre-existing attitudes towards automation, the participants were asked about their attitude towards receiving decision support through technical means (automation) in a navigational situation. On a five-point Likert scale ranging from 'very negative' to 'very positive', four participants were 'neutral', 13 participants were 'positive', and two participants were 'very positive' (Likert, 1932). The study was conducted in English as all participants were fluent and comfortable speaking English. There was always at least one native Swedish speaker on the research team present during the data collection in case of miscommunication.

2.4. Experimental design

The experiment lasted for approximately 4 h, including the familiarisation session and the group debrief and interviews at the end of the day. The participants were assigned to a ship bridge (Alpha, Bravo or Charlie) on which they completed three navigational scenarios (Anholt, Fehmarn and Halland) that were approximately 25 min each. This study followed a within-subject design, meaning all participants were exposed to both conditions: baseline condition (traditional navigation) and a decision support condition (navigation with AIM). However, they were never exposed to the same scenario in both conditions and the order in which the scenarios were tested, along with the experimental condition, were randomised to reduce any potential order effect (Creswell and Clark, 2017). There were an uneven number of trials

Table 1. *Breakdown of experimental conditions.*

Scenario	Baseline	AIM
Anholt	4	3
Fehmarn	3	4
Halland	3	4
Participants (× 3 per scenario)		
Total trials	30	33

Note: AIM, Advanced Intelligent Manoeuvring.

between baseline and AIM due to last minute cancellations related to COVID-19. Table 1 provides a summary of the experimental conditions.

2.5. Data collection

Qualitative data were collected through video and audio recordings, observations, and collective interviews. Observations were ongoing throughout the scenarios from a live audio-visual feed of the participants on the bridge, and the AIM suggestions. The interview was semi-structured and lasted for approximately 1 h. The interview questions were related to the scenarios, overall experience, interaction with AIM and perception of COLREG adherence and seamanship. The interviews were video- and audio-recorded, and a complete transcription was completed post interview and compiled with the researcher's personal notes during the interviews.

2.6. Data analysis

The collective interviews were analysed by two independent researchers to achieve intercoder reliability to improve the transparency and trustworthiness of the analysis (Patton, 2002; SAGE, 2008). The researchers each followed the same general process to complete a thematic analysis (Braun and Clarke, 2006). Once the individual analysis was completed, the researchers compared and discussed the results, generating a common list of the themes that emerged from the data and addressed any discrepancies. The researchers continued working with the data and finalised the analysis when saturation was achieved and the themes which emerged from the data were clear.

2.7. Methods discussion

Qualitative data were obtained primarily through the debrief and collective interviews. All three participants were present during the interviews since they participated together in the same traffic scenarios. This was important to understand both their individual experience and how they perceived other ships within the scenario. Although participants were encouraged to share their experiences freely, the research team ensured that each participant provided input on the targeted questions so that the conversation was evenly distributed amongst participants. Additionally, supplementary data were collected through audio-visual recordings and live observations of the AIM suggestions. This is an example of triangulation of qualitative methods which strengthened the results from the study (Patton, 2002).

2.8. Limitations

- The participant sample consisted of Swedish males who were educated and trained at Swedish maritime academies. Although a relatively homogeneous sample, their experience varied in terms of age, current role and experience, which is more representative of a real ship crew. However, the lack

of inclusion of participants from different geographical locations may limit the transferability of the results to wider seafarer populations.

- AIM is one technology of many that could provide decision support to navigators. The repeatability of the results is limited to access to AIM, which is not yet commercially available. However, the scenarios and methodological approach could be reproduced to test similar decision support systems.
- Only three scenarios were tested in this study, while an unlimited number of possible traffic scenarios could be tested. Additionally, the scenarios were designed in perfect weather and visibility conditions. Further testing in strong tidal areas and various visibility conditions should be completed to understand how or if AIM will conform with the COLREGs.

3. Results from thematic analysis

The following sections summarise the results from the thematic analysis. Two general sections are used to categorise the results: 3.1, implications for seafarers, and 3.2, critical elements of collision avoidance decision support systems. Within each section, several themes are proposed supported by evidence from the qualitative analysis.

