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A systematic review of cognitive and social factors in vessel traffic services operations

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ABSTRACT

Vessel traffic service (VTS) plays a key role in the safety of maritime navigation by organising the sea traffic, ensuring regulatory compliance, promoting information exchange and early detection of navigational hazards and assisting in collision avoidance. The cognitive and social factors influencing the performance of VTS operators require important considerations in this regard. Current developments in the maritime industry and changing operational profiles present novel challenges for VTS operators. This study aims to present the empirical findings related to the applied cognitive and social factors pertaining to VTS operations for the past two decades. A systematic literature review was conducted with a Boolean search strategy across six major databases. The literature associated with empirical investigations was extracted as per the PRISMA guidelines. The study identified 19 articles that satisfied the pre-determined inclusion criteria. A qualitative synthesis of the identified literature was performed, aggregating the findings into various sub-groups based on thematic areas and contexts. The obtained results revealed fatigue and mental workload as the most frequently examined factors, while factors such as decision-making, communication, coordination and perception also influenced the VTS operator's performance. The findings shed light on the current state of the art for research and practical applications related to cognitive and social factors influencing VTS operator performance and their impact on maritime safety. The result also identified gaps in the literature where further research is warranted, particularly related to emerging trends of automation and digitalisation in the maritime industry.

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Vessel traffic service; maritime safety; human factors; maritime navigation; systematic literature review

1. Introduction

1.1. General background

Maritime navigation, the control of the movement trajectory of a ship or vessel, guiding it from one point to another safely, is a safety-critical part of global merchant shipping.

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Maritime vessels are typically slower than other modes of transportation (e.g. road, rail or aviation). However, most vessels carry heavy cargo with large momentum and limited manoeuvrability, which increases accident risk. With ever-increasing transport of dangerous goods on ships, and a general increase in both commercial and passenger traffic, the complexity of navigation near the shores is increasing for various coastal regions and the potential for loss of human lives or ecological damage is much greater than ever before. The majority of the marine casualties and incidents during the period 2014–2022 occurred either within the "internal waters" or "territorial seas" (51.5% and 24.3% respectively), with only 20.8% incidents occurring at "open seas" (European Maritime Safety Agency, 2023). To cater for complexities with navigation of vessels near the coastal regions, additional and exclusive laws and regulatory frameworks are also enforced, such as the international regulations for preventing collisions at sea (COLREGs). Rules 8, 9 and 10, indicate the conduct of vessels when navigating in or near narrow channels, fairways and traffic separation schemes (TSS). The international association of marine aids to navigation and lighthouse authority (IALA) buoyage system marks the various approach and separation zones of the coastal regions to guide the vessels arriving or leaving the harbour areas (IALA, 2023).

To facilitate monitoring and surveillance, some coastal states require reporting of various vessel and cargo parameters before entering, while transiting and after leaving their territorial waters. Ships also employ harbour pilot services while arriving or departing from the port of call. These pilot services use specialised local knowledge to assist the navigation of vessels. Despite such existing provisions and special measures, accidents in coastal regions continue to occur, with some notable incidents in the last years. For example, the collision between oil tanker *Stena Immaculate* and containership *Solong* resulted in casualties and concerns over ecological damage to the Humber river estuary (BBC, 2025). The collision of containership *Dali* with the Francis Scott Key bridge in Baltimore resulted in six deaths in addition to economic disruptions (Adam et al., 2024). The collision between Norwegian frigate *Helge Ingstad* and oil tanker *Sola TS* in 2018, North-West of Bergen resulted in total loss of the frigate (Porathe, 2020). The grounding of the containership *Ever Given* in 2021, within Suez Canal resulted in severe financial losses, movement backlogs through the fairways and general disruption of global shipping for several days (Gerson, 2023). These incidents exemplify the need for continuous investigations of safety factors associated with maritime traffic management to make the navigation safer, especially to ensure feasible and sustainable operations in high-density coastal regions.

Maritime navigation can be considered as an activity performed in a complex socio-technical system involving multiple stakeholders such as the ship's bridge crew, harbour pilot, and the vessel traffic service (VTS) to list a few, and is carried out by multiple joint cognitive systems (da Conceição et al., 2017). Here, stakeholders refer to actors who exert direct influence on the dynamic context related to the movement of the vessels. The bridge team typically consists of the master of the vessel, along with navigation officers and watchkeeping crew members. The harbour pilot is an experienced navigator with local navigational expertise who assists the bridge team in transiting towards and from the port. VTS monitors the coastal traffic in the vicinity of the port and coordinates with the harbour pilot and the bridge team for the safety of navigation. While the primary control related to a ship's navigation resides with the bridge team, agents such as harbour pilots and VTS operators provide indispensable support and coordination to the vessels that are navigating in the coastal waters. Some of the equipment utilised for conducting maritime navigation by the above-mentioned stakeholders are Electronic Chart Display and Information System (ECDIS), Global Positioning System (GPS), Radio Detection and Ranging device (Radar), Automatic Identification System (AIS) and Very High Frequency (VHF) radio. The navigation information and parameters obtained from such equipment are monitored and continuously evaluated against the passage plan and the desirable values initially agreed. The safe navigation within a particular coastal region therefore is achieved as an outcome by joint control of the vessel.

In the present study, we investigate the role of operators responsible for executing the VTS maritime navigation. Increasing automation and digitalisation are leading to changes in how ships navigate in high-traffic sectors and how safety and traffic fluency are maintained in those regions. As a result, VTS operations are also evolving with the need to manage the maritime traffic sectors in their respective areas, provide navigational assistance and promote communications of all the actors responsible for safe navigation. The human factors that influence the performance of the VTS operator require special consideration.

