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Incorporation of seafarer psychological factors into maritime safety assessment

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ABSTRACT

Psychological factors have been a critical cause of human errors in sectors such as health and aviation. However, there is little relevant research in the maritime industry, even though human errors significantly contribute to shipping accidents. It becomes even more worrisome given that seafarers are changing their roles onboard ships due to the growth of automation techniques in the sector. This research pioneers a conceptual framework for assessing seafarer psychological factors using neurophysiological analysis. It quantitatively enables the psychological factor assessment and hence can be used to test, verify, and train seafarers' behaviours for ship safety at sea and along coasts. A case study on ship collision avoidance in coastal waters demonstrates its feasibility using ship bridge simulation. An experimental framework incorporating neurophysiological data can be utilised to effectively evaluate the contribution of psychological factors to human behaviours and operational risks. Hence, it opens a new paradigm for human reliability analysis in a maritime setting. This framework provides insights for reforming and evaluating operators' behaviours on traditionally crewed ships and in remote-controlled centres within the context of autonomous ships. As a result, it will significantly improve maritime safety and prevention of catastrophic accidents that endanger oceans and coasts.

1. Introduction

Human factors contribute to errors and mistakes which cause severe maritime accidents (Hetherington et al., 2006; Chen et al., 2020; Wrobel, 2021). Systematic control of human factors can effectively terminate system failures chain and prevent accidents. It is, therefore, essential to analyse human factors in maritime operations for safety at sea (Chauvin et al., 2013). The statistical analysis of the accident reports within the period from 2012 to 2017 by the Transportation Safety Board of Canada (TSB) and the Marine Accident Investigation Branch (MAIB) reveals that 30.77% of maritime accidents are associated with "poor communication and coordination", 32.69% with "ineffective supervision and support of the bridge team", 37.50% with "no clear order", 32.69% with "seafarers' unfamiliarity with equipment, insufficient capability, or ill-preparedness", and 15.38% "with poor lookout" (Fan et al., 2020a). From the perspective of ensuring ocean and coastal safety management, it is necessary and beneficial to reduce human errors through effective human performance measurement (HPM) and human reliability analysis (HRA). Compared to those in other sectors, maritime operations require more non-technical skills that significantly influence maritime safety, and investigations on human and organisational factors (HOFs) have been at the top of the research agenda in maritime safety (Fan et al., 2020c; Yildiz et al., 2021; Shi et al., 2021; Coraddu et al., 2020). It becomes urgent given the fast growth and development of maritime surface autonomous ships (MASS), which requires a paradigm shift of HPM moving the focus from seafarers onboard to traffic controllers in remote control centres.

Among the non-technical skills, psychological factors are critical to cooperative behaviours and appropriate competencies that impact maritime safety. For example, 21.63% of marine accidents involved operators in a low state of alertness, 16.35% under distracting conditions or not paying sufficient attention, 13.46% with fatigue, 4.81% with cognitive overload, and 1.92% with feelings of unhappiness, panic, or anger (Fan et al., 2020a). Several psychological factors of individuals, such as situational awareness (SA), are evidenced in maritime accidents (MAIB 23–2017, TSBM16P0362); these can be caused by the higher

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mental workload whilst using advanced navigation devices and autonomous techniques. Therefore, ensuring the next generation's ocean and coastal safety has become unavoidable. Quantitative methods have been applied to evaluate maritime risks, including collision avoidance (Feng et al., 2022), typhoon risks (Sajjad et al., 2020), and coastal erosion (Luo et al., 2013). However, the relevant studies aiming at human elements in maritime risk management are limited. Previous studies on human factors revealed positive correlations between individual factors and behaviours (Akhtar and Utne, 2014, 2015; Besikci et al., 2016; Tian et al., 2020). However, measuring these emerging psychological factors through traditional techniques/methods is difficult. Therefore, it is essential to develop new methods to understand and quantify psychological factors in maritime operations to evaluate the associated risk and the provision of HRA from a new perspective.

Among the most representative psychological factors in maritime operations are mental workload, fatigue, distraction, and SA. A significant number of maritime accidents, including the sinking of Titanic in 1912 (Labib and Read, 2013), the capsize of the Herald of Free Enterprise in 1987 (Chen et al., 2013), and the shipwreck of Costa Concordia in 2012 (Bartolucci et al., 2021) was attributed to mental overload, fatigue, distraction, and SA. It is also evident that mental workload affects other physiological factors (Lim et al., 2018; Wu et al., 2017). The mental workload can be utilised as one of the independent variables to calculate the level of other psychological factors (Lim et al., 2018). Such psychological factors are also frequently mentioned in accident reports, particularly fatigue (MAIB 22/2017) and mental overload (MAIB 20/2016). Psychological factors identified in accident reports are not necessarily comprehensive and often require further investigation such as the fatigue investigation by Rudin-Brown and Rosberg (2021). In the existing literature, it is evident that there is little research on the development of a robust methodology for psychological factor assessment in the maritime sector. Although relevant psychophysiological studies exist in other transport modes, such as driving behaviours in road transport (Zhang et al., 2014; Yan et al., 2015; Lafont et al., 2018), there is scant research using these techniques in the maritime domain. Physiological factor analysis, especially the interaction among the factors, sits in a back-row seat compared to the other HRA studies in the maritime sector. It reveals a significant research gap tackling HRA within the context of MASS, in which remote controllers would expect to deal with new, possibly more complicated mental workloads. The question of how to ensure their competence and performance to an acceptable safety level wants a robust and rational solution across multi-disciplines involving nautical science, psychological analysis, and safety engineering. The challenge is outweighed by the significance and implications to safety at sea and coastal pollution prevention.

Moreover, developing autonomous ships implies a reduced number of onboard crews. In other words, part of the crew's responsibility is supposed to be reallocated ashore, which will cause a fundamental change in maritime HRA and safe operations (De Vos et al., 2021; Chang et al., 2021; Wrobel et al., 2017). Whether working onboard or onshore, the human element is still one of the critical contributions to safe navigation. Neurophysiology can be utilised to quantify and analyse operator performance without overt behaviour being present. To be specific, a new methodology should be proposed to test the operators in the simulator or with the support of virtual reality technologies to explore the findings, especially for training purposes.

Both the reforming criteria of crew distribution and the novel design of the next-generation ships require a new methodology to quantify and analyse human behaviours under such circumstances. From the degree one to degree two of autonomy defined by IMO, some ship crews may be relocated to remote control centres, which requires an effective method to quantify human performance in different working places. It is an essential change for ship autonomy and maritime human factors, introducing new types of human errors and different levels of mental workload. In addition, the issue as to whether newly designed ships are user-friendly to operators needs to be tested using the new methodology. Additionally, it is essential to monitor a psychologically engaged operator in both training and practice. Considering this industrial research need, research on developing a new methodology becomes increasingly significant, given the industry's move from manned to autonomous ships, and hence the changing mental workload for the operators who remain onboard ships and the ones working in the remote control centres for autonomous vessels.

This paper aims to propose a new framework enabling the analysis of seafarer psychological factors using neurophysiological data and the incorporation of such factors into maritime safety assessment. It uses psychological tools to collect and analyse objective data to realise HPM in maritime operations. The framework is in nature, a methodology for experimental design, and the research scope is constrained to the use of psychological tools to conduct risk assessment for seafarers. The study will serve the maritime industry to evaluate and control the most critical risk factor – human factors – to improve the state-of-the-art of ocean and coastal safety management; on the other hand, it is configurated with a research focus on psychological experiment design and framework development, within which the literature and the methodology are described accordingly.

The structure of the paper is therefore illustrated as follows. Section 2 reviews psychological factors and their risk analysis in the maritime domain. Section 3 proposes an experimental data-driven framework to realise the physiological factor assessment. Section 4 then conducts a case study applying the framework to analyse the officers' mental workload in ship collision avoidance. It is followed by the conclusion in Section 5. This study serves as a stepstone for a new research direction in maritime safety to explore HOFs.