3.1. *Implications for seafarers*

3.1.1 Automation as a team member

Safe navigation requires the constant monitoring of the voyage and the ability to detect and respond to any potential hazards which might impact the planned voyage. There are navigational aids available today which provide this information, however, it still requires the operator to create a mental model supported by the respective technologies. The participants described AIM as a tool which enhanced their ability to evaluate the surrounding traffic, allowing a quicker confirmation or a challenge to their mental model. This resulted in both positive and negative reflections from the participants. When suggestions matched their mental model, they generally responded positively towards AIM, as it confirmed their plan of action. Sometimes human characteristics or metaphors were used to get their point across. The following quotes are selected to describe this result.

> It was a confirmation of my decision which felt good, I had my 'buddy' here.
> I got the feeling for one moment, that I have a co-pilot.

Other phrases used to describe AIM include 'consultant', 'option generator', 'confirmation tool' and 'thought checker'. However, AIM suggestions did not always align with the participant's plan, which caused mixed reactions. Generally, if the mismatch occurred early in the scenario, the participants strongly criticised the suggestions and quickly disregarded AIM as a useful tool and even classified it as potentially dangerous. The participants indicated that many of the risks related to having inaccurate or conflicting suggestions depend on the experience and knowledge of the user. These risks relate to misuse of and over-reliance on this technology, which occurs today with other navigational aids. However, if suggestions aligned with their mental model earlier in the traffic situation, it seemed that they were more tolerant of mismatched suggestions later in the scenario.

3.1.2. *Visualisation tool*

Another element of AIM which contributed to the participants' situational awareness and mental model development was the ability to visualise a traffic sequence. This was primarily provided by the 'play ahead' function, a feature frequently compared to the existing ARPA trial manoeuvre, which was described by several participants as the 'advanced trial manoeuvre'. Throughout the analysis it became evident that, for the participants, this feature contributed the most towards improving the safety of navigation. This functionality serves a practical use through the ability to visualise the possible consequences of a manoeuvre, an estimation of when to go back to their original route, and possible

emergency manoeuvres. These aspects of navigating are not possible to do with existing navigational equipment (e.g., ECDIS, radar, ARPA, etc.). This was captured in the following response:

> *What you see when you look at the radar is the present situation. I start to evaluate myself, of course, I cannot do as much as the computer can. For example, play ahead. Let the computer do the mathematical work, and then I try to use my seamanship to make a decision and evaluate everything.*

3.1.3. Seamanship – 'a floating abstract norm'

The participants identified that seamanship and the formal regulations are heavily intertwined, as described in the quote below. Untangling the role of seamanship for a new technology is challenging because even the COLREGs mention that action shall be taken 'with due regard to the observance of good seamanship' (COLREG Rule 8). There were discussions about what it is, if an algorithm could have it, if the AIM suggestions portrayed good or bad seamanship, and how important it should be in decision making. These questions are surprisingly difficult to answer, given that all seafarers know what seamanship is yet define it differently. However, a common factor was that the participants perceive seamanship as having a good overview of the situation, including an assessment of 'how my actions affect other vessels in the area', something which AIM is not capable of doing. The participants unanimously agreed that AIM does not have 'seamanship', nor is it possible for an algorithm to have seamanship.

> *If you go against good seamanship, you go against the COLREG.*

3.1.4. Complacency and deskilling

Participants were conflicted about the implications of manoeuvring suggestions which might impact motivation and skill to safely assess the traffic situation based on all available information. Some participants thought that this could lead to increased complacency amongst certain navigators who might take shortcuts without properly thinking for themselves. They also identified that these risks are present with existing navigational aids, including ECDIS and radar. With these risks in mind, most participants argue that knowledge of the COLREGs might be even more important when using AIM or similar tools and the core knowledge of navigation in education should not be reduced because of this type of technology. This was described by a participant in the response below.