1.2. Vessel traffic service operations

VTS can be described as a shore-side maritime traffic monitoring system that tracks vessels and provides navigational advice in a specified geographical area. The establishment of VTS by coastal states is guided by the International Convention for the Safety of Life at Sea (SOLAS) Chapter 5 – Safety of Navigation regulation 12 (IMO, 2023). Additionally, the International Maritime Organization (IMO) and the IALA have framed various resolutions, technical and operational standards for the VTS. IALA has developed a document called *VTS manual* to put forward recommendations, standards, guidelines and content of model courses for training of VTS operators (IALA, 2021). The implementation of the above-mentioned international regulations and standards is ultimately facilitated by the national law of the region where VTS is established and operated. The VTS is operated and manned by the VTS operators responsible for the fluency of maritime traffic and the exchange of relevant information related to vessel movements. The recruitment, training and certification of VTS operators are guided by the IALA G1156, which orients the competent authorities in each coastal state about the minimum competence requirements, training and assessment and model courses for continuous development of the VTS operators (IALA, 2022a). The appropriate number of VTS operators required to manage the shift in the VTS also varies and is informed by the IALA guidelines such as G1045 – staffing levels at the VTS centres (IALA, 2022b).

The services provided by VTS can also be divided into three parts, namely (1) Information Service (INS), where the VTS provides information to support safe navigation and informed decision-making of the vessel. Such information could include hydrological or meteorological data, information regarding traffic movement, presence of navigational hazards and appropriate VHF channels to use. (2) Navigation Assistance Service (NAS) where the VTS actively supports a vessel for a brief period to ensure safe transit. Such information could include suggested courses and speed to follow, bearings and distances to important landmarks or hazards and traffic-related warnings. (3) Traffic Organizational Service (TOS) where the VTS aims to regulate the overall local maritime traffic density by providing clearance for anchoring or transit, organising a particular order for movement and providing directions towards dedicated zones, lanes or areas.

A typical VTS runs 24 h with time division of two or three shifts having six or seven VTS operators with a team leader in each shift present (Yoo & Kim, 2021). However, since the deployment of VTS is nationally regulated, there are significant variations in global manning arrangements. The staffing of the VTS is influenced by several factors such as traffic density of the area under surveillance, number of workstations available, experience of the VTS operators and the types of vessels frequenting the area. Thus, the need to consider ergonomics aspects associated with the VTS operations and reduce the likelihood of safety lapses due to human factors-related issues. Figure 1 below provides an example of an operational setup from an actual VTS station in northern Europe.

The performance of individual human operators in modern work environments such as VTS is often discussed from the perspective of cognitive ergonomics. This considers the capabilities and limitations of human operators (e.g. perception, memory, reasoning and motor response) when interacting with machines and their overall fit with the task at hand and the work environment (IEA, 2024). The operator performing their work tasks first needs to perceive various information elements present in their dynamic environment and assess the situation before being able to coordinate with the other team members. The cognitive factors which are often discussed in relation to the operator performance are (visual) perception, attention, mental workload, cognitive fatigue,

Figure 1. Example of operational setup in a VTS station. Image credit: Gesa Praetorius.

decision making, situation awareness, memory and mental models, to name a few (Mehta, 2016; Oury & Ritter, 2021; Stanton et al., 2017).

As described above, VTS operations also have a social or teamwork component due to the need to collaborate with other VTS operators and the ship's bridge team in addition to the harbour pilot. Navigating a ship, especially in the coastal waters, requires the joint efforts of the above-mentioned actors. When describing the working of teams in complex socio-technical systems, certain specific social factors should be considered. A number of social factors are discussed in the teamwork literature. Rafferty et al. (2010) reviewed contemporary teamwork models and listed five social factors as particularly relevant to teams working in complex socio-technical systems: communication, cooperation, coordination, schemata (shared mental models) and (team) situational awareness. For discussing the performance of human operators and operational aspects, the cognitive and social factors as described above are critical in terms of human-machine interaction research and development efforts, and for promoting safe outcomes.

1.3 Related studies of vessel traffic service

As described above, VTS plays a vital role within the international shipping framework in ensuring the fluent movement of maritime traffic and promoting safety at sea. In recent years, due to technical, organisational and environmental advancements, the VTS operations have undergone significant changes as a response with the focus on improving overall efficiency (Praetorius, 2014). The operators working in the VTS centres are at the sharp end of an increasingly complex system with shifting attentional dynamics, knowledge and strategic factors (Cook & Woods, 2018). Understanding the human factors challenges in relation to VTS can make it more adaptable to the transforming operational scenario resulting from increased digitalisation and automation. Several recent studies are now focusing on addressing human factors related issues pertaining to VTS operations. One of the earliest studies in this regard by Praetorius et al. (2010) depicted VTS as a high-reliability organisation consisting of various inter-connected technical and non-technical sub-systems, where the operators utilise a variety of decision support systems to carry out their tasks. Subsequently, Praetorius et al. (2015), using the Functional Resonance Analysis Method (FRAM) and grounded theory approach, provided insights into various functions of the VTS, potential sources of operational variability and relationships with the larger maritime traffic environment.

Brodje et al. (2013) used the applied cognitive task analysis (ACTA) technique during simulation exercises to look at the patterns of communication between VTS operators with harbour pilots and ships. As a result of knowledge elicitation and information modelling, they presented several factors that are potentially responsible for miscommunication between all the actors during navigation. Similarly, Costa et al. (2018) analysed various factors influencing the communications by the VTS operators through active fieldwork. They listed role ambiguity, judgement, trust and over-reliance and closed versus open loop communications as the key non-technical factors influencing relevant and accurate communications by the VTS operators. Relling et al. (2020) in their research, focused on the role of operator experience, teamwork, organisational knowledge and communication in coping with operational complexity in VTS (this largely corresponds to what Salas et al. (2005), called the "big five" team factors). Through ACTA and critical decision method techniques, they tried to model the cognitive demands of the VTS operators and how non-routine situations are addressed. Furthermore, they used the lens of systems theory to illustrate the maritime traffic system with VTS as one of the key components within it. A key takeaway was how the variability of the performance by the vessel operators is responded to by the adaptability of the VTS operators. Recently, Crestelo Moreno et al. (2022) carried out a systematic literature review examining the relationship between human factors (cognitive or social factors) issues such as – fatigue, mental workload, resilience, communication, teamwork, and the performance of the VTS operators. In addition to elaborating on the 11 representative articles they selected to discuss above-mentioned factors, the study provided a detailed description of the regulatory framework, and guidelines associated with the VTS operations.

