Exploring the influence of seafarers' individual characteristics on the perceived risk in maritime emergencies: A simulator study

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Abstract

The perceived risk experienced during the operation of a ship varies among seafarers, likely due to individual differences and variations in task requirements. Hence, this study aims to investigate the impacts of seafarers' individual characteristics on their perceived risk under various emergencies by conducting a high-fidelity ship-handling simulator experiment. A linear mixed effects model is built to assess the impact of individual characteristics (e.g., age, navigational experience, profession, professional level) on the perceived risk of seafarers. Results show that the perceived risk of maritime pilots is significantly higher than deck officers under three emergency situations. The lower perceived risk is found from seafarers with higher navigational experience or at a higher professional level in situations involving poor visibility or an emergency incident. Additionally, the seafarer's age could affect the perceived risk only in the circumstance of an emergency incident. Another finding is that seafarers at a high professional level (i.e., first mate, second-class pilot) exhibit higher perceived risk than those at a low professional level (i.e., second mate, third-class pilot) under the emergency of close encounters. Seafarers' individual characteristics have different impacts in various emergency situations, with the influence of their profession being particularly significant. Maritime administrations were suggested to develop diverse training programs for various seafarers in order to reduce the occurrence likelihood of human errors in maritime accidents.

Keywords: Maritime safety; Human error; Physiological signals; Perceived risk; Individual difference; Ship-handling simulator

1. Introduction

Ship manoeuvring is a complex human-machine control system, where any potential human errors could increase the occurrence risk of maritime accidents (Fan & Yang, 2023a). It was found that about 70%-90% of maritime accidents may be attributed to human errors (Wróbel, 2021). In addition, maritime accident statistics revealed that accidents related to human errors are associated with severe consequences (Weng et al., 2019; Sheng et al., 2023). Therefore, it is necessary to investigate the human error contributory factors in order to enhance the reliability of human-machine control thereby improving safety at sea.

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As a subjective evaluation of the gravity of specific risk in traffic psychology, the perceived risk has the potential to measure the riskiness of human behaviour. The perceived risk of seafarers refers to their psychological stress in response to encountering different events during the sailing periods (Kim, 2020). In fact, the perceived risk could represent the driving behaviour type to some extent. For example, it was found that drivers with a high perceived risk usually present more risky driving behaviour (Song et al., 2021). Therefore, a complete understanding of the seafarers' perceived risk is crucial to proposing effective strategies to mitigate the occurrence likelihood of human errors. Previous studies reported that driver behaviour is complexly influenced by individual characteristics (Dixit et al., 2014). To gain a comprehensive understanding of the relationship between the seafarers' individual characteristics and their perceived risk, it is crucial to take into account a wider range of individual characteristics and various navigation scenarios.

Therefore, the objective of this study was to fully explore the effects of individual characteristics on seafarers' subjective cognition in different emergency situations. The contribution of this study is three-fold. First, objective perceived risk measured by physiological data is utilized to analyze differences among seafarers with various individual characteristics to avoid errors arising from their subjective perceptions. Second, by considering the differences in the features of the three emergency situations, this study makes an initial attempt to separately analyse the seafarers' perceived risk based on various individual characteristics. Third, this study could provide adequate support that distinct training programs and guidelines should be put forward to mitigate potential human errors of different seafarers in various emergency situations. These contributions are timely, considering the increased complexity of human-computer interaction operations resulting from the development of autonomous ships (Liu et al., 2022). It is crucial to further comprehend the perceived risk of various seafarers to provide effective guidance for the subsequent development of human-computer control systems for autonomous ships.

The paper is structured as follows. In Section 2, a literature review of related works is presented. Section 3 describes the data collection process from the experiment and the corresponding analysis methods. Section 4 shows the results of the difference analysis and the model analysis. Section 5 discusses how seafarers' individual characteristics influence their perceived risk in various maritime emergencies and provides suggestions for improving seafarer training. Finally, Section 6 concludes with a summary of the main conclusion and contributions of the study.

2. Related work

2.1 Individual characteristics

Individual differences pertain to distinct characteristics associated with qualities and behaviours that differentiate one person from another, such as gender, age and personality (Jing et al., 2023). Different individual characteristics have a significant impact on a person's performance (Dixit et al., 2014). For example, previous studies

associated with road traffic reveal teenage drivers are more frequently engaged in risky driving behaviours than adults in road traffic (Rhodes & Pivik, 2011), while older drivers are more prone to being involved in serious accidents. It should be noted that due to the unique features of maritime transportation, such as long and monotonous work hours and confined working environments, the differences in performance among ship drivers (i.e., seafarers) with different individual characteristics are even more pronounced (Zhuang & Fu, 2023).

One factor of seafarers' individual characteristics that gain much attention is navigational experiences. For instance, seafarers with longer seafaring experiences tend to exhibit lower stress levels at sea (Jonglertmontree et al., 2022), which can effectively assist them in observing navigational situations in advance and making sound decisions. Furthermore, the profession of seafarers is also a crucial influencing factor in their performance. It is found that navigational officers have higher trait anxiety compared to the general population, revealing the stress and concerns that seafarers have experienced over the long term (Shi et al., 2023).

2.2 Perceived risk

The current study on drivers' cognition is particularly interested in perceived risk, which involves subjective judgments regarding the severity and specific characteristics of a risk (He et al., 2022). This perception could significantly influence the drivers' decision-making behaviour. Perceived risk is a highly individualized concept, influenced by factors such as personal experience, and personality (He et al., 2022). Typically, a driver's perceived risk is assessed using a subjective survey or physiological measurements (He et al., 2022). However, even as human errors become increasingly prevalent, humans still perceive themselves to perform well. Therefore, perceived risk assessment based on objective physiological measurements may be more reliable in transportation research compared to subjective surveys.

The physiological measurement method has been widely used in traffic safety research for monitoring the driver's state. Liu et al. (2023) utilized the ultra-short-term HRV analysis to detect the stress levels of drivers under real-world driving conditions. These studies suggest that HRV serves as a valuable tool for assessing the subjective mental state of drivers. Current research on the cognitive state of drivers suggests that perceived risk could be effectively measured using physiological indicators, such as HRV (Kim, 2020; He et al., 2022). Additionally, the HRV of drivers during accident situations tends to be higher compared to non-accident situations (Weigl et al., 2021). This may indicate that heightened perceived risk increases the occurrence likelihood of accidents.