> *If you take it a few steps more, I am worried that some things will disappear that are vital in the 'art of navigation'.*

This passage also conveys an interesting point about describing navigation as an 'art'. AIM assumes that other ships will keep their course and speed, which provides the user with a mathematical solution to one aspect of a complex problem. To solve this complex problem, these mathematical solutions must be cross-checked by the user. The ability to do this requires an understanding of the entire navigational situation, which is possible through many years of formal education, practical experience and continuous training to treat navigational situations as more than a mathematical equation, and more like an 'art'.

3.2. Critical elements of collision avoidance decision support systems

Throughout the analysis it was determined that although AIM was useful as a navigational aid, many gaps were identified that reflect critical elements needed to further develop automation to ensure that navigators are supported.

3.2.1. Integration and transparency of systems

The implementation of ECDIS has changed the role and work practice of the navigator. However, there are concerns amongst participants about the understanding and transparency of system

functionality. Participants indicated that many ECDIS functions are not well understood, presenting a risk which could be compounded by adding on new technology without integrating existing systems according to human-centred design standards. This is a major safety issue, one which is acknowledged in the maritime industry. The consensus amongst participants was that better training in existing systems, including how to deal with system failures, should be prioritised over adding on new features. This was described by a less experienced participant in the following passage:

> *I am fairly against adding systems and screens. Looking for ECDIS to be a more integrated system. Adding functions in ECDIS won't help me. You have more functions than most people know about. It is unnecessary, it's complicated, and it's hard to find.*

In addition to the integration of systems, participants identified that to develop trust in a technology, it should be more transparent. The participants were interested in knowing additional information about the suggestions, and how/why they were generated. It was mentioned several times that AIM is a 'black box' and one would be hesitant to trust it. There must be clear communication of the capabilities and limitations of the system. The participants were acutely aware, however, of the potential trade-off between additional information and information overload. They still argued that increasing transparency in new or existing automated systems could improve the human-automation relationship so that practical trust and reliance in the technology can be developed through an informed understanding. This was captured through the following response:

> *You also must not be afraid to say that AIM is wrong. Must make sure it is your own decision. Same discussion all the time, comes back to over-reliance on systems and complacency. It is so easy to trust the systems for the human mind when you see it on the screen than reality. The mind finds it easier to accept that.*

Participants also explored the notion that ships should 'talk to each other', which reflects the concepts of information and route exchange explored within the STM project. There were suggestions to integrate AIM with a route sharing function which they believe could provide better situational awareness and potentially reduce the number of assumptions related to how other vessels might manoeuvre. Some participants believe this should be the next step towards higher degrees of automation.

3.2.2. *Blunt but useable system*

The results generated two seemingly opposite themes: (1) AIM is a blunt decision support system, but (2) AIM is user friendly. It was evident amongst the participants that AIM was limited in what it could do, resulting in a theme we called *blunt*. AIM was effective from an own ship viewpoint in that it had an 'egocentric' perspective but it lacked the birds-eye overview of the entire traffic situation to consider situations between other ships. This was seemingly something the participants wanted from this technology, which AIM could not provide. This would also require a more complex approach to how decision support systems are developed. It was discussed that AIM is simple because its suggestions are based on mathematical calculations of straight vectors, aligning with the COLREGs. However, the task of navigation is complex and considers a social aspect in navigation which is far beyond the current capacity of AIM. This finding also highlighted the importance that this system should only be used by proficient navigators and should not be a substitute for poor training or limited experience. This can be described by the following passage:

> *In the hands of a good navigator it is a supportive tool but not more than that.*

Yet, surprisingly, the participants still really liked AIM. This caused slight confusion amongst the research team for some time, trying to understand the value in the system if it was so simple. Part of the answer emerged when the user interface and overall usability of the system was discussed, which resulted in an overwhelmingly positive response. Unfortunately, user-centred solutions are few and far between in the maritime industry, making AIM stand out amongst the participants in this study because it was

easy to use and did what it was supposed to do. This was described simply by one of the participants, and echoed by almost everyone:

> *Extremely easy to use. Interface was easy to use. No unnecessary functions and it did what it was supposed to do. It was straightforward.*

4. Discussion

This study aimed to explore how navigators perceive a collision avoidance decision support system for navigation. The research question was to investigate the benefits and potential challenges associated with a decision support collision avoidance system.