1.4 Research scope and aims

With the transitional changes occurring in maritime navigation, many research studies, as mentioned in the previous sections, have focused on describing VTS-specific issues of interest. There has been an increasing number of studies in recent years that suggest solutions for accommodating increased digitalisation and automation in maritime navigation. However, there is relatively less discussion of the cognitive and social factors that would be specific to day-to-day operations for VTS operators. Understanding the human factors challenges associated with the VTS operations is necessary due to the potential of safety improvements, error prevention and optimisation of training approach. The comparison of study designs, empirical data and emergent key findings influencing the performance of the operators could aid in filling an existing knowledge gap related to VTS research literature. The present study will systematically synthesise and analyse the existing research pertaining to cognitive and social factors in VTS operations for the last two decades and outline prospective research directions for the VTS operations.

2. Methods

2.1. Systematic literature review

This section describes the sequence of steps taken for extracting the relevant literature. To meet the stated research aims, a systematic literature review was performed as per the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines and Boolean key words search strategy (Moher et al., 2009; Page et al., 2021). A Boolean search strategy refers to using multiple keywords in a search with their relationships defined by Boolean operators such as AND, OR and NOT to define the focus of literature extraction from the database. The following combinations of keywords were used in searching for the relevant literature in the initial identification stage ("vessel traffic service" OR "vessel traffic services" OR "VTS") AND ("workload" OR "decision making" OR "situation awareness" OR "fatigue" OR "attention" OR "vigilance" OR "teamwork" OR "communication" OR "coordination" OR "collaboration" OR "shared mental models" OR "schemata" OR "mental model" OR "human factors").

The search was performed across six databases: Web of Science, ScienceDirect, ProQuest Psychology, ProQuest Social Sciences, PubPsych and APA PsychInfo. These six databases were selected from a pool of available databases due to their focus on archiving psychology and human factors-related research. A total of 600 records were extracted initially through a Boolean search strategy approach.

The extraction of the records from the above databases was carried out on 1st February 2024 and the reference manager software Zotero was used to store and arrange the records. Thereafter, de-duplication of records was carried out step by step by manually comparing the titles and other identifying details in each record. A total of 510 records remained after removing duplicates. Thereafter, abstract screening of records was carried out using two authors in two stages. In Stage-1, the first 20 abstracts were screened parallelly by two authors using the inclusion criteria as described below:

(1) The study discussed cognitive and/or social factors in the context of VTS operations.
(2) The study had collected empirical data either in actual VTS and/or in VTS simulators.
(3) The study was published in the English language.
(4) The study was published as a peer-reviewed research article between the years 2000–2023

Both authors achieved 100% agreement on the screening results of the first 20 abstracts. Subsequently, the first author carried out the screening of the remaining records. A total of 471 records were excluded at the conclusion of this stage, and a total of 39 records were deemed suitable for full-text review. Thereafter, the full text review of 10 articles was carried out in parallel by two authors using the same inclusion criteria as described above. An agreement rate of 80% was achieved in this step. The cases where disagreements arose were viewed as edge cases and were further discussed by both authors. This discussion re-evaluated the cases against the agreed criteria, and mutual consensus regarding their eligibility was achieved in all cases after the clarifications. Subsequently, the first author carried out the full-text review of the remaining articles. A total of 26 records were excluded after full-text review, which did not explicitly have cognitive and social factors in the VTS operations as a research focus, only leaving 13 articles with empirical results for the qualitative synthesis process. An additional six articles were identified after a citation analysis of the articles screened for the full text evaluation. These articles were flagged during the full-text reviews of the 39 records and their listed references in the previous stage. A total of 1734 references, which were screened in this process, yielded six articles meriting further consideration. A full-text review process was conducted again, and the articles were evaluated through the same predetermined inclusion criteria for consideration in the final list. Therefore, a total of 19 articles were finalised and included for the literature review, qualitative comparisons and discussions with regards to the cognitive and social factors of the VTS operators. Grey literature was not included in the current study as the focus was directed towards peer-reviewed journal articles for ensuring methodological consistency. The screening approach involving both authors in two stages as described above enabled a comprehensive review of records from the six databases while also minimising biases and accounting for inter-rater reliability. The following Figure 2 describes the PRISMA flow diagram, the number of records extracted from each of the six databases, the de-duplication process and the associated steps related to the systematic extraction of the relevant articles for further analysis.

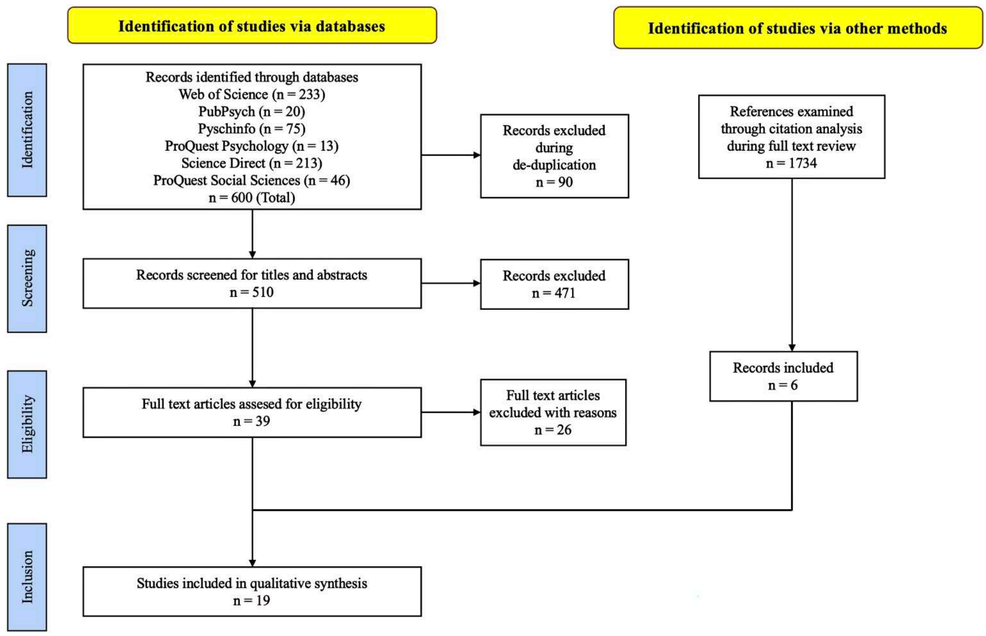

Figure 2. PRISMA 2020 flow diagram for new systematic reviews, which include searches from databases and registers only. Adapted from Page et al. (2021).