Furthermore, the driving environment, such as urban or rural roads, plays a significant role in affecting both operational and perceived risks. However, current literature offers limited research on the impact of the navigation environment on seafarers' perceived risk. Studies in the field of navigation have suggested that emergency situations demand a higher level of performance from seafarers (Cohen et

al., 2015). Efficient response to emergency situations in shipping requires a good perceived risk and situation awareness by seafarers (Nordström et al., 2016). Specifically, seafarers are expected to respond rapidly when facing an emergency, which may result in significant psychological consequences such as increased psychological stress and perceived risk (Cohen et al., 2015). For instance, Kim (2020) evaluated the perceived risk of ship operators in the last moment of a collision encounter, which showed that perceived risk increased for ship operators as the distance between two ships decreased and pressure mounted. The perceived risk at a high level often leads to a short-term reduction in the performance of seafarers and an increased risk of maritime accidents (Simon & Corbett, 1996). Hence, exploring the perceived risk among seafarers in different emergency situations is essential to evaluate the associated navigation risk.

2.3 Summary

As previously mentioned, existing literature has conducted extensive research on the performance differences in individual characteristics among seafarer and their perceived risk. However, there are still some issues that need to be addressed. Firstly, although current studies have separately examined the differences in individual characteristics, there is a need for a more comprehensive investigation into how various individual characteristics influence seafarers' perceived risk. This can offer a more detailed understanding, encompassing factors such as age, navigational experience, profession, and professional level impact on seafarers' perceived risk. Secondly, due to the high requirements of seafarers' response ability in emergencies, more emergency situations should be considered to investigate differences in various seafarers' capacities. Therefore, it is revealing a strong need for conducting new and bespoke experiments to test and examine the impact of seafarers' characteristics on their behaviour and states for the maritime sector to propose suitable training programs, thereby ensuring maritime safety. This study aims to address these research gaps.

The experiment was conducted to explore the following hypothesis:

H1: The impact of different emergency scenarios on seafarers' perceived risk varies.

H2: Various individual characteristics of seafarer will influence their perceived risk under emergency situations.

3. Method

3.1 Participants

According to the report from the Ministry of Transport of the People's Republic of China (MOT, 2018), seafarers aged between 20-50 account for 91% of all Chinese seafarers. Consequently, a total of 28 seafarers within this age range were randomly recruited to undertake the simulated sailing experiment. The individual characteristics and physiological data of these seafarers were recorded and utilized. However, the information of two seafarers was excluded from this study due to the uncompleted data record. These participants included 14 marine pilots and 12 deck officers, with a range

of 26 to 49 years old (Mean=33.07, SD=4.87) and 3 to 17 years of navigational experience (Mean=8.69, SD=3.35). All participants were recruited from the professional rank training exams and maintained good physical condition. Compared with other seafarers who did not participate in this experiment, these participants need to maintain a high level of concentration in simulated scenarios in order to effectively respond to emergency situations as part of their examination requirements. Hence, the performance of seafarers in this experiment is similar to that in real-world navigation. The detailed information of these participants is shown in Table 1. Specifically, according to the individual characteristics of these participants, the age and navigational experience of participants are classified into young/mature (Mean=30.25 years old, SD=2.35; Mean=37.6 years old, SD=4.45) groups and experienced/less experienced (Mean=11.42 years, SD=2.57; Mean=6.35 years, SD=1.82) groups, respectively. It should be noted that the age and navigational experience of seafarers were grouped into two categories using mean values. The professional level is categorized based on their current license levels.

3.2 Experiment apparatus

This study conducted the experiment using a ship-handling simulator from Shanghai Maritime University, China. As shown in Fig. 1, the simulator is equipped with seven LED display screens to provide a visual experience similar to that of an actual ship's bridge. It can therefore simulate various ship encounter situations during the whole navigational process and provide an actual navigation environment. To assist seafarers in monitoring the navigational environment and controlling the ship, a range of aid instruments for navigation such as marine radar, a control display system and other aid equipment are installed in the ship-handling simulator. It has been used for seafarer skill training and examinations to obtain yearly higher-level qualification certificates, showing the advance of the simulator and its fitness to support the designed experiment in this study.

Due to the high activity requirements of seafarers involved in a lookout for navigation situations during the voyage, there is a high need for physiological monitoring devices. A wireless physiological data recording system was used to collect the physiological data in this study. The PhysioLAB wireless physiological device is lightweight with little interference to participants, developed by the German company Egroneers. It enables steady ECG signal collection even during intense exercise situations, which makes it suitable for monitoring the activities of seafarers in this study. The ECG data collection device and acquisition process is shown in Fig. 2.

3.3 Scenario design

Due to the presence of various emergency situations in actual maritime environments during a ship's sailing periods, it is necessary for seafarers to take appropriate measures to prevent accidents. Therefore, this experiment is designed to collect the response status of seafarers in three common types of emergency situations: poor visibility,

multi-ship encounters, and emergency incidents. More detailed scenarios of emergency situations are also described and shown in Table 2.

The shipping route from the Waigaoqiao Port to the Yangshan Port in China is chosen for the sailing simulation using a ship-handling simulator in this study, as it represents the typical complex restricted waters in navigation. When navigating in this water area, any negligence regarding emergency situations by the seafarers could potentially lead to serious maritime accidents (Weng and Li, 2019; Li et al., 2021). Compared with other water areas, this challenging navigational environment is representative and suitable for measuring the perceived risk of seafarers during the sailing periods.

The entire sailing experiment was segmented into three successive phases, as shown in Fig. 3. Firstly, seafarers need to manoeuvre the ship safely departing from the port. Secondly, they performed regular navigation tasks during the normal cruising state, where they may encounter 2-3 types of emergency situations until reaching the next port. After each emergency situation occurs, there is a period of noninterference navigation in waters to mitigate the influence of the last emergency situation on seafarers. Therefore, the impact of various emergency situations on seafarers is assumed to be independent in this study. Finally, the ship is operated to safely berth at the destination port. The complete sailing experiment lasted approximately 50 minutes. This entire navigation process is designed to ensure that the seafarer can maintain a navigational state.