2. Literature review

This section is outlined in two subsections. First, the most significant psychological factors influencing maritime accidents are reviewed by a pattern of the definitions, followed by a real accident case to illustrate their importance, justify their selection, and analyse the status of their studies. Secondly, the neurophysiological methods and their applications to analyse the psychological factors in maritime operations are reported. In this process, the research contributions and novelties are highlighted at the end of each subsection. It is also noteworthy that classical HPM and HRA applications in maritime operations are criticised significantly by a summary of their disadvantages. Given the large number of relevant studies in this context and the focus/scope of this study, the literature review in this section is mainly about psychological factors and analysis in the maritime area.

2.1. Psychological factors in maritime accidents

Human factors are in nature risk factors derived from unsafe actions or omissions of people, which, within the maritime operation context, are associated with navigational factors, environmental factors, operational factors, and organisational factors. In addition, human errors refer to where people went wrong and explain how people's actions made sense at the time (Dekker, 2014). The complex mechanism of how people succeed and sometimes fail to get success makes human error analysis essential after the fact (Woods, 2010). Various studies have been conducted on human errors and human factors in maritime transport to illustrate their individual or joint causal evolution in accidents. Most studies on psychological factors in maritime accidents were based on the maritime human factors concept, involving an established framework for accident analysis (Zhang et al., 2020; Qiao et al., 2020; Weng et al., 2019), cyber risk perception modelling (Larsen and Lund, 2021), psychological assessment for maritime training (Makarowski et al., 2020), and safety behaviour investigation (Xi et al., 2021; Endrina et al., 2019). In addition, psychological studies aimed at maritime industry divided the psychological issues into specific factors to investigate their correlations and predictions using surveys and self-reported methods (Hjellvik and Saetrevik, 2020; McVeigh et al., 2019; Jonglertmontree et al., 2022).

However, the specific classification of maritime psychological factors in the literature is basic and relies heavily on maritime accident reports. Psychological factors, such as mental workload, fatigue, distraction, and situational awareness relate to ship manoeuvring, human performance, and seafarer competency (Fan et al., 2020a). The criticality of such factors is evident in both maritime accident reports and lessons learned from historical accident data from maritime accident investigation authorities/organisations (e.g., IMO and MAIB). Although the above four factors were highlighted as critical individual issues in accident reports, none has been comprehensively investigated in the context of maritime operations. In the subsequent sections, each of the four factors will be elaborated through the combination of: 1) a definitive description, 2) maritime accidents involving the factor as a contributor, and 3) the state of the art of its study in the current literature.

2.1.1. Mental overload

Mental workload represents an interaction between the operator's skills and the task's objective demands (Young et al., 2015). Mental workload has been identified as a risk factor that contributes to human performance on board (Fan et al., 2017, 2018, 2021). Both mental overload and underload cause insufficient perception and attention, which in turn influence performance (Wickens, 2017).

On April 15, 2015, a collision happened between the stern trawler Karen (B317) and a dived Royal Navy submarine in the Irish Sea. The fishing gear of the trawler Karen was snagged by the dived Royal Navy submarine, which caused Karen to heel heavily to port and be pulled underwater. There was no evidence the submarine took any action for assistance as the command team was unaware of such an accident until 3 h later. The accident report (MAIB 20/2016) states that there was probably cognitive overload in the command team and sonar operators because of heavy traffic, a noisy acoustic environment, and an unnecessarily high speed. As a result, the cognitive overload led to degraded situational awareness and poor decision-making of the sonar and command teams.

At Eastern Daylight Time, the bulk carrier Heloise collided with the tug Ocean Georgie Bain while transiting the St. Lawrence River on August 03, 2013 (TSB M13L0123). The accident caused the tug damage, although no pollution or injuries occurred. It was evident that the Marine Communications and Traffic Services officer omitted the downbound Heloise when reporting traffic to Ocean Georgie Bain. His mental workload was at a high level at that critical time. In addition, the master of Ocean Georgie Bain did not use available navigational equipment, and neither did the other seafarer report sighting the vessel. As a result, the master of Ocean Georgie Bain was unaware of Heloise. From this perspective, the mental workload levels of both seafarers onboard and officers onshore are critical to human performance as well as safe navigation.

In the maritime sector, the mental workload was quantified by subjective measures such as the National Aeronautics and Space Administration's Task Load Index (NASA-TLX) (Yan et al., 2019b; Cezar-Vaz et al., 2016; Yoshida et al., 2021), performance indices or physiological measures including eye response (Yan et al., 2019b; Martinez-Marquez et al., 2021), ECG (Kim et al., 2007), EEG (Wu et al., 2017; Liu et al., 2020), and fNIRS (Fan et al., 2021). The relevant methodologies of mental overload analysis help evaluate, train, and assess seafarers' performance in maritime simulators (Wu et al., 2017). They assessed the operator with a quantitative mental workload measurement by evaluating physiological indices. For instance, the EEG-based brain states, cognitive workload and stress, and heart-rate-related measures were obtained during maritime exercises and analysed using a support vector machine or statistical methods. The results were utilised in developing a prediction model in real cases to offer support to operator competency. In simulated maritime operation tasks, time pressure significantly affected operation accuracy and eye movements (Cui et al., 2021). Regarding maritime autonomous surface ships (MASS), generated conflicted situations, visibility constraints, and reliability of MASS affected the mental workload of operators measured by NASA-TLX, further illustrating the changing cognitive overload situations (Yoshida et al., 2021).

2.1.2. Fatigue

The fatigue factor, both physical and mental, has been accepted as a critical attribute of human error causes (Akhtar and Utne, 2014; Besikci et al., 2016; Fan et al., 2020b). It was evident that lapsing or microsleep has a more significant influence on fatigue. Therefore, getting enough sleep and adequate resting periods were discussed to reduce the level of fatigue.

The bulk carrier Muros ran aground on the east coast of the United Kingdom on December 3, 2016, where the ship was re-floated 6 days later (MAIB 22/2017). It was stated that the second officer had revised the passage plan less than 3 h before the accident, even without approval from the master. When the ship crossed the 10 m safety margin into shallow water, the second officer in charge of the ship position monitor did not take any action. It was evident that the second officer's performance was influenced by a very low level of arousal and a lack of periodical sleep, as well as by the time of day (at 0248 (UTC+1)). It proved the existence of a fatigue issue. The ECDIS alarm was broken, which degraded the situation and contributed to unsuccessful alerts for the accident. It should be noted that there are various risk factors contributing to an accident. The description of fatigue (or other psychological factors) in the accident report shows its existence and significance, which was interacted with other risk factors to contribute to the occurrence of the accident.

The fishing vessel Louisa foundered at anchor off the Isle of Mingulay on April 9, 2016 (MAIB 17/2017), which further proved the existence and significance of the fatigue issue in accidents. The skipper and crew, who had been fishing continually for 4 days and working around 20 h per day, had woken suddenly as the vessel was sinking rapidly by the bow. They escaped to the deck and donned lifejackets but were unable to inflate the life raft as they abandoned the vessel. During those 4 days, they had mainly sustained themselves by eating snacks, had no meal breaks, and only slept when possible, during the short transits between each string of creels. Besides being short of dedicated rest, the crews were exhausted by the physical work of shooting and recovering the creels' strings and processing the catch. Ultimately, the skipper had anchored the vessel because they were too tired to continue fishing safely. Instead of managing work routines to prevent fatigue, the skipper led the crew and himself into tiredness that compromised the safety of the vessel.

Mental fatigue is associated with reaction time, decision-making, and situation awareness (Monteiro et al., 2020). It can be measured by a fatigue inventory (Leung et al., 2006), the Symptom Checklist 90-Revised (SCL-90-R) (Besikci et al., 2016), an EEG (Monteiro et al., 2021), and surveys (Andrei et al., 2020). Among these, the self-assessment of mental fatigue lacks reliability and tends to be integrated with physiological sensors to assess the fatigue states of seafarers (Monteiro et al., 2020). Moreover, the fatigue issue comprises more than long hours of work. It was evidenced that risk perception of ship accidents increased with the fatigue level of seafarers, and the fatigue predicted by the safety climate was related to poor sleep quality (Hystad et al., 2017). In addition, a study using the Bayesian Network Modelling on accident reports found that the most decisive fatigue-related factors were vessel certifications, quality control, and manning resources (Akhtar and Utne, 2014). Effective fatigue risk management encouraged regulators and the maritime industry to understand the causes and consequences of fatigue, which indicated the necessity of developing defensive layers to manage fatigue risks (Grech, 2016).