4.1. The impact of a decision support system

Decision support systems are the next step towards the adoption of MASS and should be better understood. MASS Degree 1 means the operator will remain in control and can choose to use decision support or ignore it and the ship will function as normal. However, if navigators opt to use a decision support system, there will be an impact on numerous aspects of navigation as it exists within its complex socio-technical system. The safe navigation of a ship requires flexibility and adaptability due to the inherent complexity of traffic situations at sea. Small changes in the system architecture can impact upon judgements, roles, relationships and weightings on different goals, resulting in vast changes of system function (Grech et al., 2008; Woods and Dekker, 2000). Potential impacts of collision avoidance decision support are discussed from the navigator's perspective drawing on human-automaton interaction and information processing theoretical frameworks.

4.1.1. Human-automation interaction (HAI)

Human-automation interactions are complex and trust and reliance in automation evolve based on personal history, cultural and organisational factors (Lee and See, 2004). Shipping still has hierarchical command structures on board and an 'old versus new' mentality between older and newer seafarers, creating a more transactional leadership environment. Seafarers are still trained in traditional navigation practices as they must know what to do when technology fails, even while technologies become more advanced. Throughout the interviews, several themes emerged which provided indications of how trust could be developed in technology from the participants' perspective. While the operator is in full control of the decision selection (Level 3) and action implementation (Level 4), communication to the user about how, what and why information is being presented, also known as system opacity, is important (Lee, 2008; Helldin, 2014; Westin et al., 2016). In a recent review paper exploring empirical evidence of automation transparency, for 'agent-generated proposals', where *agent* is interchangeable with automation, there appears to be a positive effect of automation transparency on operator performance, SA, and mental workload (van de Merwe et al., 2022). Increased transparency should provide navigators with an increased understanding and predictability of the system to better evaluate whether to use this information instead of trying to evaluate why it was presented (Endsley, 2017; van de Merwe et al., 2022). A balance must also be achieved between automation transparency and information overload. Several participants suggested combining AIM with information sharing services, such as the STM ship-to-ship route exchange, because predicting the actions of another ship and correctly understanding its intentions is crucial to the art of navigation. Uncertainties, in particular the inability to anticipate the actions of another ship, have been listed as a causal factor in ship collisions (Langard et al., 2015; Wickens et al., 2020). However, the projection of a future state of events is based on accurate input data and the assumption that ships are following the data they are broadcasting. This situation could complicate basic navigational scenarios which could be solved by the COLREGs and existing navigation practices. Unless integrated, merging these two automated functions could cause unnecessary information overload. However, these solutions should be considered for future developments of decision support systems. Further work is

needed to determine the critical level and type of information needed for different aspects of navigational tasks.

From an information processing perspective, automating information is intended to support human cognitive processes in decision making, providing the most useful information to the operator (Parasuraman et al., 2000). Revisiting the automation framework proposed by Parasuraman et al. (2000), the AIM system provides Levels 1–3 of input functions. AIM provides information acquisition (Level 1) through supporting the human sensory process of organising incoming data from surrounding ships, information analysis (Level 2) through mathematically predicting the most optimal route and the optimal time to act, and partial decision selection (Level 3) in the form of augmentation as the system provides suggested manoeuvres to solve a traffic situation. The visualisation of the manoeuvring alternatives to solve a traffic situation was not previously possible with existing navigational aids, supporting the human sensory, memory and inferential processes. In terms of operator performance, according to Endsley's situation awareness model, AIM should enhance the perception, comprehension and projection of future actions assuming that the information from the system is correct (Endsley, 1995). However, increasing the type and level of automation from a formerly manual operation (e.g., information acquisition) could conversely have a negative impact on their situational awareness (Parasuraman et al., 2000). Today, these manual tasks are what keeps the operator active and 'in the loop'. Therefore, a balance must be achieved so that the operator can maintain and improve their situation awareness from the use of such systems.