3.4 Experiment procedure

To ensure the reliable performance of seafarers' response to emergency situations, each participant in this study is only involved in a single experiment. The potential data errors caused by fatigue and familiarity with the scenarios are minimised. A total of 28 completed experiments were carried out in June and November 2021. Upon their arrival at the ship-handling simulator, participants were initially briefed by an instructor about the experiment, including the navigation instruments and tasks involved. Subsequently, all participants were required to familiarize themselves with the simulator’s operation to prepare for the experiment. Afterwards, participants were equipped with a wireless physiological device and performed the formal simulated sailing task. Each experiment was carried out by a team of three seafarers, comprising a captain, chief mate, and helmsman. The participant in this study served as the captain of the team to undertake the task. They were required to maintain vigilance to prevent any potential risks. Meanwhile, the occurrence time of all emergency situations during the experiment was recorded to calculate seafarers' corresponding perceived risk when encountering this situation.

3.5 Measurement

Seafarer’s perceived risk could be defined by the acute physiological stress occurring in response to emergency situations. Namely, some studies indicated that HRV

indicators, particularly SDNN (Standard Deviation of NN intervals), can effectively assess an individual's perceived risk condition. For instance, Zhou et al. (2019) demonstrated the positive correlation between SDNN and an individual's perceived risk by exploring the association between various physiological indicators and perceived risk. Liu et al. (2023) indicated that the HRV of drivers increases with higher levels of stress. Moreover, Kim (2020) assessed changes in seafarers' perceived risk during navigation using subjective questionnaires and objective HRV monitoring. The result demonstrated that both subjective questionnaires and SDNN were effective in evaluating their perceived risk, which provide a reliable research foundation for this study. Therefore, the objective physiological measurement method is chosen to assess seafarers' perceived risk when facing emergency situations. Generally, the raw data acquired from physiological data acquisition equipment requires pre-processing to obtain HRV indicators. The software of Python 3.8.8 is implemented to pre-process the ECG data and the specific procedure is documented in Shi et al. (2023). The indicator (units: ms) representing perceived risk in HRV can be expressed as follows:

$$\text{Perceived risk} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(RR_i - IBI\right)^2} \tag{1}$$

$$IBI = \frac{1}{N}\sum_{i=1}^{N} RR_i \tag{2}$$

where IBI represents inter-beat intervals (units: ms); N represents the number of inter-beat intervals; RR_i represents the i th inter-beat intervals.

The measurement of perceived risk involved 30 seconds before the emergency situation and 2 minutes after the emergency situation, which is divided by 30 seconds intervals into a total of 5 segments. This measurement aims to assess the change in the perceived risk of seafarers during ultra-short periods. It has been demonstrated that 30 seconds ultra-short term HRV can effectively characterize short-term changes in a person's physiological state (Wu et al., 2020). The perceived risk of seafarers is extracted from physiological data under three types of emergency situations defined in Table 2. Figs. 4(a)-(d) illustrate the experiment scenarios under situations of normal, poor visibility, close encounters, and emergency incidents, respectively. For the emergency situation of poor visibility, as navigational weather changes are global in nature, the captain is able to immediately detect this emergency situation. Therefore, the moment of weather change is recorded as the specific time point for this condition and extracts the perceived risk from seafarers. Regarding the emergency situation of multi-ship encounters and emergency incidents, these events need to be observed by the captain to make a response. Therefore, the moments when the participant observed these events are recorded and the perceived risk of seafarers is extracted.

3.6 Data analysis

To identify significant factors influencing the perceived risk of seafarers, statistical analysis methods are employed to examine the differences between different categorical groups. In this study, the nonparametric tests are used to compare the differences in the perceived risk of seafarers among different categories, such as profession (deck officer and marine pilot), age (young and mature), navigational experience (less experienced and experienced), and professional level (Level 1, Level 2, Level 3). The data analysis software of SPSS (version 26.0) is utilized for conducting nonparametric tests in the data analysis process. Nonparametric tests are developed for statistical analysis that does not require a distribution to meet the required assumptions to be analyzed. Compared with common parametric tests, it has a wider application range and is more effective when dealing with data from unknown population distributions. In this study, the dataset is evidenced to not follow a normal distribution based on the Kolmogorov-Smirnov (K-S) test (p<0.05), which violates the assumptions required for using t-tests and analysis of variance (ANOVA). Therefore, the Mann-Whitney (M-W) test is utilized to examine the difference in data between two categorical groups, such as profession, age, and navigational experience, and the Kruskal-Wallis (K-W) test is used to survey the difference in data among three categorical groups such as professional level (Stephens et al., 2021; Sajid Hasan et al., 2022).

Considering that multiple factors influence the perceived risk of seafarers, this study builds a Linear mixed effects model (LMM) analysis to quantify the impact of various factors on their perceived risk. LMM is a commonly used statistical analysis method, which could be employed to solve issues related to multilevel data, and repeated measures. By accounting for inter-individual correlations through random effects, LMM could provide an accurate assessment of the relationship between influencing factors and dependent variables. In this study, the perceived risk of seafarers is designed as the dependent variable. The independent variables of fixed effects include seafarers' individual characteristics (i.e., age, navigational experience, profession, and professional level). The participant ID is considered as the independent variable of random effect, taking into account individual differences among the participants. In reality, the perceived risk of seafarers may change over time, e.g., the perceived risk may decrease in response to successfully dealing with emergency situations. To account for the effect of time on the response variable, time could be added as an additional explanatory variable of fixed effects into the LMM model shown in Eq. (3), namely,

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_t X_t + u_i + e \tag{3}$$

Where Y shows the perceived risk of seafarers as an independent variable; X_i (i=1, 2, 3, 4) represents the four individual characteristics of seafarers (i.e. age X_1, navigational experience X_2, profession X_3, and professional level X_4) as explanatory variables, respectively; β_i is the coefficient associated with the i th independent variable, in which β_0 is the constant term in this model; t indicates the time variable;

u_i represent the random deviation of the *i* th participant from the participants with same baseline characteristics; *e* represents the error term. Furthermore, it should be noted that the time variable in this study is measured in a 30-second interval. This variable could be treated as a categorical variable to compare the differences in perceived risk among seafarers before and after the occurrence of emergency situations.