2.2 The qualitative synthesis process

After extracting the final count of articles, they were analysed in full text and grouped as per various human factors influencing the performance of operators in complex socio-technical systems as described earlier. The grouping was carried out after examining the content of the articles and their objectives and areas of investigation. To pursue these methodological steps systematically, a qualitative synthesis framework was followed. Qualitative synthesis can be defined as "the process of pooling qualitative and mixed method data and then drawing conclusions regarding the collective meaning of the research" (Bearman & Dawson, 2013, p. 252). The results were classified accordingly. Furthermore, the evidence was juxtaposed following the integrative narrative summary process as outlined by Dixon-Woods et al. (2005). According to the authors, the integrative review and synthesis of selected literature need not strictly be positivist as in aggregating the quantitative data but may involve providing a descriptive summary with already defined concepts or variables (Dixon-Woods et al., 2005).

3. Results

3.1. Summary of the articles

The articles that were selected for inclusion in the current review are summarised in Table 1. After full text review, information was extracted about the selected articles' author affiliation, sample size, country of origin, the methodological design of the studies and the human factors discussed. In the case of the country of origin of the

Table 1. Summary of the selected articles.

S. no	Authors	Sample size	Country of Origin	Study design	Cognitive/Social factors investigated
1	Li, Chen, Lee et al. (2020)	68	Singapore	Interviews / Survey	Fatigue
2	Song et al. (2022)	4	Japan	Experiment	Situation Awareness, Decision making
3	Brodje et al. (2013)	7	Sweden	Applied Cognitive Task Analysis / Simulation	Decision making, Communication
4	Crestelo Moreno et al. (2023)	23	Spain	Field Study	Fatigue, Mental Workload
5	Li, Chen, Xu et al. (2020)	42	Singapore	Interview / Case study	Fatigue, Mental Workload, Situation Awareness
6	Xu et al. (2020)	7	Singapore	Interview / Field Study / Experiment	Fatigue, Mental Workload
7	Aylward et al. (2020)	16	Sweden/UK/ Norway	Simulation / Observation	Communication, Mental Workload
8	Relling et al. (2020)	7	Norway	Applied Cognitive Task Analysis / Simulation	Communication, Teamwork
9	Mansson et al. (2017)	18	Australia	Interview / Focus group discussions	Teamwork, Coordination, Perception
10	Praetorius et al. (2015)	8	Sweden/ Germany	Functional Resonance Analysis Method	Communication, Coordination, Decision making
11	Costa et al. (2018)	7	Sweden	Grounded Theory	Communication, Decision making
12	Li et al. (2019)	8	Singapore	Case study / Machine learning	Fatigue
13	de Vries (2017)	7	Sweden	Functional Resonance Analysis Method	Communication, Decision making, Perception
14	Brodje et al. (2010)	13	Sweden	Interview	Perception, Situation awareness
15	Murai et al. (2015)	7	Japan	Field Study	Mental Workload
16	Yen et al. (2016)	95	Taiwan	Survey	Fatigue
17	Kum et al. (2008)	98	Turkey/Japan	Survey / Field study	Mental Workload
18	Baldauf et al. (2023)	14	Germany	Survey / Simulation / Focus group discussions	Communication, Decision making
19	Relling et al. (2022)	26	Norway	Focus group discussions / Simulation	Coordination, Decision making

selected articles, affiliation of first author is used to characterise the origin if no explicit information is provided of the sample respondents. The studies had predominantly Singapore, Sweden, Japan and Norway as their country of origin among others. The sample sizes in the studies tended to vary noticeably. This could to an extent be attributed to the choice of study design employed, in which the survey-based studies have large sample sizes, whereas field studies while interview-based studies have relatively small sample sizes. A wide variety of research designs were observed to be employed in the studies depending on the human factors being investigated. The relative proportion in percentage of the factors featured in the literature review is illustrated in Figure 3.

3.2. Qualitative synthesis of the studies

The selected articles were analysed and compared with regards to the cognitive and social factors being described by them through empirical evaluation. In the following sections, we will present the topics that emerged as the following dominant factors in the articles.

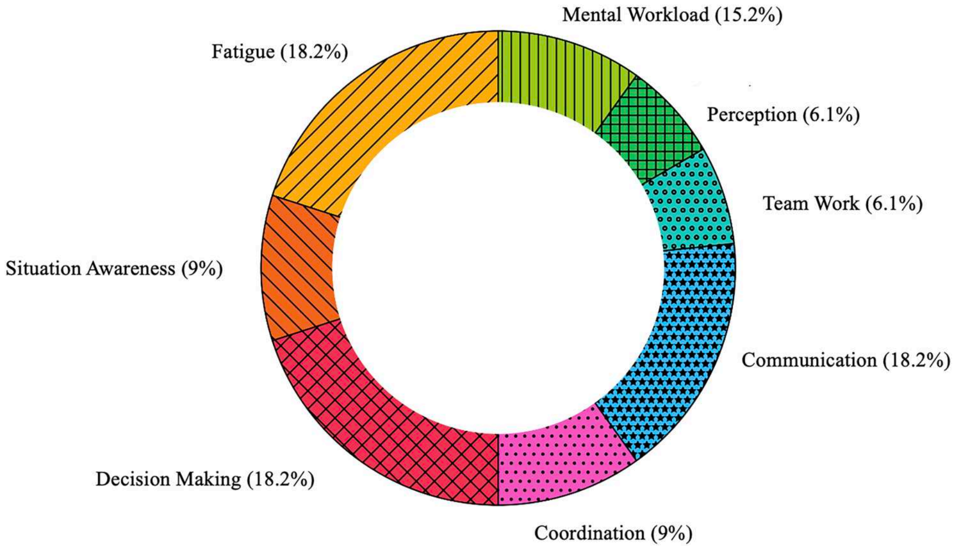

Figure 3. Relative proportion (%) of the factors featured in the literature review.

3.2.1. Fatigue

Fatigue is one of the most discussed performance factors in the VTS operator literature we reviewed. When investigating complex socio-technical systems, it may be challenging to find a uniform definition of "fatigue" and is interpreted differently between contexts.