According to the participants, a facilitated ability to visualise a manoeuvre within a future traffic situation was one of the most valued aspects of AIM. The feature called 'play-ahead' can contribute to a more complete overview of a situation and the ways it could unfold, while keeping in mind that this function is based on the TGs keeping their course and speed (which may not be the case). The participants reported that AIM either confirmed or challenged their mental model and that they found the system particularly likeable when the suggestions aligned with their mental model. This human-automation agreement occurred most of the time, which made sense for a 'simple' three-vessel scenario. There was little need for seamanship, as the solutions were primarily rule-based, grounded in the COLREGs, which is also the basis of the AIM algorithms. Maritime accident data in recent years indicate that 56% of collisions at sea are caused by violations of the COLREGs (Statheros et al., 2008; Liu et al., 2016; Abilio Ramos et al., 2019). Live traffic situations with more than three vessels are more complex and dynamic; they can be resolved safely based on several factors including adherence to the formal rules (COLREGs) and their interpretation of good seamanship. It seems that AIM supported the operator in their weaknesses (e.g., visualisation and computation), allowing them to use their strengths (seamanship) to have a more accurate situation awareness. Therefore, although AIM was described as a blunt tool which primarily contributed to the mathematical calculations or strict application of the COLREGs, the participants believe that even its basic functionality has an important role in the safety of navigation.

4.1.2. The future seafarer

Another challenge identified by the participants was the potential impact of decision support systems on seafarer training, skill maintenance and development. The role and qualifications of the future seafarer has been identified by IMO as one of the most complex issues to be addressed with the adoption of MASS (IMO, 2021). The future competencies of seafarers and their role within the maritime ecosystem has been an important area of research interest over the last decade (Man et al., 2015; Baldauf et al., 2019; Mallam et al., 2019a; Kim and Mallam, 2020; HVL, 2021). However, most of these works target higher levels and degrees of automation and MASS adoption, while little is known about the role of the seafarer for MASS Degree 1. According to the results of this study, the potential impacts should not be ignored as there exists a possibility for skill degradation without proper training for automated systems. The participants almost unanimously agreed that while seafarers are still on board and in control, the education and training for 'core navigational knowledge' is essential. It was further identified that the potential consequences of complacency and over-reliance associated with the use of any automated system, even at low LOA, should be taken seriously. These risks are also present with existing navigational aids, as highlighted in the recent investigation into the application and usability

of the ECDIS (MAIB, 2021). The participants were clear that decision support solutions should not replace existing navigational competencies. Instead, at this early stage of MASS adoption, decision support should be advisory in nature and provide well-trained officers with rule-based information (COLREGs) to make the final decisions for safe navigation.

4.1.3. Moving forward

Other safety-critical industries are continuously working to utilise automation to support operator performance. A computer operator support system, also known as a 'recommender system' or 'operator advisory system' has a long history in the nuclear power and aviation industries. These can assist operators in monitoring performance, diagnosing faults, predicting future states, recommending mitigations and decision support (Boring et al., 2015; Westin et al., 2016). The basis for an operator advisory system is that it supports the operator with a task and aids them in the completion of the task when possible while being minimally intrusive to manual operations (Boring et al., 2015). This has facilitated the maturation of less brittle and more resilient socio-technical systems. Although AIM is a decision support system, perhaps it could be sub-classified as an advisory system given the broad scope of decision support systems. Advisory systems are used to support the human decision-making process in unstructured, complex or open-ended situations, such as navigation. The participants even described AIM as an 'option generator', 'buddy' or 'co-pilot', aligning closely with the synonyms presented for such systems. Shipping4.0 will provide an abundance of automated systems and features and there should be a better, more descriptive classification of what type of decision support is provided to the operator.