4. Results

4.1 Descriptive analysis results

The final dataset consists of 378 sets of data, which are obtained by the measurements of perceived risk from the participants in various emergency situations mentioned above. An initial analysis of the dataset is conducted, and the summarized descriptive statistics can be found in Table 3. Due to the exploratory nature of this study and the complexity of the human factors and emergency situations investigated, a more lenient threshold of 0.10 was chosen to assess the statistical significance of the tests. This significance level is widely applied to assess human factors in the transportation field (Weng & Yang, 2015). According to the results of M-W tests and K-W tests, it can be seen that the perceived risk of seafarers has significant statistical differences among different categorial groups of seafarers (p<0.05). This indicates the effectiveness of the classification used in this study.

With regard to the profession of seafarers, the mean value of the perceived risk of deck officers is 43.82 ms (SD=1.71) while the value of marine pilots is higher on average at 106.46 ms (SD=3.52), indicating marine pilots are more prone than deck officers to experience risk during emergency situation periods (p<0.05). Similarly, the mature seafarers' average perceived risk in an emergency situation is 57.25 ms (SD=2.37) while young seafarers' average perceived risk is 98.40 ms (SD=4.49). It presents a significant difference in different age groups (p<0.05). The difference between navigational experience is significant (p<0.05), and the average perceived risk values of low-experience and high-experience seafarers are 85.84 ms (SD=3.46) and 56.38 ms (SD=3.04), respectively. In addition, in terms of different professional levels of seafarers, the perceived risk significantly decreases in the following Level 3 (Mean=118.24 ms, SD=4.65), Level 2 (Mean=64.29 ms, SD=2.71), and Level 1 (Mean=33.99 ms, SD=1.81) in order when encountering emergency situations. This suggests that more mature, more experienced, and higher-ranking seafarers perform better in responding to risks, highlighting the significance of rational training in maritime accident prevention.

Moreover, the K-W test reveals that there is a significant difference in perceived risk among seafarers under different emergency situations at a 90% level of confidence (p=0.082<0.10). Hence, hypothesis H1 has been confirmed, indicating that different emergency situations have an independent influence on seafarers. The perceived risk of the seafarers is an average of 70.32 ms (SD=4.27) for poor visibility, whereas for close encounters and emergency incidents, the values are 81.86 ms (SD=4.58) and 65.59 ms (SD=3.80), respectively. The highest perceived risks are exhibited under close

encounter situations while the lowest ones are shown under emergency incident situations. The difference in perceived risk among different seafarer groups under various emergency situations is presented in Table 4. Results indicate that there are significant differences in different groups of age, navigational experience, profession, and professional level of seafarers under various emergency situations. Under different emergency situations, marine pilots, and young, less experienced and lower professional levels of seafarers are presented with high perceived risk and are more likely to make human error when responding to emergency situations.

Overall, the results of the descriptive statistical analysis are consistent with the current understanding in the field, indicating that more mature, more experienced, and higher professional-level seafarers are handled great in emergency situations. However, this study shows the superiority by pioneering the attempt of quantifying the differences among different groups. A more detailed analysis is provided in subsequent sections.

4.2 Results of the LMM under different emergency situations

The perceived risk of seafarers is comprehensively influenced by multiple factors. Therefore, an LMM method is utilized to investigate the influence of different individual factors on perceived risk (i.e., H2). The LMM procedure in the Statistical software of data science (SPSS 26.0) is performed to model a separate LMM analysis for different emergency situations. To ensure the validity of LMM results, the collinearity of explanatory variables is first tested. The results of collinearity diagnostics in the SPSS indicate that the variance inflation factor (VIF) for all factors is less than 5, with the highest VIF being 2.603.

4.2.1 Influence of seafarer's characteristics on perceived risk under poor visibility

Table 5 shows the LMM analysis results for the influence of seafarers' individual characteristics on perceived risk under poor visibility. In this model, the main effects of different individual characteristics are deck officer, young seafarer, less experienced seafarer, Level 3 seafarer and Time 0, respectively. The specific parameters are as follows: β_0 is 58.07, β_1 is 50.57, β_2 is 11.34, β_3 is -22.94, β_4 is -25.42 (corresponding to Level 1 seafarer) or -27.07 (corresponding to Level 2 seafarer), and β_t as 11.41 (when t=1), 10.36 (when t=2), 0.22 (when t=3), or 16.54 (when t=4), respectively. These parameters present their relationships with the main effects. It can be found that the profession, navigational experience and professional level of seafarers significantly influence the perceived risk when encountering poor visibility situations (at a significance level of 0.10) while the age of seafarers is not significant in influencing perceived risk. Specifically, there is a significantly positive correlation between the profession of seafarers and perceived risk, namely marine pilots performing a higher perceived risk compared to deck officers. The navigational experience and professional level of seafarers have a significant negative influence on perceived risk. In particular, seafarers with higher experience and professional levels

exhibit a lower level of perceived risk than others. Furthermore, it could be found that the time variable does not have a significant impact on perceived risk. It's worth noting that at Time 4 (i.e., the fourth 30-second after the occurrence of poor visibility), the perceived risk of seafarers is significant at the 10% significance level in relation to the main effects (i.e., Time 0). This may indicate a delayed impact of poor visibility on seafarers.