2.1.3. Distraction

Distraction is related to the attention and decision-making process of seafarers. It was evident from the wreck of the Costa Concordia that distraction on the bridge affected the timely and efficient muster and departure in the case of an emergency evacuation (Alexander, 2012). However, there is rare literature on onboard distraction. Most of its significance is revealed in maritime accident reports.

The distraction issue can be found in a collision between high-speed passenger catamaran Typhoon Clipper and the workboat Alison, on the river Thames on December 5, 2016, where and when Alison capsized and sank (MAIB 24/2017). When Alison went past the pier, the helmsman was distracted observing another vessel pass ahead so he could time his turn to starboard. The evidence showed that such distraction and the assumption that Typhoon Clipper was still berthed resulted in the collision risk not being recognised by Alison. In addition, neither vessel obeyed the rule of making the sound signal to inform the other of their entrance to the fairway. Although the roar of Typhoon Clipper's engines eventually alerted the helmsman of Alison, it was too late to take collision avoidance actions effectively.

The cargo ship Daroja and the oil bunker barge Erin Wood collided on August 29, 2015, at 4 nautical miles southeast of Peterhead, Scotland, which stated a distraction issue in the accident report (MAIB 27/2016). The evidence showed that the chief officer, also the Officer of the Watch (OOW), onboard Daroja, missed multiple opportunities to detect Erin Wood. Due to the repetition of the voyage and a lack of support from the master, the chief officer had become complacent about his watchkeeping duties and omitted the proper lookout. In addition, he was distracted by cargo paperwork, a phone call, and potentially using a tablet computer. It was stated that if the cargo paperwork had to be completed at that time, the chief officer should have delegated another officer to take over the watch or called for the support of the bridge team.

2.1.4. Situation awareness

The SA in the maritime industry is the effective and comprehensive understanding of activity and situations onboard that impact maritime safety and security. The SA is divided into three types: perceiving the situation, failure to comprehend the situation, and projecting the situation (Sandhaland et al., 2015; Cordon et al., 2017).

The ro-ro passenger ferry Hebrides lost control, grounding when approaching Lochmaddy, North Uist, Scotland on September 25, 2016 (MAIB 20/2017). Because the control of the ferry's port controllable pitch propeller was lost due to a mechanical failure, the master was unable to control the ferry's movements and prevent it from running over mooring pontoons. In addition, it was surmised that the stress and panic reduced the master's situational awareness, given the loss of the port controllable pitch propeller.

The similar issue can be found in the grounding of the scallop dredger St Apollo on a rocky shelf in the Sound of Mull, Scotland (MAIB 14/2016). The vessel was listed on the falling tide without damage. The report stated that the cause of such grounding was either navigational error, equipment malfunction, or both. In such a case, the watchkeeper still had enough time to act. However, he did not attempt to turn St Apollo towards safe water or put the engine astern to stop. It showed panic of some degree probably due to inappropriate situation awareness, limited device knowledge, and a low state of arousal.

Relying on the information from the surrounding environment, the cognitive situation awareness framework was proposed for the maritime domain using sensor networks and uncertainty management methods (Clemente et al., 2014). Interacting with the ship, equipment, route, and weather, the SA of operators was proved to be impacted by communication, attention, and individual factors (Sharma et al., 2019) and associated with the willingness to take risks (Sandhaland et al., 2017). The relevant tasks during maritime navigation have been provided for evaluating the stress differences between experts and novices, which helped develop the self-training system (Xue et al., 2021). In addition, operators' high level of SA during navigation training was related to Heart Rate Variability (HRV) modulation and suppression and recovery of HRV (Saus et al., 2012). The MASS concepts induced the development of a regulatory framework for the competence of remote operators, and the SA was re-defined and analysed by integrating the International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers (STCW) and Goal-Based Gap Analysis (GBGA) (Yoshida et al., 2020).

2.1.5. Summary

The above four psychological factors are among the common individual causes of maritime accidents and represent high risks in the process of maritime operations. Among them, each psychological factor may be associated with other human factors, vessel conditions, and environmental factors, resulting in risks in oceans and coasts. They are analysed individually and collectively to evaluate human performance in maritime operations under various circumstances. Faced with harsh working environment onboard, seafarers exposed to time-zone crossings, noise, heat, cold, and vibration and the motion of vessels find it hard to rest regularly. The factors which are affected by these circumstances could result in the reduction of seafarers' performance on duty. In addition, it is a challenge for them to maintain good performance at multi-tasks such as watchkeeping, communication, cargo handling, paper charts, emergency response, and human resources management at a satisfactory level. Most current studies rely on the subjective data collected from surveys, accident reports, and self-assessment questionnaires, which often introduce bias for the factor analysis. As mentioned previously, psychophysiological studies remain scarce in the maritime domain. With the advantages of wearable sensors, i.e., fNIRS, such technologies are applicable to illustrate neurophysiological activations to highlight human performance. Furthermore, the implementation of fNIRS in the study does not intervene with subjective bias and serves as a performance predictor aiding psychological factor assessment. Given these previously highlighted shortcomings in existing studies, developing a new and robust methodology for assessing psychological factors is necessary and significant.

2.2. Psychological factor analysis and neurophysiological methods in the maritime sector

Seafarers have to learn and master a variety of technical and non-technical skills, such as identification of malfunctions, workload management, proper watchkeeping, implementation of the best solution, response to the changes of information, clear and concise communication, concentration management, and ability to handle stress (O'connor and Long, 2011). During the navigation, individuals' unsafe acts, including errors and violations, may be induced by the psychological effects of the tasks on board (O'connor and Long, 2011). The mental workload levels under given tasks can influence the action execution of operators. Considering this perspective, psychological factor analysis helps quantify the mental workload given tasks with different complexities and evaluate human performance in different scenarios. It has been widely applied to evaluate operators' efficiency on assigned tasks and the practical capability of the designed system (Dijksterhuis et al., 2011; Ngodang et al., 2012). The investigation of psychological factors complements HRA by measuring humans' response to critical situations, which further uncovers the causes of maritime accidents.

Even with the transition from traditional ships to autonomous vessels, human factor studies sustain an enormous value for its development (Wu et al., 2022). With the development of modern shipping, the MASS has consolidated the Human Factors Analysis and Classification System-Maritime Accidents (HFACS–MA) framework to emphasise the significance of maintaining psycho- and physiological conditions for remote operators (Wróbel et al., 2021). It further proves the critical role of psychological factors in both traditional ships and autonomous shipping. However, in the current literature, such factor-related research was mainly conducted on road transport safety (Rakauskas et al., 2008) and aviation transportation (Gateau et al., 2015). It means that in the maritime sector, seafarers' factor analysis is scarce (Lim et al., 2018), revealing a significant research gap to fulfil.

In light of neuroscience knowledge, psychological factors require objective techniques to measure operators' brain or physiological activities, for which there is little relevant research in the maritime operations field (Fan et al., 2017). These psychological factors can be measured directly using neurophysiological and psychophysiological methods (Dehais et al., 2020). The physiological signals are utilised to operationalise those psychological factors using techniques such as electrocardiography (ECG), electroencephalography (EEG), skin electrical response, and eye tracking (Hou et al., 2015). Physiological factors, such as mental fatigue, were assessed in the maritime domain (Monteiro et al., 2019). Convolutional neural networks proved to be highly accurate in classifying mental fatigue. From a neuroscience perspective, the increasing mental workload was associated with increasing prefrontal cortex activation (Ayaz et al., 2012), while a low level of mental workload led to decreases in prefrontal cortex activation (Molteni et al., 2008; Borghini et al., 2014). Regarding physiological sensors, a wearable eye-tracking device was integrated with simulators, motion capture devices, and augmented reality to understand operators' gaze patterns in various scenarios (Martinez-Marquez et al., 2021). The heart rate is usually integrated with brain activity measurement to assess operators' workload (Wu et al., 2017).