Li, Chen, Lee et al. (2020, p. 1344) addressed this issue by defining fatigue as "a suboptimal physical, emotional, motivational, cognitive condition caused by a prolonged period of exposure to task-related stimuli". Furthermore, they state that the VTS operators suffer from multi-dimensional fatigue with physical fatigue being relatively more dominant than cognitive fatigue. They did an observation study of VTS operators, follow-up interviews and review of standard operating procedures using the SHELL model (Edwards, 1981), the "Swiss cheese model" (Reason, 1990) and a network-based evaluation. The authors identified 12 core causal factors for fatigue: (1) rest/recovery (2) workload (3) health and wellness condition (4) safety culture (5) amount of information (6) organisational rules (7) overlap of vessel information (8) subjective feelings (9) unknown markers/ notes left by other operators (10) continuous monitoring (11) language barrier and (12) unnecessary alarms (Li, Chen, Lee, et al., 2020).

Similarly, Crestelo Moreno et al. (2023) performed a field study in a Spanish VTS with VTS operators being evaluated through task attention control software and other self-reported standardised fatigue and sleepiness rating scales. The VTS operators were evaluated against these measures in morning, evening and night shifts with the data collected at the beginning and the end stages for the scales and throughout the shift duration for task attention control response. They found that the VTS operators had relatively higher fatigue and mental workload during their night shift. The operators reporting sufficient sleep (i.e. minimum 8 h) rated the onset of fatigue during their shift lower than those who had insufficient sleep (i.e. less than 8 h). However, the amount of sleep was not found to have a statistically significant effect on the reported mental workload during the shifts.

Li, Chen, Xu et al. (2020) focused on mitigating alarm-induced fatigue. Utilising a user requirement-driven approach with the theory of inventive problem solving, quality function deployment and process-based elicitation from VTS operators in Singapore, the authors come up with seven core user requirements. These requirements were listed as: (1) accurate alarms, (2) effective alarms, (3) comfort, (4) safety, (5) ease of use, (6) responsiveness and (7) informative alarms. The authors further recommend that conventional visual and audible alarms should be replaced with multimodal alarms that have visual, sound and haptic feedback. This could reduce the VTS operators' workload and improve their situational awareness.

Measuring and managing cognitive fatigue during operations can be difficult, without those measurements themselves being disruptive to the work being performed. Li et al. (2019) proposed using non-obtrusive eye-tracking with gaze bin analysis instead of using saccades and fixation duration. They utilised an experimental approach involving eight participants from VTS Singapore and the use of fatigue detection scales such as Samn-Perelli fatigue scale and Mackworth clock test. The gaze bin analysis method in eye-tracking context can be helpful as it divides the continuously obtained eye-tracking data metrics, such as fixation, saccades and gaze duration, into discrete time or spatial intervals (bins). Using this novel approach, the authors attempted to provide an alternate method to train a machine learning algorithm for human fatigue level detection. Their gaze bin analysis algorithm achieved a relatively better performance in terms of accuracy, sensitivity and specificity than the classical linear regression, decision tree and support vector machine models. However, the authors cautioned that while this approach could be a good task-independent fatigue indicator for VTS operations, it cannot yet distinguish between medium-level fatigue and alertness.

While it remains challenging to resolve how operator fatigue influences VTS operations, the recommendations, guidelines and novel methodology being developed shed light on mitigation strategies, preferred procedures, design requirements and its pro-active avoidance. Crestelo Moreno et al. (2023) recommend the need to strictly regulate rest periods and operator shifts in VTS to proactively counteract the advent of fatigue. Getting sufficient sleep (i.e. minimum 8 h) emerged as one of the protective factors for mitigating fatigue in their study. Similarly, structural equation modelling of survey data on sleep, workload and fatigue (Yen et al., 2016) found sleep quality to be the most important factor for VTS operators mental and physical fatigue levels. The perceived workload was also found to be important, whereas the work environment itself was deemed relatively unimportant.

3.2.2. Mental workload

Much of the reviewed literature emphasises the mental workload of the VTS operators. The evaluation of the mental workload of the VTS operators has direct bearings on operational safety, work procedures and human-machine interface aspects of the VTS. Furthermore, it influences the resources planning, allocation and training of personnel. Two of the studies (Kum et al., 2008; Murai et al., 2015) specifically had mental workload as their main focus.

Kum et al. (2008) found no difference in mental workload (self-reported with NASA-TLX) between two survey cohorts of VTS operators' routine operations. Mental workload was independent of the level of experience, age and nationality of the operators, but varied with task-specific and individual factors. The authors suggested that NASA-TLX should be used in conjunction with other objective or physiological measures. This study appears to be one of the earliest attempts to quantify and discuss the mental workload construct and its implications in VTS operations.

Murai et al. (2015) adapted a more objective measure and employed thermal camera measurement of VTS operators' facial temperature as a proxy for determining their mental workload. They argue that facial temperature fluctuations accurately represent short-term changes in mental workload and overall long-term trends. More experienced VTS operators had more stable facial temperatures.

Other studies also discussed the issue of mental workload albeit obliquely or secondarily. Crestelo Moreno et al. (2023) found VTS operators' mental workload (measured with NASA-TLX) to be associated with fatigue levels. Li et al. (2020) hypothesised that smart alarm systems can reduce mental workload and promote safety. Xu et al. (2020) stated that the number of vessels and their speed are the most crucial factors influencing the mental workload of the VTS operators. They suggest replacing current "one size fits all" shift policies with adaptive rotating shifts based on the Automatic Identification System (AIS) output. A well-rested operator can cope with task demands better and have a lower mental workload. In contrast, reducing certain task demands, such as by providing ease of communication between vessels and the VTS, or the possibility of early route-information exchange might not have the intended effect on the perceived mental workload (Aylward et al., 2020). However, more research may be needed to determine the impact of increased ship-shore information exchange and the mental workload of the VTS operators.

3.2.3. Communication

Communication is one of the most important social factors influencing the daily performance of the VTS operators. Flin et al. (2008) described communication as consisting of four components: *what* (content), *how* (means), *why* (reason) and *who* (target). Several of the featured studies highlighted the importance of communication in ensuring the safety and efficiency of the VTS operations.