4.2.2 Influence of seafarer's individual characteristics on perceived risk under close encounters

As shown in Table 6, the results of parameter estimate are as follows: β_0 is 55.73, β_1 is 60.84, β_2 is -17.33, β_3 is -1.84, β_4 is -15.2 (corresponding to Level 1 seafarer) or 10.4 (corresponding to Level 2 seafarer), and β_t as -6.26 (when t=1), 5.28 (when t=2), -3.23 (when t=3), or -3.91 (when t=4), respectively. Similarly, the perceived risk during close encounter situations is significantly influenced by the individual characteristics of seafarers such as their profession (at a significance level of 0.05). On the contrary, the navigational experience and professional levels of seafarers do not have a significant effect on the perceived risk, as well as age and time. This result shows that marine pilots have a higher perceived risk than deck officers when encountering close encounters. It should be noted that the results of this study are different from the research by Kim (2020), which found a significant influence of professional level and navigational experience on perceived risk during close encounters. This difference may be attributed to the fact that differences in selected close encounter scenarios were defined in the two experiments. Compared to the fixed close encounter scenarios (Kim, 2020), the randomly occurring close encounter scenarios better reflect reality. Therefore, in order to reduce potential human error resulting from close encounter situations, it is necessary to strengthen the training of marine pilots in dealing with close encounters.

4.2.3 Influence of seafarer's individual characteristics on perceived risk under emergency incidents

The analysis results for emergency incidents are shown in Table 7. The specific parameters are as follows: β_0 is 87.94, β_1 is 27.96, β_2 is 19.18, β_3 is -20.65, β_4 is -58.11 (corresponding to Level 1 seafarer) or -49.8 (corresponding to Level 2 seafarer), and β_t as 11.14 (when t=1), 7.56 (when t=2), 4.08 (when t=3), or 11.38 (when t=4), respectively. The profession, navigational experience and professional level of seafarers all influence the perceived risk under emergency incidents. Similar to encountering poor visibility, the profession of seafarers presents a positive correlation with perceived risk while navigational experience and professional level of seafarers show a negative correlation with perceived risk. It should be noted that age also does not have a significant influence on the perceived risk of seafarers. Furthermore, there is no significant difference observed in the perceived risk of seafarers between the situation before emergency incidents and the one after its occurrence. Consequently,

more attention needs to be focused on marine pilots, and seafarers with less experienced and professional levels during emergency incidents to reduce human error caused by emergency incidents.

4.3 Comparison of the marginal effects of influencing factors in different situations

Table 8 presents the marginal effects of the individual characteristics of seafarers and the time factor on the perceived risk in different emergency situations. The results are discussed with regard to each individual characteristic of seafarers and the time factor. In this study, the marginal effect of various factors could be defined as the estimated perceived risk of various categorical seafarers, while controlling for the influence of other factors.

4.3.1 The marginal effects of seafarers' characteristic

The marginal effects associated with deck officers are 44.48 ms for poor visibility situations, 42.92 ms for close encounters and 58.07 ms for emergency incidents. This result means that deck officers have a higher perceived risk during emergency incidents than in other situations, which presents a high risk of maritime accidents. However, marine pilots exhibit the lowest marginal effect (86.03 ms) during emergency incidents, while close encounters have the highest marginal effect (103.76 ms).

Mature-aged seafarers (75.43 ms and 69.31 ms) are more likely than young-aged seafarers (64.10 ms and 62.46 ms) to be presented with a high perceived risk during poor visibility and emergency incidents. However, in close encounter situations, the marginal effect of mature-aged seafarers (82.01 ms) is significantly lower than young-aged seafarers (64.67 ms).

The marginal effects associated with low-experience seafarers are found to increase in close encounter situations (74.26 ms), poor visibility (81.24 ms), and emergency incidents (82.37 ms). However, the marginal effects of high-experience seafarers exhibit a different order, with poor visibility (58.30 ms), emergency incidents (61.72 ms), and close encounters (72.42 ms). In the close encounter situation, both the low-experience and high-experience seafarers present a similar degree of perceived risk. Compared to low-experience seafarers, lower levels of perceived risk when encountering poor visibility and emergency incidents are exhibited by high-experience seafarers.

Overall, seafarers with a higher professional level have a significantly lower perceived risk during emergency situation periods, consistent with the previous study (Kim, 2020). Specifically, the perceived risk of seafarers at Levels 1 (61.84 ms) and 2 (60.20 ms) is similar in poor visibility situations and significantly lower than that at Level 3 (87.26 ms). When encountering emergency incidents, there is a decrease in the perceived risk of seafarers with an increase in the professional level, particularly a significant increase from Level 3 (108.02 ms) to Level 2 (58.22 ms). It should be noted that in close encounter situations, the highest perceived risk of seafarers is exhibited at professional Level 2 (85.34 ms), followed by Level 3 (74.94 ms) and Level 1 (59.74

ms). In addition, the highest marginal effect occurred in third-level seafarers when encountering emergency situations (108.02 ms).

4.3.2 The temporal variation in seafarers' marginal effects in different situations

For clear visualisation, the results of temporal variation in seafarers' marginal effects across different situations are shown in Fig. 5. The marginal effects of seafarers exhibit varying effects when they encounter different emergency situations. For instance, it can be clearly found that the opposite trends of marginal effects are exhibited between close encounters and the other situations from Time 0 to Time 1. This may be due to the fact that seafarers maintain a high level of perceived risk during the close encounter period, and there may be a temporary decrease in perceived risk due to the effective decision-making response to this close encounter situation in Time 1. Moreover, when encountering poor visibility and emergency incident situations, the perceived risk of seafarers increases (i.e., from Time 0 to Time 1), and subsequently remains stable with an upward trend (i.e., Time 1 to Time 4). This implies that seafarers need to maintain a high level of perceived risk under sustained conditions of poor visibility to avoid potential risk.

5. Discussions and implications

5.1 Discussions

Existing studies on human factors in maritime safety fields have primarily focused on unsafe behaviour and states of seafarers (Ding et al., 2023; Fan & Yang, 2023b), with limited studies exploring the impact of individual characteristics of seafarers on navigational safety. In this study, a ship-handling simulator and wireless physiological record equipment were used as the experimental equipment, and the HRV indicator extracted from ECG was selected as the perceived risk of seafarers when encountering emergency situations. This study investigates the effect of seafarers' individual characteristics on seafarers' perceived risk during various emergency situation periods from an objective perceptive. The results indicate that the individual characteristics of seafarers significantly affect the perceived risk under various emergency situations.