With the development of non-invasive technology applications in the transport field, wearable functional near-infrared spectroscopy (fNIRS) and EEG have become effective tools for quantifying neurophysiological factors in human operations. The fNIRS is a non-invasive brain imaging modality for measuring cortical hemodynamic activity (Fishburn et al., 2014) and is a key component in psychological factor assessment in some high safety-sensitive sectors (e.g. neuroergonomic application (Liu et al., 2017; Aghajani et al., 2017) like road transport (Foy et al., 2016) and aviation (Causse et al., 2017)). Such a novel neuroimaging technique records the changes in oxygenated and deoxygenated haemoglobin concentration based on the different absorption spectra of near-infrared light. Compared to functional magnetic resonance imaging (fMRI), the fNIRS does not confine participants in a supine position, which produces more chances for the natural scenario design. However, the use of neurophysiological techniques in maritime HRA is fragmented, and the existing research is limited (Fan et al., 2017, 2021). There are no well-accepted methodologies in the current literature to support the relevant study, nor experiments to allow their advantages to be fully explored for maritime safety.

To understand and improve human performance in maritime operations, a ship simulator is considered an effective tool to establish complex scenarios and analyse operators' behaviours in this dedicated system. Referring to the simulation study in other sectors, such as aerospace research, a range of psychological parameters have been utilised including eye tracking (Wang et al., 2020), fNIRS (Causse et al., 2017), EEG, and ECG (Villafaina et al., 2021). However, most studies allocate the pilot to a confined flight simulator without body movement, while the ship simulator requires operators to walk around to monitor the navigation. Therefore, the application of these methods for maritime operations must consider the effects of movement. In addition, there are communication and cooperation tasks for seafarers, meaning that missions need to be executed by a group of operators instead of individuals. Hence there is a requirement to measure physiology from multiple participants working together on the same task. Regarding road transport, the physiological variables are measured while associated with driving data such as speed, steering wheel angle, acceleration, and deceleration (Yang et al., 2018, 2019; Yan et al., 2019a). Such data measured by in-vehicle sensors reflect the instant human response in face of changed situations. However, the response mechanism of operators in maritime operations is not the same as the one for drivers. Seafarers make decisions based on the data and situational awareness obtained from multiple resources. These decisions do not immediately influence the result of the manoeuvre made onboard due to ship manoeuvring characteristics. Such time delay makes it difficult to associate driving data with psychological factors for seafarers.

Therefore, the maritime HRA urgently requires a novel methodology framework for seafarers' psychological factor assessment. In addition, most simulation-based HRA studies rely on questionnaires or expert judgment through which it is impossible to measure the objective responses of seafarers. Physiological measures offer benefits to testing in maritime simulators; these are objective, can be continuously monitored, and do not require overt behaviour. To the authors' best knowledge, previous research on maritime HRA does not incorporate any neurophysiological methodology into maritime simulation for seafarers' performance assessment. Because the application of psychological factor assessment in the maritime domain can be difficult to interpret due to movements and communication, it should be carefully designed and managed. This experimental methodology pioneers a data-driven framework for assessing psychological factors in maritime operations and provides a guideline for HRA within risk scenarios from a neurophysiological perspective for the first time.

2.3. Summaries and contributions of this study

The increasing use of psychological measurements in maritime human factors study addresses the need to develop a framework to standardise such measurements. The psychological factor assessment is contextual since it heavily relies on scenario settings. The existing methods applied in aviation and road safety studies cannot be adapted to the maritime sector as navigation scenarios, decision-making processes, and behaviour responses significantly differ at sea and along coasts. Considering empirical studies in the marine sector, the methodologies used in the current literature are diverse, as shown in Table 1.

Although designed according to specific research objectives and questions, the contextual experimental procedures in the current literature still reveal many common characteristics. Therefore, developing a new framework incorporating psychological factors into maritime safety assessment is feasible and beneficial.

The contributions of this study include: 1) the development of a new framework for meeting the increasing demand for psychological measurements in maritime human factors studies; 2) the standardisation of the procedure of using psychological methods in HRA in maritime to popularise the results for cross-fertilisation purposes; 3) the insightful implications for regulating the incorporation of psychological factors into maritime education and training to improve human reliability in maritime.

3. An experimental framework for psychological factor assessment

An experimental framework for psychological factor assessment in maritime operations is outlined in this section to address the identified research gaps on human factors in maritime operations and to illustrate the quantitative measurement and data-driven analysis of psychological factors. It was developed by combining the general knowledge gained from a large number of experiments in relevant industries, such as road

Table 1
Experimental study summaries.

Literature	Psychological factor assessment procedure
Liu et al. (2016)	Mental workload and stress calibration, simulator-based exercise, data processing.
Fan et al. (2018)	Emotion calibration, emotion recognition, questionnaire, debrief, data processing.
Monteiro et al. (2019)	Experimental setup, sensor setup, scenario-based experiment, questionnaire, data pre-processing, data processing, assessment.
Liu et al. (2020)	Brain state calibration, brain state recognition, data processing, assessment decision.

and air transportation, and the specific and unique experience from successful experiments in maritime operations (Fan et al., 2018, 2021; Liu et al., 2020). The hierarchy of the framework was established by considering the literature learnt from road and air transportation, while the supporting techniques were developed within the maritime context by the best practice. For example, the studies in aviation applied neuroimaging technologies to investigate mental workload, given the supportive NASA-TLX surveys (Ayaz et al., 2012; Gateau et al., 2015). The simulation has been widely utilised in road transport to conduct human behaviour studies (Boyle et al., 2008; Rakauskas et al., 2008; Yan et al., 2015). The theoretical rigour of developing an experimental psychological framework can be ensured by learning from the well-established methodologies in the other transport modes, while the details support and tailor the experiments to be bespoke in the maritime domain.

The framework creates a new paradigm for the quantitative assessment of HRA in maritime operations through neurophysiological measurements. It allows the use of neuropsychological data to evaluate mental states and their relations to human performance through ship simulators. The new framework consists of three critical phases: 1) Pre-examination, 2) intra-examination, and 3) post-examination. The whole framework is described as a manual to guide new developments in using psychological means to test seafarers' performance/reliability. The foci are therefore on the most possible encountered challenges and their possible solutions. In this process, all the completed experiments are used as illustrative examples for good lessons to learn. The established procedures for normal psychological experiments are briefly outlined or supported by a reference. The pre-examination contains the preparation steps before commencing an experimental study, which sorts out the planned procedures and allocates hardware and software resources to the examination. The second phase represents the whole process of the experiment, including the requested paperwork and questionnaires. The third phase consists of the procedures dealing with data, findings, and post-study issues. These steps are naturally linked with the critical activities for conducting an objective assessment using neurophysiological data. Such activities are described in the ensuing sections, while the interconnected flow among the phases and steps is shown in Fig. 1.

3.1. Pre-examination

The pre-examination contains the steps of criteria definition, scenario design, investigator training, sensor setup, ethics application, and participant recruitment.

The criteria can be defined by literature review, accident reports, industry magazines, and expert knowledge. Critical psychological factors in navigation at sea are identified for guiding the experimental study design. For instance, it has been revealed that 35.26% of international seafarers have slight or medium depression (Yang et al., 2016); fatigue was the contributory factor of 23% of maritime accidents (Hetherington et al., 2006; Fan et al., 2017). Such concerns can be used to guide criteria definition. The criteria definition configures the aims, research questions, and hypotheses. The experimental procedure is contextual and designed at this stage according to specific research objectives and questions defined. For instance, Fan et al. (2018) explored the effect of seafarers' emotions on human performance on the ship bridge. To measure the emotional states of seafarers, sound clips of the International Affective Digitized Sounds (IADS) were used to induce the emotion types before seafarers commenced the navigation in the simulator. Lim et al. (2018) investigated the workload recognition algorithm using EEG. It trained the data recorded during a Stroop colour word test, followed by the data classification of the simulator exercise. At the same time, the EEG-based stress recognition used the IADS database to induce different emotional states before the exercise.