5. Conclusion

This study explored ship navigators' perceptions and performance employing a collision avoidance decision support system. The participants described the decision support system as a tool to evaluate their mental model through the visualisation of potential future traffic situations. This functionality was identified as an important addition to existing navigational aids from a human information processing perspective. The decision support was appreciated, and most participants indicated they would like to use it in real life. However, the integration of any technology can have wider impacts on the maritime socio-technical system, and this was no exception. There are concerns about mis-placed trust, over-reliance and complacency, which could be improved with greater system transparency and additional user testing. Certain findings, primarily the integration of existing systems and the training and skill development of tomorrow's seafarers, should remain a high priority for IMO as higher levels of MASS are adopted. The transition towards Shipping 4.0 is exciting; digital solutions will change the shipping industry as we know it. However, we must proceed with caution and attempt to fill some of the major research gaps facing today's seafarers to better prepare for tomorrow.

References

Abilio Ramos, M., Utne, I. B. and Mosleh, A. (2019). Collision avoidance on maritime autonomous surface ships: Operators' tasks and human failure events. *Safety Science*, **116**, 33–44.

Aiello, G., Giallanza, A. and Mascarella, G. (2020). Towards Shipping 4.0. A preliminary gap analysis. *Procedia Manufacturing*, **42**, 24–29.

Aylward, K., Johannesson, A., Weber, R., MacKinnon, S. N. and Lundh, M. (2020a). An evaluation of low-level automation navigation functions upon vessel traffic services work practices. *WMU Journal of Maritime Affairs*, **19**, 313–335.

Aylward, K., Weber, R., Man, Y., Lundh, M. and MacKinnon, S. N. (2020b). 'Are you planning to follow your route?' The effect of route exchange on decision making, trust, and safety. *Journal of Marine Science and Engineering*, **8**, 280.

Bainbridge, L. (1983). Ironies of automation. *Automatica*, **19**, 775–779.

Baldauf, M., Fischer, S., Kitada, M., Mehdi, R., Al-Quhali, M. A. and Fiorini, M. (2019). Merging conventionally navigating ships and MASS – merging VTS, FOC and SCC? *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, **13**, 495–501.

Boring, R. L., Thomas, K. D., Ulrich, T. A. and Lew, R. T. (2015). Computerized operator support systems to aid decision making in nuclear power plants. *Procedia Manufacturing*, **3**, 5261–5268.

Braun, V. and Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, **3**, 77–101.

Creswell, J. W. and Clark, V. L. P. (2017). *Designing and Conducting Mixed Methods Research*. Cincinnati, OH, USA: Sage Publications.

Endsley, M. R. (1987). The Application of Human Factors to the Development of Expert Systems for Advanced Cockpits. *Proceedings of the Human Factors Society Annual Meeting*, SAGE Publications, Los Angeles, CA, 1388–1392.

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors*, **37**, 32–64.

Endsley, M. R. (2017). From here to autonomy: Lessons learned from human–automation research. *Human Factors*, **59**, 5–27.

Grech, M., Horberry, T. and Koester, T. (2008). *Human Factors in the Maritime Domain*. Boca Raton, Florida, USA: CRC Press.

Hancock, P. A., Jagacinski, R. J., Parasuraman, R., Wickens, C. D., Wilson, G. F. and Kaber, D. B. (2013). Human-automation interaction research: Past, present, and future. *Ergonomics in Design*, **21**, 9–14.

Helldin, T. (2014). *Transparency for Future Semi-Automated Systems: Effects of Transparency on Operator Performance, Workload and Trust*. Örebro, Sweden: Örebro Universitet.

HVL. (2021). Human Maritime Autonomy Enable (HUMANE) [Online]. https://www.hvl.no/en/project/591640/. Available at: https://www.hvl.no/en/project/591640/ [Accessed 25 January 2022].

ICS. (2020). Global Supply and Demand for Seafarers [Online]. Available at: https://www.ics-shipping.org/shipping-facts/shipping-and-world-trade/global-supply-and-demand-for-seafarers [Accessed 30 January 2020].