The factor of the profession has a significant influence on the emergency response of seafarers when encountering various emergency situations in restricted waters. Marine pilots present a significantly higher level of perceived risk compared to seafarers. The significant differences in their work environment contribute to the observed disparities. For example, marine pilots may rely more on their navigational expertise in port waters, such as port environment knowledge to make decisions, where poor visibility can potentially lead to misjudgements and traffic accidents (Shi et al., 2023). Marine pilots working in dangerous and congested waterways have a greater sensitivity to the potential risk involved in close encounter situations. In addition, marine pilots possess rich experience in dealing with emergency incidents in complex waters due to their working environments. However, deck officer has a lower

probability of encountering emergency incidents in complex waters compared with other situations, which leads to a lack of experience in handling this situation.

Age has the least influence on the emergency response of seafarers when facing emergency situations in restricted waters. Especially, it does not have a significant influence on close encounters, poor visibility, and emergency incident situations. This is similar to the findings of previous research on the influence of ship operators' perceived risk in the last moment of a collision encounter (Kim, 2020). This could be due to age's potential impact on seafarers' operational abilities, such as a reaction speed decrease. Additionally, although age does not have a significant impact on the perceived risk of seafarers under close encounter situations, young seafarers may exhibit a relatively higher level of perceived risk than mature seafarers in other emergency situations. One possible reason is that due to the difference in reaction speed among different ages seafarers, seafarers are required to be in immediate response in the situation of emergency incidents, while seafarers can continuously observation of the encounter situations to make an appropriate decision under close encounters.

Regarding the influence of seafarers' navigational experience, the perceived risk of high navigational experience seafarers has significantly lower than low navigation experience seafarers under poor visibility and emergency incidents. This is similar to the results of previous research on the neurophysiological activation of experienced and inexperienced seafarers concerning collision avoidance, which presents significant differences between different experienced seafarers (Fan & Yang, 2023b). This could be attributed to seafarers with higher experience having greater expertise in dealing with these situations. Compared to the age factor, the results of this study indicate that extensive navigational experience is more crucial for navigational safety. In addition, the navigational experience of seafarers does not significantly influence perceived risk when encountering close encounter situations. It can be found from Table 8 that both experienced and less experienced seafarers exhibit similarly high levels of marginal effects. It should be noted that in close encounter situations, less experienced seafarers exhibit the lowest perceived risk while highly experienced seafarers present the highest perceived risk compared to other emergency situations. This indicates that under close encounter situations, high navigational experience seafarers may be more sensitive to potential risks, while low navigational experience seafarers may lack sufficient experience and knowledge to accurately assess risks.

For the impact of seafarers' professional level, there are significant influences on perceived risk under poor visibility and emergency situations in restricted waters. Compared to seafarers at profession level 3, Level 2 and Level 1 seafarers exhibit lower perceived risk. This could be attributed to seafarers with higher professional levels possessing more extensive professional skills, which could help them effectiveness response those emergency situations. However, it can be observed from Table 8 that Level 2 seafarers exhibit higher perceived risk in close encounter situations compared to Level 3 seafarers. This may be due to the higher level of responsibility in navigational safety that is assumed by seafarers at Level 2 compared to Level 3. Furthermore, it is

interesting that the seafarers from Level 3 to Level 2 show the greatest decrease in perceived risk under emergency incidents. In particular, Level 3 seafarers show the highest perceived risk under emergency incidents, while Level 2 seafarers present the lowest perceived risk when encountering emergency incidents among three emergency situations. This shows that emergency incidents are the events in which seafarers are most likely to respond effectively through training.

Overall, the impact of seafarers' individual characteristics on perceived risk has been validated across three emergency situations. Taking into account the temporal variation in seafarers encountering emergency situations, situations of poor visibility and emergency incidents have a sustained impact on the perceived risk of seafarers. Compared to these two situations, close encounters have relatively short periods of impact on seafarers' perceived risk, which is limited to a short period following the occurrence of the event. However, the highest perceived risk of seafarers presents in Time 2 under close encounters. This may suggest that seafarers need to maintain a higher level of attention to the current encounter situation after making decisions to complete the entire avoidance process.

5.2 Practical recommendations

In order to reduce maritime accidents caused by human errors, it is necessary to take effective measures to reduce potential unsafe behaviour and states lead to human errors. As mentioned previously, the findings regarding the relationship between seafarers' individual characteristics and their perceived risk during different emergency scenarios can assist maritime authorities in formulating effective strategies for seafarers' skill training, thereby enhancing their emergency response capabilities. First, the difference in the profession of seafarers should be considered in the skill training and provide targeted training accordingly. For example, the training for handling emergency incidents in complex waters should be strengthened for deck officers. Second, it is necessary to emphasize the training of response capabilities in the training of mature seafarers. In the future development of intelligent ships, navigation aid equipment should be provided for mature seafarers to help them deal with situations that require a quick response. Third, strengthening training for close encounter situations can help reduce maritime risk caused by low navigational experience seafarers. Fourth, enhancing training in emergency incident scenarios can improve seafarers' emergency response abilities and effectively reduce the likelihood of human errors during such incidents. In addition, physiological monitoring equipment is recommended in seafarers' certification examinations, which could help examiners with valuable insights into seafarers' objective states, serving as an additional reference for evaluating the test results.

6. Conclusions

Taking into account the differences in the individual characteristics of various seafarers, this study has investigated the influence of the individual characteristics of seafarers on

perceived risk. The perceived risk under various emergency situations and individual characteristics of seafarers are collected from 28 participants. The results of nonparametric tests imply that marine pilots, young, less experienced and lower professional levels seafarers exhibit a high level of perceived risk when encountering various emergency situations. Based on these results, further analysis of the relationship between individual characteristics and the perceived risk of seafarers is separately developed for different emergency situations using the LMM model.