Scenarios are often designed with the aid of simulators. Although both ship simulation and real ships can support the experimental study, the former is much more economical and safer. Experiments using real ships expose a high risk of intervening in human operations during navigation in the case of an emergency. In addition, it is much more difficult to create scenarios where operators' performance can be effectively detected in the real world. In other words, it will take a longer testing time than expected to experience the dedicated scenarios. Scenarios are designed against research aims. Some studies use complex navigational scenarios and assess human performance while conducting the exercise. Fan et al. (2018) aimed to investigate the relationship between seafarers' emotions and human errors to utilise the scenario database of qualification examinations. It consists of multi-ship encounter situations, poor visibility, and emergency events in open sea navigation. The seafarers' errors and mistakes when working in such scenarios were recorded by examiners and were analysed to show their relationships with EEG data. Liu et al. (2020) assessed the workload of the pilot and conducted the exercise of the pilot manoeuvring the vessel safely to the port with the help of the vessel traffic officer, which lasted 60 min. In addition, there was a simplified bespoke scenario mimicking the watchkeeping during a collision avoidance exercise along a North/South axis to better accommodate a realistic reporting system (Fan et al., 2021). It reflected the reporting missions at the same intervals and explicitly indicated the distances when the ship encountered,

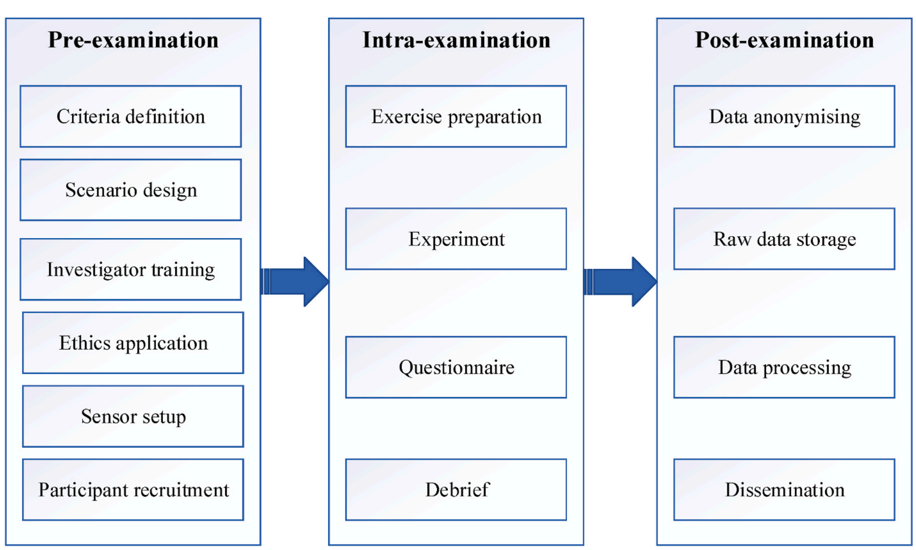

Fig. 1. A data-driven psychological factor assessment framework.

and collision avoidance actions were taken. Such measurements were used as behavioural data for statistical analysis and as input into the regression model. The challenge of scenario design lies in: 1) the conversion of research aims into appropriate scenarios, 2) the allocation of resources to synchronise the physiological data and manually record data, and 3) expertise in psychology and nautical science.

The investigator should be appropriately trained to use novel techniques properly. Various non-invasive technologies are applicable for quantitative data collection to measure psychological factors. Typically, there are a large number of wearable devices applied to psychological data collection in the maritime sector, including Emotiv mobile EEG (Wang et al., 2021; Liu et al., 2016; Monteiro et al., 2019), NeuroSky Mindwave (Fan et al., 2018), NIRSport 88 fNIRS device (Fan et al., 2021).

After the above steps, the ethics application must be submitted for approval before any activity occurs in real experiments, which is required for research involving human participants.

Once obtained ethical approval, the sensor can be set up. The sensor/hardware will be set up based on the experimental design to meet the measurement demands, including a bridge simulator and a recording device such as EEG, fNIRS, eye-tracking sensors, etc.

The participants will be recruited using excluded/included criteria. Within the ship bridge simulation study, all participants should have some navigation experience to ensure they are familiar with the ship simulator. This makes participant recruitment more challenging compared to road transport (Fan et al., 2018). Untrained candidates are not qualified for the examination due to the lack of appropriate ability to use the ship simulator. All participants will receive a full explanation of the experiment's purpose, procedures, risks, and benefits to be familiar with the experimental environment and specific requirements. The ethically approved participant information sheet should be read and signed by any participant before the experiment. In addition, the number of recruited participants is discretionary, as seen in Table 2.

3.2. Intra-examination

The intra-examination phase is a vital part of the experimental study; it includes preparation of exercises, experiments, questionnaires, and debriefs. The whole process is diversified and contextual and depends on what specific research questions are to be solved.

Exercise preparation is carried out at this phase to satisfy the experiment requirements. The software and hardware should be appropriately adjusted for the experiment during this procedure. Any wearable devices for participants need to be correctly set up. In this step, all the paperwork and other preparations should be done against the criteria stipulated in the ethical approval document. To ensure effective data collection, a pilot test is recommended before the experiment. In maritime cases, seafarers walking around the bridge simulator room face the challenge of data collection (Fan et al., 2021). The expected measures can be taken by: 1) limiting the movement of participants by asking them to sit in the operator's chair instead of walking around; 2) restricting the view of participants by turning off the rear screen in the simulator.

Afterwards, the simulation-based experiment can be conducted. Different tools (e.g., EEG, fNIRS, ECG and eye tracking) are utilised to collect neurophysiological data when the exercise starts. It should be mentioned that ethical guidelines for experiments with human participants mean that participants should be able to freely withdraw from the study during and after the exercise.

Table 2
The number of recruited participants.

Source	Number of participants	Psychological factor	Technology
Monteiro et al. (2019)	6 pilots	Mental fatigue	EEG
Liu et al. (2020)	4 maritime pilots	Workload	EEG
Fan et al. (2018)	11 deck officers	Emotion	EEG
Fan et al. (2021)	40 qualified seafarers	Mental workload	fNIRS

During data collection, the subjective questionnaires collected serve as a supportive measurement of psychological factors. The NASA-TLX was used to quantify the subjective measurement of mental workload (Yan et al., 2019b; Cezar-Vaz et al., 2016; Yoshida et al., 2021). The Self-Assessment Manikin (SAM) scale rating questionnaires were utilised to recognise emotion states (Geethanjali et al., 2017; Fan et al., 2018). Such questionnaires will complement the measurement of psychophysiological factors in maritime operations.

The debrief is taken for participants to mimic the natural maritime training process. The challenge of this phase lies in the modification of experiment procedures, and it can be significantly improved by conducting pilot studies. With every detail of the examination confirmed, the pilot test takes advantage of expert knowledge and practical setup to ensure the quality of the study.

3.3. Post-examination

The post-examination stage relates to data anonymisation, raw data storage, data processing, and dissemination.

Data anonymisation and raw data storage should comply with ethics requirements. For those maritime participants interested in the examination results, the raw data cannot be shared. The withdrawal of participation will not influence the anonymised data.

The data pre-processing consists of checking discontinuities and spikes, reducing noises, and removing motion artefacts (Fan et al., 2021), followed by data processing such as wavelet analysis (Fan et al., 2018), statistical analysis (Fan et al., 2021), machine learning, or deep learning algorithms (Liu et al., 2020; Monteiro et al., 2019).

Finally, the analysis findings can be collated and disseminated through publications that encourage multi-discipline research and provide recommendations on maritime training and risk management from practical perspectives. In addition, the lessons from designing experimental studies can be shared; the anonymised psychological data may generate a new database for maritime human factors research.