Costa et al. (2018) carried out multiple field studies of the VTS centres with a qualitative bottom-up "grounded theory" approach to describe communication factors. The following were seen as pertinent to VTS operator's judgement and decision-making abilities: (1) role ambiguity, (2) judgement trust and over-reliance (3) closed or open loop communications. Role ambiguity often comes into play when monitoring the traffic sector area and coordinating with multiple ships. The VTS operators often adopt an indirect approach when communicating with ships on safety matters and prefer asking clarification questions instead. The VTS operators by merely sensing the communication patterns of the ship's Officer on Watch (OOW) can form an initial judgement regarding how much focus or caution should be exercised on that particular vessel. Prior acquaintance with the vessel in case of repeated port visits also helps in this regard and influences how much care and frequency of communication is undertaken. Any deviation from established, albeit informal norms of traffic movement call for further communication and resolution of the situation. The closed-loop communication between VTS and vessels is a must, especially in the conflicting situations where the former factors of role ambiguity and trust levels are not being satisfactorily met between the VTS and vessel.

Brodje et al. (2010) also discussed communication factors and presented a cognitive model of the information sharing processes for VTS operators. Operators use vessel size, speed, location, traffic intensity and anomalies to construct a mental picture of the ongoing scenario. Apart from the visual sensors available to them, a primary means for ascertaining important information is the VHF radio. Taking the past traffic patterns into account, current deviation and trust level on the vessel being monitored, the VTS operators choose to intervene or further delay in carrying out their role-specific actions. Similarly, to the issues mentioned by Costa et al. (2018), the VTS operators are cautious about not intervening in anticipatory actions to avoid being perceived as interfering with the ship's bridge team or pilot. The issues of role ambiguity and the performance protocol therefore appear central to the communication factors influencing the VTS operator´s actions.

3.2.4. Decision making

Understanding decision-making processes for VTS operators is crucial for improving system design, risk management and overall efficiency, as discussed by Song et al. (2022), Praetorius et al. (2015) and de Vries (2017). They use a wide variety of methods to describe decision-making processes occurring during the VTS operations. For example, Song et al. (2022) used the framework of "recognition primed decision making" (Klein, 1998) to describe the VTS operators' cognitive processing in terms of three stages: situational awareness, situation judgement and decision making. They proposed an instructional tool, namely – Vessel Traffic Routine, to aid the decision-making processes of the relatively inexperienced VTS operators. This involves recognising developing risks in the traffic sector, comparing the positional relationship between vessels and giving advice that is aligned with a suggested action. They found that such tools had faster and more accurate risk prediction, although results should be replicated in a larger sample size.

Praetorius et al. (2015) and de Vries (2017) used the cognitive engineering approach "functional resonance analysis method" (FRAM) to inform decision-making and performance issues of the VTS operations. This approach describes system variability and complex system dynamics through the portrayal of functional divisions and inter-dependencies. Praetorius et al. (2015) compared two VTS centres in Europe and found that VTS systems contribute to safety and traffic management primarily in two ways: by shaping preconditions for the vessels in their traffic sector and by creating foresight for the other actors in the port services such as pilots and harbour services. Observation of the two VTS centres also highlighted the adaptability for unforeseen events. While tight coupling of multiple actors helps in planning ahead, too many inter-dependencies can lead to a more "brittle" system that prevents adapting to unexpected situations. Constraints (such as tidal window, channel depth, jetty length, etc.) assist in the decision-making aspects of the VTS operations by increasing the predictability of actions.

Similarly, de Vries (2017) used FRAM to analyse the navigational assistance that pilots and VTS operators provide in the pilotage phase of navigation. The study provided an overview of the navigational assistance process, which showed how VTS operators contribute to maritime safety. A Successful navigation assistance process depends upon (1) adequate preparations, use of local knowledge and foresight to integrate all relevant information (2) mutual trust and communication between vessel, pilot and VTS. The study describes the use of vessel trajectory vectors in ECDIS/Radar for monitoring and anticipating actions, the use of VHF radio to confirm the vessel's intentions and use of online services to forecast weather and environmental conditions. The role of local knowledge and preparations cannot be over-emphasised in the navigation assistance process. Knowledge of local geography, prior experience as navigator and understanding of local traffic patterns were termed vital for VTS operators. Reciprocally, the VTS operators preferred to interact with the vessel via local pilots and felt more confident when doing so.

The above two studies demonstrated the complex traffic management performed by VTS centres, highlighted potential sources of performance variabilities, and suggested strategies VTS operators use to work within the safety envelope.

3.2.5. Perception

Perception in this context refers to how VTS operators interpret the information presented to them. The technological advancements and ongoing digitalisation of maritime navigation also affect how VTS operators process information available to them.

Brodje et al.'s (2010) interview study used the ACTA technique to identify key sensors used for anomaly detection and pattern recognition by the VTS operators. The VTS operators utilised only a few of the available information sources: VHF radio, radar, Closed Circuit Television (CCTV) cameras, AIS, meteorological sensors and databases. VHF radio is used not only to exchange information but also to monitor communication between navigation actors and understand their intention and has been mentioned as the primary means of communication also in other studies (Brodje et al., 2013; de Vries, 2017), Radar is mentioned as one of the main visual tools (along with ECDIS), and is used to locate ships and other crafts in the VTS sector and to obtain parameters such as their heading, speed, closest point of approach, etc. Additional sources of visual information, such as CCTVs, can be used to double check and confirm the information, especially with regards to specific points of interest to the VTS operator. The ECDIS system with electronic navigation charts and overlays of navigational information from equipment (Radar, AIS, GPS, and other instruments) have significantly improved the efficiency of traffic information exchange. They can merge several information sources and present them on one screen. The VTS uses this for orientation, as they display similar traffic situations to ship's bridge team and are indirectly instrumental in developing shared mental models during navigation (de Vries, 2017). The selective use of sensors and information sources depended on the experience and expert judgement of the VTS operators.