IMO. (1972). Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs). International Maritime Organization Available at: http://www.imo.org/en/About/conventions/listofconventions/pages/colreg.aspx

IMO. (2015). Revised Guidelines for the Onboard Operational Use of Shipborne Automatic Identification Systems (AIS). London, United Kindgom: International Maritime Organization.

IMO. (2017). Revised strategic plan for the organization for the six-year period 2018 To 2023. *Resolution A.1149(32)*. 32nd session, London, United Kingdom: International Maritime Organization, 1–29.

IMO. (2019). Guidelines for the Standardization of User Interface Design for Navigation Equipment. London, United Kingdom: International Maritime Organization.

IMO. (2018). IMO takes first steps to address autonomous ships. International Maritime Organization [Online]. Available at: http://www.imo.org/en/MediaCentre/PressBriefings/Pages/08-MSC-99-MASS-scoping.aspx [Accessed 1 October 2019].

IMO. (2021). Autonomous Ships: Regulatory Scoping Exercise Completed. International Maritime Organization [Online]. Available at: https://www.imo.org/en/MediaCentre/PressBriefings/pages/MASSRSE2021.aspx [Accessed 11 April 2021].

Jenkins, D. P., Stanton, N. A., Salmon, P. M., Walker, G. H. and Young, M. S. (2008). Using cognitive work analysis to explore activity allocation within military domains. *Ergonomics*, **51**, 798–815.

Kim, T.-E. and Mallam, S. (2020). A Delphi-AHP study on STCW leadership competence in the age of autonomous maritime operations. *WMU Journal of Maritime Affairs*, **19**, 163–181.

Langard, B., Morel, G. and Chauvin, C. (2015). Collision risk management in passenger transportation: A study of the conditions for success in a safe shipping company. *Psychologie française*, **60**, 111–127.

Lee, J. D. (2008). Review of a pivotal human factors article: 'humans and automation: use, misuse, disuse, abuse'. *Human Factors*, **50**, 404–410.

Lee, J. D. and See, K. A. (2004). Trust in automation: Designing for appropriate reliance. *Human Factors*, **46**, 50–80.

Likert, R. (1932). A technique for the measurement of attitudes. *Archives of Psychology*, **22**(140), 5–55.

Liu, Z., Zhang, Y., Yu, X. and Yuan, C. (2016). Unmanned surface vehicles: An overview of developments and challenges. *Annual Reviews in Control*, **41**, 71–93.

MacKinnon, S. N. and Lundh, M. (2019). Gaps in regulations, pedagogic needs and human/automation interactions in the shipping industry: a pre-study for Lighthouse. Gothenburg, Sweden: LIGHTHOUSE reports.

MAIB. (2021). Application and Usability of ECDIS Safety Study. Marine Accident Investigation Branch. Available at: https://www.gov.uk/government/publications/application-and-usability-of-ecdis-safety-study

Mallam, S. C., Nazir, S. and Renganayagalu, S. K. (2019a). Rethinking maritime education, training, and operations in the digital era: Applications for emerging immersive technologies. *Journal of Marine Science and Engineering*, **7**, 428.

Mallam, S. C., Nazir, S. and Sharma, A. (2019b). The human element in future maritime operations – perceived impact of autonomous shipping. *Ergonomics*, **63**, 1–12.

Man, Y., Lundh, M., Porathe, T. and MacKinnon, S. (2015). From desk to field – human factor issues in remote monitoring and controlling of autonomous unmanned vessels. *Procedia Manufacturing*, **3**, 2674–2681.

Nautilus, F. (2018). *Future Proofed? What Maritime Professionals Think About Autonomous Shipping*. London, UK: Nautilus Federation.

Ożoga, B. and Montewka, J. (2018). Towards a decision support system for maritime navigation on heavily trafficked basins. *Ocean Engineering*, **159**, 88–97.

Parasuraman, R., Sheridan, T. B. and Wickens, C. D. (2000). A model for types and levels of human interaction with automation. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans*, **30**, 286–297.

Parasuraman, R., Sheridan, T. B. and Wickens, C. D. (2008). Situation awareness, mental workload, and trust in automation: Viable, empirically supported cognitive engineering constructs. *Journal of Cognitive Engineering and Decision Making*, **2**, 140–160.