4. Case study

Along with the illustrative examples in each step in the methodology in Section 3, this section describes a real experimental case to systematically demonstrate the proposed framework. The case study uses a ship bridge simulator to analyse seafarers' mental workload in collision avoidance. The case investigated the association between mental workload and neurophysiological activation in sustained attention and decision-making process during collision avoidance. Experienced and inexperienced seafarers were recruited to accomplish the watchkeeping tasks in a ship bridge simulator. The mental workload was induced by a voyage along a North/South axis, and participants were supposed to keep a proper lookout. The scenario was designed with two mental workload levels. The non-distraction group undertook the low mental workload scenario, while the distraction group executed the high mental workload scenario. Specifically, the high workload scenario distracted the seafarers by reporting the vessel's position at intervals and communicating with Vessel Traffic System (VTS), which is an everyday task requiring a temporal mental workload in the navigation case. The watchkeeping period ended when participants spotted a target vessel. The decision-making period was from the end of the watchkeeping period to the action made for collision avoidance. Regarding the data collection, fNIRS data and subjective questionnaires were recorded to measure the neurophysiological activation and mental workload. In addition, the time and distance of the ship spotting the target ship and when the former altered course were recorded. When participants made manoeuvrers for collision avoidance, the human performance was recorded given such situations.

The experimental framework demonstrates the three phases of the physiological factor assessment for maritime operations below.

4.1. Pre-examination

4.1.1. Criteria definition

The case study was carried out to investigate the mental workload of experienced and inexperienced seafarers and their neurophysiological activation during decision-making in collision avoidance. The study used a mixed design to explore the differences, where two groups of participants (experienced and inexperienced group) were allocated depending on their professional seafarer qualifications. Both groups undertook the watchkeeping scenarios, presented either in 1) non-distraction or 2) distraction. The mentioned distraction means the scenario was associated with tasks that distracted human operators during the decision-making process, to reflect changes in mental workload. The experimental procedure was approved by the ethics committee of the host institution. The procedures of the experiment in a ship bridge simulator were designed as follows.

a. To exclude the participants suffering from high blood pressure, blood pressure was measured before the experiment.
b. Participants needed to read the information sheet and give informed consent.
c. Participants were required to take 5 min of training on the bridge simulator to familiarise themselves with the equipment.
d. The fNIRS was worn by participants to measure oxygenated and deoxygenated haemoglobin levels.
e. Participants were classified into the experienced or inexperienced groups to perform the trial. There were two conditions (non-distraction and distraction) for each group. The trial took approximately 30 min.
f. The NASA-TLX questionnaires were required to be completed after the trial,
g. A debrief was given to each participant to review their performance.

4.1.2. Scenario design

The scenario was designed and developed based on training exercises to mimic watchkeeping using the ship bridge simulator, where TRANSAS simulation software was used to create scenarios. Although the bridge simulator enables a 360° field-of-view, there was a 180° field-of-view display to minimise head and upper body movement to reduce artefacts in the fNIRS data. The design of the navigation scenarios was based on expert knowledge, which highlighted two mental workload levels. The experts consisted of a psychophysiology professor, an experienced captain, and a chief mate. The task scenario was designed along a North/South axis. The given task was to keep watch over 180° field-of-view of the open sea. This watchkeeping period was terminated when participants spotted a "target" vessel that appeared randomly in the field of view. The target vessel was the only other craft in the investigation water in the whole task simulation, with a speed of approximately 15–20 knots. The target vessel approached the own ship on a course that would lead to a collision if the action of changing course was not made. All participants in tasks were required to keep a proper lookout in the open sea, with good visibility, weather condition and sea condition, all of which together present a minimal disruptive level by external factors to the ship safety. The watchkeeping period ended when participants spotted a target vessel, while the decision-making period ended when collision avoidance actions were taken.

The case study aimed to find statistical differences between groups, which requires minimum sample size. 40 participants were required for a minimum conventional sample size in order to get a sampling distribution that approximates normality. They pressed the buzzer button when they spotted the target vessel in the experiment. When they pressed the button, the time and distance between the target vessel (dangerous ship) and their ship (participant ship) were recorded as a dependent variable. On average, the duration of the watchkeeping period was 19min: 42sec. The target vessel approached the ship on a route that would lead to a collision if no action was taken to avoid it. Once participants pressed the button, the exercise went into a decision-making phase. This phase ended when the participants made the evasive manoeuvre; otherwise, it terminated when the collision happened. At the same time, the distance between the target vessel and the ship was recorded as a dependent variable. On average, participants made an evasive manoeuvre at 24min: 26sec.

Considering the distraction scenario, participants were asked to execute an additional reporting task in addition to the proper lookout. The participants made a verbal report of the position of their vessel, then replied to the questions given by the control room via radio communications, i.e., the vessel's flag, type of vessel, speed, and IMO number. The task scenario was designed along a North/South axis to better accommodate a realistic reporting system that kept the participant occupied in a time framework. Specifically, there were horizontal lines with fixed intervals on the screen of ECDIS (Electronic Chart Display and Information System), representing predetermined reporting points. Participants were required to monitor the ECDIS to report numeric coordinates of the ships' current positions when the vessel crossed each minute of latitude as displayed on the ECDIS. With their vessel steering a northerly course at 20 knots speed, the reporting task occurred approximately every 3 min.

4.1.3. Investigator training

To objectively measure the mental workload of seafarers, this study used the fNIRS device to measure brain activations during navigation scenarios. Therefore, the investigators received appropriate training on fNIRS equipment before conducting the pilot test and experiments. A group of experts are composed of a senior professor with rich experience in using fNIRS for mental workload assessment, the manufacturer of the fNIRS equipment used in the experiment, and two experts of nautical science and ship simulation from the host institution attended the fNIRS training. The possible problems (e.g., noisy data due to head movements) during the experiments were assumed, and control measures were prepared in advance.

4.1.4. Sensor setup

The Nirsport 88 device was utilised to measure the prefrontal cortex activity of seafarers. This device performed dual-wavelength continuous wave near-infrared (NIR) measurements. The 8 sources emitted near-infrared light at 760 nm and 850 nm wavelengths, while the 8 detectors absorbed the light mainly by deoxygenated and oxygenated haemoglobin.

According to the brain functions, the montage of the fNIRS was designed to detect the prefrontal cortex's haemodynamic activity, which was associated with seafarers' working memories and decision-making. Regarding the hardware setup, this case utilised 7 sources and 7 detectors with a total of 15 channels of HbO and HbR. In terms of the montage, the brain area in the study was divided into three parts: left dorsolateral prefrontal cortex (DLPFC) covering channels 1–5; central DLPFC covering channels 6–10; right DLPFC covering channels 11–15, as seen in Fig. 2.

4.1.5. Ethics application

The institutional ethics committee approved the experimental protocol for the study before data collection. Participants were provided with written informed consent and were adequately trained for the study.

4.1.6. Participant recruitment

Participants were recruited among adults (>18 years old), without head injury or suffering from high blood pressure because such situations may impact the quality of fNIRS data collection. Last, 41

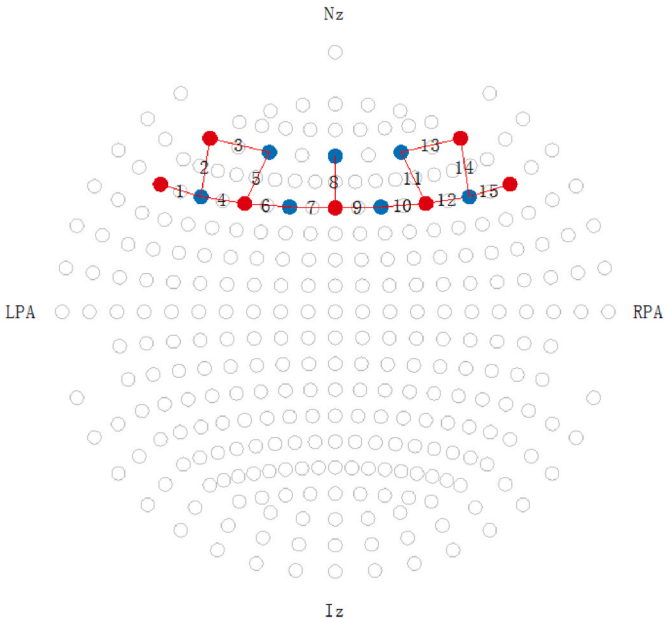

Fig. 2. fNIRS montage, where red lines refer to channels (Fan et al., 2021).

participants were recruited to attend the examination, and 40 pieces of data were valid for further analysis.