The reviewed studies show conflicting experiences for how AIS is used, which broadcasts parameters such as vessel's name, coordinates, speed, heading, navigational state, and destination to a limited geographical area. Since its induction in 2002, it has had a significant impact on traffic management and collision avoidance (Svanberg et al., 2019). However, Brodje et al. (2010) found that VTS operators did not use AIS extensively, and that some of them did not trust the information. This may be due to the fact that while some information is automatically added from the ship's sensors, other information related to collision avoidance needs to be manually updated. Therefore, AIS was described as strictly complementary to other information sources, such as the VHF radio. However, Mansson et al. (2017) mentioned that AIS is used as a primary tool for monitoring traffic and forming a shared situational picture among the VTS operators. It was also used by other shore-side service providers, such as tug master and the pilot, who also coordinate with the VTS operators while manoeuvring the vessels. Certain weather events, such as reduced visibility due to heavy rainfall, might also increase the reliance on AIS overlay on the ECDIS, as the radar overlay in such scenarios will produce excessive clutter (de Vries, 2017).

3.2.6. Coordination

Coordinating the coastal traffic with other navigational actors such as pilot, shore services and the vessels themselves is one of the central functions of the VTS. Therefore, the factors affecting coordination merit further discussion. In this regard, Relling et al. (2020) utilised the ACTA methodology to understand how VTS operators cope with complexities in their everyday work. One of the primary findings from their study was that the operator's prior experience, such as background and years of experience, is a major source for coping with operational complexity. The more experienced an operator is, the easier it becomes for them to perform coordination tasks. However, they also mention that in the active-duty team of the VTS operators, relatively less experienced operators are often teamed up with experienced operators to provide a reasonable team composition. Clearly outlined and detailed procedures often aid the operators in carrying out their duties seamlessly. Due to the advances in technology, it is also possible to have such procedures digitally stored, which are reproduced on demand by the VTS operators in their computers and then actions are taken accordingly.

Aylward et al. (2020) also described how the coordination issue is being addressed with novel modes of communication and information exchanges through technical solutions. Most noticeably, they described a Sea Traffic Management (STM) approach. This innovative concept originated from a number of inter-connected EU research projects between 2009 and 2014 (Porathe & Brödje, 2015). Its primary functions involve route optimisation, strategic route exchange, port call synchronisation and monitoring services (STM, 2024). Route exchange between the actors involved in coastal maritime navigation (including VTS) should improve predictability, planning and execution of coordination tasks when the vessels arrive in the VTS sectors.

A simulation validation (Aylward et al., 2020) found that VTS operators evaluated the STM services positively and that they may improve real-time coordination. Particularly, the participants felt that the communication functions offered by the STM service can potentially mitigate the need to use VHF radio in the future. However, participants were also concerned that STM could increase workload. Furthermore, as STM services have now been introduced worldwide, further research might be required in this direction.

The reviewed literature also discussed the reliance of VTS operators on the marine pilot for coordination with the vessels in their sector. Mansson et al. (2017) described the central role played by the pilot in coordination activities. Similar to the finding from de Vries (2017), they mentioned that VTS operators minimised communication with the ship's bridge team until or unless the pilot gets involved. This is partly to avoid miscommunication but also hints towards the role of trust in coordination. These statements show the VTS operators' dependence on marine pilots to facilitate communication and coordination with the vessels. The VTS operator and pilots along with shore service providers such as tug master, work in the same geographical region in contrast to the bridge team of the vessel and therefore an element of understanding and implicit trust is often present during coordination.

4. Discussion

4.1. Summary of the findings

The current systematic literature review and qualitative synthesis process identified several pertinent findings from the included studies related to the VTS operations. While digitalisation and automation are causing changes in operations of VTS and improvement in the overall efficiency, the operators would also need to adapt to evolving technological landscapes to carry out their actions safely and maintain the risks within acceptable limits for the overall maritime traffic system (Crestelo Moreno et al., 2023; Relling et al., 2022). Cognitive and social factors such as fatigue, mental workload, communication, decision making, perception and coordination issues demonstrated both challenges as well as emergent opportunities for the VTS operations. Some of the reviewed articles (e.g. de Vries, 2017; Mansson et al., 2017; Praetorius et al., 2015) also commented on their role in the larger maritime traffic system and described inter-connections with the pilot and ship's bridge team. It can be argued that the role of the VTS is predominantly oriented towards providing area-specific information to vessels, traffic fluency organisation and navigational assistance. The duties of the VTS operator will change as automation and remote pilotage are introduced in coastal areas. This might entail a more active and tactical role as mentioned by Relling et al. (2022) and can also influence the workload and team composition in VTS centres. However, it may be challenging to resolve what the role of the pilot would be after such a transition. Several of the studies stated that the pilot acted as a mediator between the vessel and the coastal state during coastal navigation and communication (Brodje et al., 2010; de Vries, 2017; Mansson et al., 2017). As the pilot provides most of the coordination in the maritime traffic system, it will require deliberate planning and preparation to provide an alternative to the pilot's functions.

Among the cognitive factors affecting the performance of the VTS operators, several authors emphasised fatigue. Some studies distinguish between physical fatigue and cognitive fatigue (Li, Chen, Lee et al., 2020). Several strategies to reduce the impact of physical fatigue were suggested, such as providing adequate rest periods, practising sleep hygiene and shift rotation (Crestelo Moreno et al., 2023; Yen et al., 2016). Advanced analytics and adaptive approaches, such as those mentioned by Xu et al. (2020), could provide an evidence-based solution. Cognitive fatigue is related to mental workload and may be more challenging to measure in the operational scenarios for the VTS operators. Suggested strategies ranged from using self-reported measures such as NASA-TLX (Kum et al., 2008) to non-intrusive, objective measurement techniques such as the facial temperature measurements using thermal cameras, as proposed by Murai et al. (2015). Additional objective techniques, such as heart rate variability, pupil dilation or galvanic skin response measurement, can also be employed in certain scenarios (but would require wearable devices for the VTS operators). Future research could be directed towards obtaining psychophysiological measurements coupled with predictive algorithms to proactively determine fatigue development in VTS operators. The advantage of using such an approach would entail not only more objective data collection than self-reported measures but also proactive detection and monitoring. Furthermore, using psychophysiological measures can also enable longitudinal data collection at the VTS centres, which can aid in developing tailored interventions and support the safety performance of the operators long-term. Estimating the cognitive state of the VTS operators and understanding its impact on performance, therefore, remains an area of ongoing investigation for the maritime stakeholders.