Results show that the navigational experience, profession, and professional level have a significant impact on the perceived risk of seafarers under poor visibility situations. All individual characteristics in this study are observed to have an effect on the perceived risk of seafarers during emergency incident periods. However, only the factor of profession affects the perceived risk of seafarers when encountering multi-ship encounters. It is probably because of the various requirements for seafarers' performance in dealing with different emergency situations. The analysis results of marginal effects show that during close encounter periods, the navigational experience factor does not significantly affect the perceived risk of seafarers. Moreover, it is observed that seafarers at professional level 2 have a higher perceived risk compared to those at professional level 3, which can be attributed to their higher responsibilities in ensuring maritime safety. The results also show that seafarers' perceived risk is consistently affected during periods of emergency situations. Especially in close encounter situations, seafarers need to maintain a higher level of perceived risk after making collision avoidance decisions.

The limitations of this study could be further solved in future. Initially, this study assesses the navigation risk solely from an objective physiological perspective. In subsequent research, seafarers' decision data and ship trajectory data will be collected to further evaluate the operational performance of seafarers. Second, the data from other seafarers in the team, including the chief mate and helmsman, could also be recorded, as their error if any occur, can potentially contribute to maritime accidents.

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Fig. 1 Ship-handling simulator

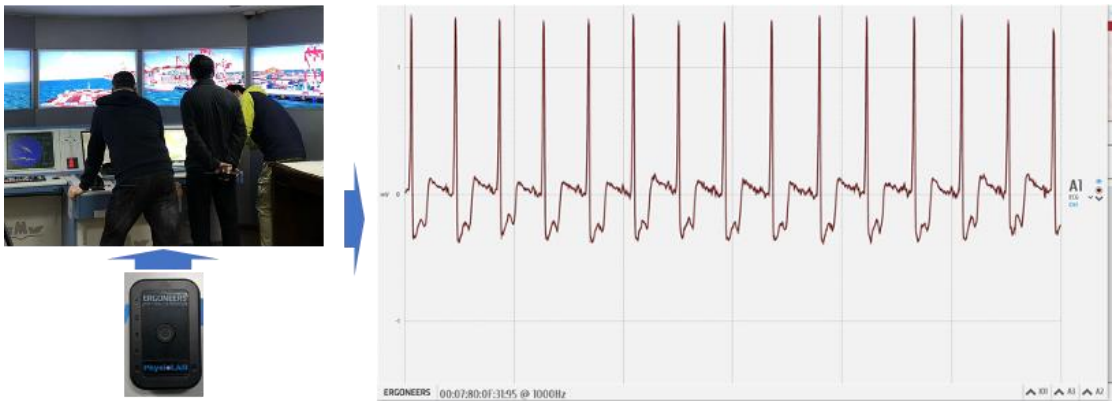

Fig.2 ECG data acquisition process

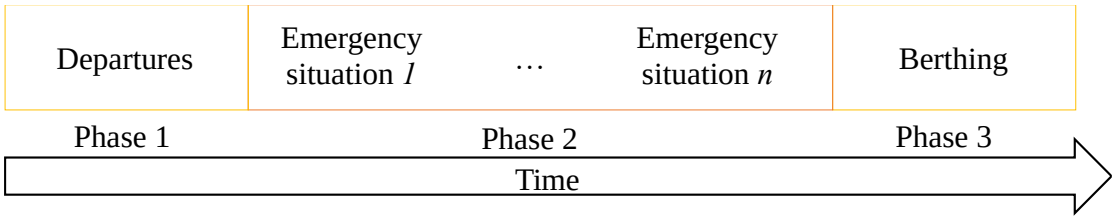

Fig. 3 The overall process of the experiment

(a) Normal

(b) Poor visibility

(c) Multi-ship encounter

(d) Man overboard

Fig. 4 Navigational scenarios in the experiment

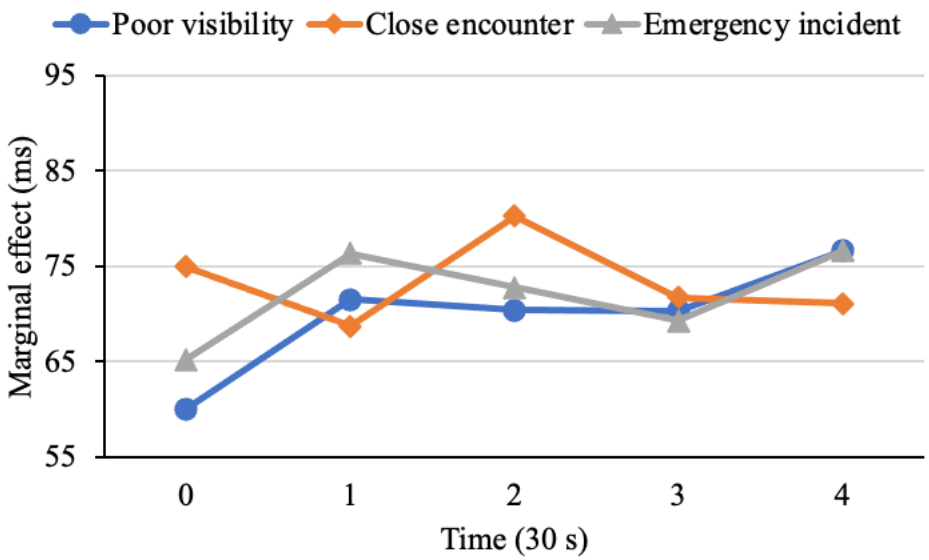

Fig. 5 The temporal variation in seafarers' marginal effects in different situations

Table 1 Demographic characteristics of participants

Characteristics	Classification	Subject number	Percentage	Describe
Profession	Deck officer	12	46	
	Pilot	14	54	
Professional level	Level 1	3	12	Captain, First-Class pilot
	Level 2	17	65	First mate, Second-Class pilot
	Level 3	6	23	Second mate, Third-Class pilot
Age	Young	16	39	≤33 years old
	Mature	10	61	>33 years old
Navigational experience	Less experienced	12	46	≤8 years
	Experienced	14	54	>8 years

Table 2 The emergency scenarios in the experiment

Type	Emergency scenario
Poor visibility	Fog navigation
	Night navigation
Multi-ship encounter	Overtaking situation
	Head-on situation
	Cross situation
Emergency incident	The main engine is out of control
	The whole ship losing power
	Radar malfunction
	Man overboard