Participants were grouped into two levels based on their professional qualifications. Specifically, they were divided based on their STCW qualification rather than navigation time. Seafarers with master mariners (MM), chief mates (CM), and OOW qualifications belonged to experienced group; those who were AB (able seaman) or cadets were in inexperienced group. Last, the data of 20 experienced seafarers who had 213.4 months of navigation experience at sea and 20 inexperienced seafarers who had 27.2 months of experience were kept for further analysis, see Table 3 (Fan et al., 2021).

4.2. Intra-examination

4.2.1. Exercise preparation

The experiment was conducted in a ship bridge simulator configurable for various ship types using TRANSAS simulation software, where interactive environment variables such as tides, currents, wind, light, visibility, fog, and rain were set up. The ship bridge simulator for this case study is seen in Fig. 3. In addition, it was fitted with fNIRS equipment placed on the desk in the back of the room and with NASA-TLX questionnaires.

4.2.2. Experiment

During the experiment, the participants wore the montage cap containing infrared sensors and detectors. The oxygenated and deoxygenated blood flows of experienced and inexperienced groups were recorded. Each participant experienced the scenario under the timeline of baseline, watchkeeping, and decision-making periods. The non-distraction condition and distraction condition were displayed respectively, as seen in Fig. 4. To be specific, the distracting tasks for the distraction group were performed at reporting points (*Rn*) during the experiment. They took place at the same intervals, which required them to report the vessel's position and reply to the questions raised by the

Table 3
Experienced and inexperienced participants (Fan et al., 2021).

Group	Qualification	Nautical experience (month)
Experienced	MM, CM, OOW	213.4 (SD = 188.8)
Inexperienced	AB, Cadets	27.2 (SD = 30.5)

Fig. 3. The ship bridge simulator (Source: the authors).

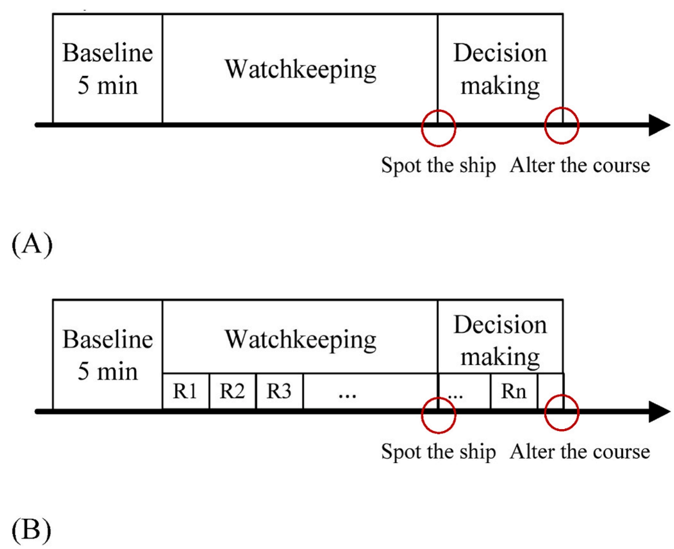

Fig. 4. The experiment timeline for (A) non-distraction and (B) distraction, where *R* represents reporting.

control room. Such distraction is common to the seafarers' daily bridge activity.

The participants were required to press a button when they spotted the target ship. Once it occurred, the experiment entered the decision-making phase. Then the participants were supposed to monitor the route of vessels and the changing variables in the scenario. They were required to alter the course if they judged a possible collision. The exercise stopped when collision avoidance was executed. On average, the scenario lasted approximately 30 min.

4.2.3. Questionnaire

After the exercise, a modified NASA-TLX questionnaire was fulfilled by participants. Each participant was required to self-assess their perceived workload, rating 1–10 in each question given six scales. The questions were based on their subjective feelings about the whole exercise. The questionnaire was designed based on a 10-point scale, 1 being "Very Low" and 10 being "Very High". Regarding the six scales, there were "Mental Demand", "Physical Demand", "Temporal Demand", "Performance", "Effort", and "Frustration". In addition, the time and distance between the ship and the target ship were recorded by the simulation software at the points of the target ship being spotted and the course being altered.

4.2.4. Debrief

After the exercise, the participants received a 5 min debrief from instructors to review their actions. They were not given any judgment on the manoeuvring results of altering the ship's course in the debrief. Lastly, they were acknowledged for their time and received a gift voucher. Additionally, this step helped instructors to sort out the results of the exercise.

4.3. Post-examination

4.3.1. Data anonymisation

Participants cannot be directly or indirectly identified in data and publication. The identifiable personal information of seafarers was not included in the data record which used numbers only. Regarding the necessary personal data collected during the study, it remained confidential and then anonymised. The identifiable personal information was removed before data processing. After anonymisation, such data enabled the use for subsequent research.

4.3.2. Raw data storage

The raw data should be securely stored. Regarding fNIRS raw data, it may contain personally identifiable data during the collection. This was transferred to secure storage in a managed client university computer and was deleted from the fNIRS device as soon as possible. In terms of the questionnaire, it contained no personal information about the participants. Other anonymous information which was not identifiable was stored securely, and only the investigator had access to the data. The consent forms were stored and retained for as long as necessary to defend the study process if required.

4.3.3. Data processing

Regarding data pre-processing, the fNIRS data were firstly pre-processed using the interpolate function that filled the data of channels with detector saturation. For those channels with too much data loss, it was not applicable. The poor-quality channels that contained weak signals were identified using the data quality function. After removing discontinuities and spike artefacts, the data were filtered to reduce high-frequency and physiological noise, i.e., fast cardiac oscillations. Finally, the modified Beer-Lambert law was applied for haemodynamic state calculation (Sassaroli and Fantini, 2004). The changes in oxygenated haemoglobin (HbO) and deoxygenated haemoglobin (HbR) were obtained.

As for data analysis, the Correlation-Based Signal Improvement (CBSI) method was used to transform the data, which forced HbO and HbR to be negatively correlated and controlled for head movement (Cui et al., 2010). This study only used HbO data for the subsequent study. Then the montage was classified into left, central, and right prefrontal cortex areas. To explore brain activities along the time frame, the watchkeeping period was divided into four periods of equal duration based on the sampling frequency, and the decision-making period was divided into two periods of equal time. These six segments and three regions of interest were analysed in the models. In addition, the graph theory was utilised to calculate the density and local clustering of brain activities for functional connectivity analysis. Data was analysed using ANOVA and MANOVA models. The sphericity was tested using Mauchly's Test for repeated-measures component models.

4.3.4. Dissemination

The study simulated the watchkeeping and decision-making for collision avoidance via a ship bridge simulator. The fNIRS was utilised to quantify neurophysiological changes and the mental workload of seafarers onboard. During the distraction exercise, the participants were distracted by reporting the vessel position and answering questions at specific intervals. This section demonstrates how the proposed framework is applicable in maritime operations, and the main results are shown below.

- There was higher oxygenation in seafarers during decision-making periods given distraction [d1, $t(36) = 2.17$, $p = .04$; d2, $t(36) = 2.69$, $p = .02$], illustrated in Fig. 5 (Fan et al., 2021). It explained that reporting tasks distracted the seafarers when they were making a decision to alter the course.
- Decreased connection density (Fig. 6) and higher clustering (Fig. 7) across a frontal montage were related to action selection at decision-making compared to vigilant attention at earlier watchkeeping (a significant main effect of connection density for task period [$F(5, 28) = 15.88$, $p < .01$, $\eta p^2 = 0.33$]. Here w1-w4 represented the four periods of watchkeeping and d1-d2 represented the two periods of decision-making (Fan et al., 2021). Specifically, it revealed a significant increase in connection density during w4 for no-distraction group compared to the distraction group. There was a significant main effect of local clustering for task period [$F(5,28) = 2.60$, $p = .05$, $\eta p^2 = 0.32$]). It revealed that the clustering coefficient was significantly lower at w4 compared to w1 and d2 for the no-distraction group.
- Increased density and local clustering of frontal montage were associated with a greater distance between two vessels when the target ship was spotted. On the other hand, reduced density was associated with a greater distance between two vessels when the manoeuvre was made. The detailed regression model and other results were documented in Fan et al. (2021).