Communication is another arena where complexity, interdependence and variability in methods are assumed to impact safety outcomes. Due to the global nature of the maritime industry, issues surrounding accurate and standardised communication practices persist for all the actors involved in navigation. While developments in the information and communication technologies can provide additional means for VTS operators to exchange information with the bridge team, the preliminary results about operational advantages have been mixed (Aylward et al., 2020). The prior exchange of navigational route information before the commencement of the voyage and additional modalities of communication should benefit in manoeuvring preparations and shared mental model development for both the vessel and the VTS centre. However, the reviewed literature did not provide conclusive answers to this issue. The VHF remains the primary means of communication by the VTS operators to determine the intentions of the vessels they are monitoring (Brodje et al., 2010; de Vries, 2017). Much of the communication between VTS operators and ships remains brief and follows established communication protocols. However, despite closed-loop communication being formally required, episodes where the ship's crew only acknowledge receipt of the message without correctly repeating it can lead to confusion (Costa et al., 2018). The issue of mistrust in communication, where the VTS operator avoids pointing out their concerns to the pilot or the ship's crew anticipating a negative reaction and deviance from using international language such as English in certain locations, can compound the existing communication challenges and lead to undesired outcomes (Brodje et al., 2010). Potential power imbalance between ships and outside parties may also impact communication (Sætrevik et al., 2018).

In terms of the impact of automation and digitalisation, the selected literature points out to the evolution of maritime navigation over the years, with a variety of technological solutions and decision support systems now available to the VTS operators; however, evaluation of their feasibility and integration into the workplace remains a work in progress. For example, the studies conducted by Brodje et al. (2010) and de Vries (2017) pointed out that VTS operators used a rather limited amount of information and sensors utilised in their routine tasks. The operators thus use only a sub-set of the total information elements available to them through various available equipment. The decision support tools, such as ECDIS and AIS, aggregate multiple navigation parameters and present them in one screen output. While the VTS operators appreciated the redundancy offered by multiple sources of information, some issues regarding the reliability and organisation of such information were also raised. For example, while the concept of the STM interface to support traffic coordination was positively received, its overall efficiency and usability issues require additional investigation (Aylward et al., 2020). Similarly, VTS operators use navigation equipment such as radar and AIS extensively but may not completely rely upon them (de Vries, 2017). An indication of the accuracy or confidence level of the information parameter presented could support their informed decision making.

The analysed results and findings present avenues for further research, which can be pursued to find solutions to some of the identified challenges. As evident in the examined literature, VTS forms one component of the maritime traffic system along with other actors such as pilots, the ship's bridge team and other coastal services actors. A structured analysis of the informational requirements of each sub-component and how the decision-making processes are impacted due to distributed cognition in the dynamic operations could shed light on future training needs as well as optimal interface design and information presentation to the operators. Furthermore, the impact of novel decision support systems and varying levels of automation within the VTS centres would also correspondingly require research into the possible impact on mental workload and attentional dynamics of the operators.

4.2. Limitations

Certain limitations were present when conducting the systematic review and qualitative synthesis of the selected research articles. Selection and interpretation bias are evident in all qualitative literature review studies. The current review selected articles based on research questions determined by the authors and a pre-defined inclusion criterion. Although the PRISMA guidelines and screening mechanisms help filter the articles deemed suitable for further analysis, the authors' assumptions and preconceptions can introduce subjectivity to the research framework.

Reviews are also influenced by publication bias in the existing literature. If certain findings are over-represented in the published research articles, they will also have an oversized impact on the review. For example, even though most VTS studies focus on individual operators, that does not mean that the team is not an interesting unit of analysis. Furthermore, it is also plausible that more relevant studies have been conducted, but have gone unpublished (e.g. due to unfavourable results), and are therefore not represented in the review. These should be considered limits to the review's generalisability. Additionally, one of the inclusion criteria being the studies published in English could result in limited visibility of other nations where similar studies in local languages could be present but were filtered out from the present investigation. However, such a regional bias could also be the result of the database indexing procedures. Future research approaches can extend the scope of the review by considering additional sources such as these and the inclusion of grey literature for broadening the evidence base.

The literature review was designed to explore only the relationship between the selected human factors and the overall context. The review was not intended to explore potential causal relationships between human factors. For instance, we did not aim to explore what impact a changed mental workload would have on operators' situational awareness, or what impact fatigue could have on communication and decision-making. Examining such linkages in cognitive and social factors of the VTS operators requires additional effort.

Finally, not all of the expected cognitive and social factors were found in the extracted literature. The Boolean search strategy employed a wide variety of keywords covering most of the expected keywords related to human factors. However, in the selected literature, no studies focused on attention, shared mental models or vigilance. While there may be some studies that discuss these factors, the present study only discusses the factors featured in the extracted articles.

5. Conclusion

The present study aimed to elaborate on the cognitive and social factors influencing VTS operations by performing a systematic review and qualitative synthesis of the past 23 years of VTS-related literature. A total of 19 research articles describe the prominent issues encountered by VTS operators in detail. The research output from this study provides insights into performance influencing factors for the VTS operators, practices and procedures in everyday operations. The review outlined factors such as fatigue, mental workload, communication, perception, coordination and decision making of the VTS operators and enumerated practical challenges faced by them and some possible solutions.

The theoretical contribution of the study stems from aggregating a small but increasing number of studies from recent years that focus on VTS operations, along with elaborating on technological and organisational issues surrounding the routine operations and their role in the larger maritime traffic system. This review of the current state of the art could be used to assess the research methods employed in the domain so far, before planning future investigations. The study puts the focus on the role of human elements in VTS operations, the challenges and limitations faced by them in performing critical tasks of managing maritime traffic while balancing safety and efficiency dimensions.

The policy implications for the maritime stakeholders mainly point towards improving the reliability of the operations by further clarifying the strategic role of the VTS operators, identifying vulnerabilities in communication issues, and further standardisation of the maritime traffic system to reduce ambiguity. By adopting a more proactive approach to studying human factors issues for the VTS operators, such as fatigue development, measurement of mental workload, and adequately integrating technological solutions, according to the capabilities and limitations of the operators, the safety of maritime navigation can be supported.

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