Patton, M. Q. (2002). Qualitative interviewing. *Qualitative Research and Evaluation Methods*, **3**, 344–347.

Perera, L. P. and Batalden, B. (2019). Possible COLREGs Failures Under Digital Helmsman of Autonomous Ships. OCEANS *2019*, Marseille, 17-20 June 2019, 1–7.

Pietrzykowski, Z. and Wołejsza, P. (2016). *Decision Support System in Marine Navigation*. Cham: Springer International Publishing, 462–474.

Porathe, T. (2021). Human-automation interaction for autonomous ships: Decision support for remote operators. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, **15**, 511–515.

Porres, I., Azimi, S., Lafond, S. E., Lilius, J., Salokannel, J. and Salokorpi, M. (2021). On the verification and validation of AI navigation algorithms. *arXiv pre-print server*.

Ramos, M., Utne, I. B., Vinnem, J. E. and Mosleh, A. (2018). Accounting for Human Failure in Autonomous Ship Operations. *European Safety and Reliability Conference ESREL 2018*, Trondheim, Norway.

Ramos, M. A., Thieme, C. A., Utne, I. B. and Mosleh, A. (2020). Human-system concurrent task analysis for maritime autonomous surface ship operation and safety. *Reliability Engineering & System Safety*, **195**, 106697.

SAGE. (2008). *The SAGE Encyclopedia of Qualitative Research Methods* [Online]. Thousand Oaks, CA: Sage. Available at: https://methods.sagepub.com/reference/sage-encyc-qualitative-research-methods [Accessed].

Schwab, K. (2017). *The Fourth Industrial Revolution*. New York, USA: Currency.

Sepehri, A., Vandchali, H. R., Siddiqui, A. W. and Montewka, J. (2021). The impact of Shipping 4.0 on controlling shipping accidents: A systematic literature review. *Ocean Engineering*. **243**, 110–162.

Statheros, T., Howells, G. and Maier, K. M. (2008). Autonomous ship collision avoidance navigation concepts, technologies and techniques. *The Journal of Navigation*, **61**, 129–142.

Van de Merwe, K., Mallam, S. and Nazir, S. (2022). Agent transparency, situation awareness, mental workload, and operator performance: A systematic literature review. *Human Factors*, 00187208221077804.

Westin, C., Borst, C. and Hilburn, B. (2016). Automation transparency and personalized decision support: Air traffic controller interaction with a resolution advisory system. *IFAC-PapersOnLine*, **49**, 201–206.

Wickens, C. D., Williams, A., Clegg, B. A. and Smith, C. A. P. (2020). Nautical collision avoidance: The cognitive challenges of balancing safety, efficiency, and procedures. *Human Factors*, **62**, 1304–1321.

Woerner, K. (2016). *Multi-Contact Protocol-Constrained Collision Avoidance for Autonomous Marine Vehicles*. Cambridge, Massachusetts, USA: Massachusetts Institute of Technology.

Woerner, K. L., Benjamin, M. R., Novitzky, M. and Leonard, J. J. (2016). Collision Avoidance Road Test for COLREGS-Constrained Autonomous Vehicles. *OCEANS 2016 MTS/IEEE Monterey*. IEEE, 1–6.

Woerner, K., Benjamin, M. R., Novitzky, M. and Leonard, J. J. (2019). Quantifying protocol evaluation for autonomous collision avoidance. *Autonomous Robots*, **43**, 967–991.

Woods, D. and Dekker, S. (2000). Anticipating the effects of technological change: A new era of dynamics for human factors. *Theoretical Issues in Ergonomics Science*, **1**, 272–282.

Zhang, R. and Furusho, M. (2016). Constructing a decision-support system for safe ship-navigation using a Bayesian network. In: Duffy, V.G. (ed.). *Digital Human Modeling: Applications in Health, Safety, Ergonomics and Risk Management*. 9745, Switzerland: Springer International Publishing, 616–628.