The findings not only prove the best practice in nautical science training but also provide quantitative assessment results for experienced and inexperienced seafarers.

It undoubtedly improves crew training and reliability in maritime operations toward safety at sea. For instance, the proposed psychological factor assessment framework can be applied to seafarer training, which helps analyse their psychological data when completing given navigation tasks in simulator courses. It complements the objective indicator for human performance measurement given by experts or questionnaire feedback. In addition, it is also applicable for psychological factor assessment in the remote-control centre of MASS. The proposed methodology can be utilised as a tool to evaluate the mental workload of operators given multi-tasks in the remote-control room. Under various remote-control scenarios, it shows a possibility to monitor and assess the operator's performance and competence to improve ocean and coastal management.

5. Conclusion

To address physiological factors in maritime operations, an experimental framework is proposed and employed as an approach to

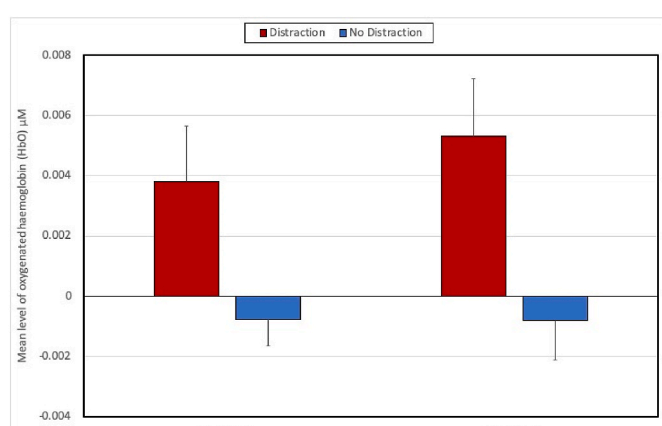

Fig. 5. Average HbO and standard error for task period × distraction Interaction (Fan et al., 2021).

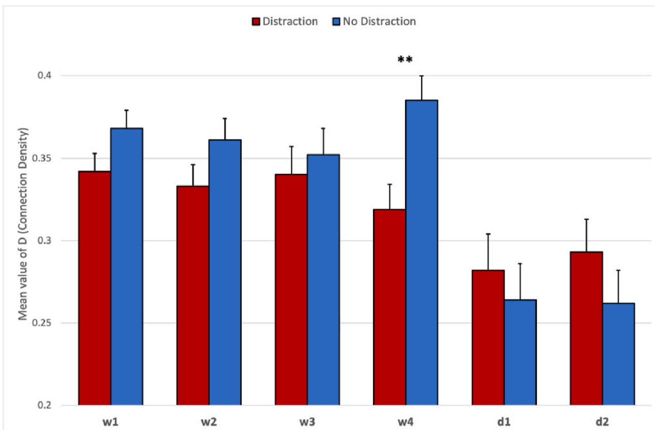

Fig. 6. Interaction between distraction × task periods for connection density (Fan et al., 2021).

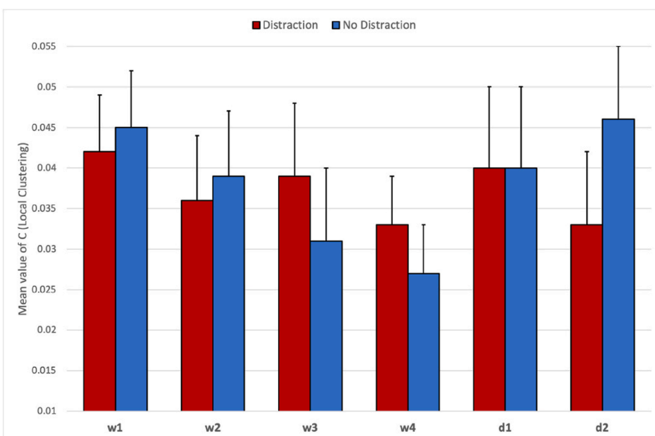

Fig. 7. Interaction between distraction × task periods for clustering (Fan et al., 2021).

incorporate psychological factors and neurophysiology into maritime HRA studies. It creates a new paradigm for marine human factor analysis. The framework consists of pre-examination, intra-examination, and post-examination phases, demonstrating the critical assessment steps. These steps are linked with the essential activities for conducting an objective assessment using neurophysiological data. A case study is conducted to demonstrate its feasibility, in which a ship bridge simulator with 40 qualified professionals is utilised. The experimental framework effectively aids to evaluate the neurophysiological response of seafarers and consolidates maritime human reliability analysis from a neuroscience perspective, which fills the blank space for neuroscience applications in maritime transportation.

This study pioneers a conceptual framework for assessing the psychological factors in maritime operations. It plans the study carefully to reflect accident scenarios or pre-accident conditions via conditions or activities on the ship bridge. Also, it enables quantitative assessment and hence can be used to test, verify, and train seafarers' safety behaviours. The experimental framework can effectively evaluate the contribution of psychological factors to human behaviours and operational risks. The case study, through measurement of neurovascular activation and functional connectivity in the context of maritime operations, provides general insights and implications of managerial significance in oceans and coasts. For instance, the experimental case study illustrates how the mental workload of seafarers in collision avoidance can be measured through ship simulation to ensure safety at sea. Not to overclaim and dismiss this work's novelty, the detailed numerical results of the case study are presented in Fan et al. (2021). The results assist in understanding the mental workload of seafarers with different qualification levels during the tasks, which can be used to evaluate how training can help reduce mental workload and improve human reliability. Moreover, governmental bodies and maritime authorities can use the framework to develop new tools to assess the marine operator's fatigue, mental workload, stress, and emotion, to improve the seafarer qualification process in oceans and coasts.

The proposed framework adheres to ethical guidelines for experiments with humans. Considering participants, it enables the recruitment of training individuals and uses ambulatory monitoring apparatuses to measure the psychological factors of seafarers. In addition, it designs a data processing pipeline to remove systemic effects like head movement and walking. The behavioural outcomes have been related to neurophysiological data. From this perspective, it guides maritime authorities to develop training courses for superior performance of seafarers working at sea and along coasts by referring to brain functional connectivity.

To further explore scenarios, sophisticated tasks such as communication and teamwork could be introduced to create a cognitive workload in a naturalistic case. The diverse database for the scenarios provides decision-makers with useful information to allocate sufficient human resources to deal with different situations. Also, ship designers can use the proposed new framework to investigate the human performance for the tasks within the new design system. The ship's ergonomic design development helps ship designers build a comfortable workplace for seafarers. Using this framework, the experimental study will generate more objective data for risk evaluation than the traditional empirical study.

The fNIRS utilises haemoglobin concentrations to illustrate seafarers' neurophysiological activations, which supports the explanation of human performance. Underlining the already emphasised advantages of generating values of the haemodynamic response, implementing fNIRS could be considered a performance predictor aiding psychological factor assessment. Regarding the MASS development, the remote human-centred design of operators and the co-existence of autonomous ships and traditional ships will introduce new scenarios and challenges for the physiological factor assessment of operators working at oceans and costs.

There are a few limitations to be explored in the future. Although the movement of participants was restricted by the scenario design in this study, its impact on the data collection is inevitable, which is also a significant difference from other transport sectors. Additionally, the number of participants is diverse in different studies because it is difficult to invite many professional seafarers to a ship simulator site due to their nautical duties. The input data collection and analysis in the proposed methodology should strictly follow national research ethics in different countries. If and when it does not obey the relevant regulations from any state (e.g., employers have no right to analyse their employee's health records), extra concerns and advice from professionals should be addressed for the appropriation and applicability of the methodology. This work proposes the framework to incorporate seafarer psychological factors into maritime safety assessment, using a fNIRS case study. Therefore, the proposed framework will be enhanced in the future by utilising other advanced technologies. This novel technique will monitor and assess human performance with various methodologies capable of consistent application at sea and along coasts, opening a new human reliability analysis stream.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zaili Yang reports financial support was provided by European Research Council.

Data availability

The authors do not have permission to share data.

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