Table 3 The descriptive statistics of the perceived risk of seafarers in different category groups

Category	Mean	Std. Err.	p-value
Profession			
Deck officer	43.82	1.71	<0.001[a***]
Pilot	106.46	3.52	
Age			
Young	98.4	4.49	<0.001[a***]
Mature	57.25	2.37	
Navigational experience			
Less experienced	85.94	3.46	<0.001[a***]
Experienced	56.38	3.04	
Professional level			
Level 1	33.99	1.81	<0.001[b***]
Level 2	64.29	2.71	
Level 3	118.24	4.65	

[***] $p<0.01$, [**] $p<0.05$, [*] $p<0.10$, [a] Mann-Whitney test, [b] Kruskal-Wallis test

Table 4 The results of nonparametric tests in different groups under various emergency situations

Category	Poor Visibility			Close encounter			Emergency incident		
	Mean	Std.Err.	p-value	Mean	Std.Err.	p-value	Mean	Std.Err.	p-value
Profession									
Deck officer	38.29	2.67	<0.001[a***]	40.35	2.43	<0.001 [a***]	49.43	3.00	<0.001 [a***]
Pilot	98.59	5.83		113.3	5.35		108.08	7.59	
Age									
Young	92.68	7.55	<0.001 [a***]	103.01	7.38	0.001 [a***]	99.33	8.63	<0.001 [a***]
Mature	55.99	4.37		64.76	4.89		52.76	3.23	
Navigational experience									
Less experienced	84.14	5.93	<0.001 [a***]	91.71	6.58	0.068 [a*]	81.93	5.45	<0.001 [a***]
Experienced	54.67	5.52		69.28	5.82		46.16	3.95	
Professional level									
Level 1	36.56	3.21	<0.001 [b***]	29.94	2.69	<0.001 [b***]	35.34	3.38	<0.001 [b***]
Level 2	60.51	4.67		79.38	5.65		55.31	3.46	
Level 3	118.35	8.40		114.94	7.82		122.74	7.97	

[***] $p<0.01$, [**] $p<0.05$, [*] $p<0.10$

[a] Mann-Whitney test, [b] Kruskal-Wallis test

13 Table 5 The analysis results of individual characteristics influenced perceived risk
14 under poor visibility

Variable	Coef.	Std. Err.	t	P>|t|	95% Conf. Interval	
Profession***						
Marine pilot	50.57	8.60	5.88	<0.001***	33.55	67.59
Age						
Mature	11.34	12.89	0.88	0.381	-14.20	36.87
Navigational experience**						
Experienced	-22.94	10.35	-2.22	0.029**	-43.44	-2.44
Professional level*						
Level 1	-25.42	14.38	-1.77	0.080*	-53.90	3.06
Level 2	-27.07	12.02	-2.25	0.026**	-50.87	-3.26
Time						
1	11.41	9.83	1.16	0.248	-8.05	30.88
2	10.36	9.94	1.04	0.299	-9.32	30.03
3	10.22	9.94	1.03	0.306	-9.46	29.90
4	16.54	9.832	1.68	0.095*	-2.93	36.00
Intercept	58.07	12.51	4.64	<0.001***	33.30	82.85

Akaike's Information Criterion (AIC)=1209.054, Hurvich and Tsai's Criterion (AICC)=1209.088, Bozogan's Criterion (CAIC)=1212.825, Schwarz's Bayesian Criterion (BIC)=1211.825.
*** $p<0.01$, ** $p<0.05$, * $p<0.10$.
15

Table 6 The analysis results of individual characteristics influenced perceived risk under close encounters

Variable	Coef.	Std. Err.	t	P>|t|	95% Conf. Interval	
Profession***						
Marine pilot	60.84	10.47	5.81	<0.001***	40.10	81.58
Age						
Mature	-17.33	16.26	-1.07	0.289	-49.54	14.88
Navigational experience						
Experienced	-1.84	12.49	-0.15	0.883	-26.58	22.91
Professional level						
Level 1	-15.20	14.45	-1.05	0.295	-43.83	13.43
Level 2	10.40	11.33	0.92	0.361	-12.05	32.85
Time						
1	-6.26	10.13	-0.62	0.538	-26.33	13.81
2	5.28	10.13	0.52	0.603	-14.79	25.35
3	-3.23	10.13	-0.32	0.751	-23.30	16.84
4	-3.91	10.36	-0.38	0.707	-24.44	16.61
Intercept	55.73	13.70	4.07	<0.001***	28.58	82.87

AIC=1160.736, AICC=1160.772, CAIC=1164.463, BIC=1163.463.

*** $p<0.01$, ** $p<0.05$, * $p<0.10$.

Table 7 The analysis results of individual characteristics influenced perceived risk under emergency incidents

Variable	Coef.	Std. Err.	t	P>|t|	95% Conf. Interval	
Profession**						
Marine pilot	27.96	10.97	2.55	0.012**	6.23	49.69
Age						
Mature	19.18	11.87	1.62	0.109	-4.34	42.70
Navigational experience**						
Experienced	-20.65	7.34	-2.82	0.006**	-35.18	-6.13
Professional level**						
Level 1	-58.11	17.13	-3.39	0.001**	-92.03	-24.19
Level 2	-49.80	15.79	-3.15	0.002**	-81.06	-18.54
Time						
1	11.14	8.51	1.31	0.193	-5.73	28.00
2	7.56	8.51	0.89	0.376	-9.30	24.42
3	4.08	8.51	0.48	0.633	-12.79	20.94
4	11.38	8.79	1.29	0.198	-6.03	28.79
Intercept	87.94	13.67	6.44	<0.001***	60.88	115.01

AIC=1164.371, AICC=1164.405, CAIC=1168.133, BIC=1167.133.

*** $p<0.01$, ** $p<0.05$, * $p<0.10$.

Table 8 The marginal effects of individual characteristics and time factor on the perceived risk of seafarers under different emergency situations

Variable	Poor visibility			Close encounter			Emergency incident		
	Margin	95% Conf. Interval		Margin	95% Conf. Interval		Margin	95% Conf. Interval	
Profession									
Deck officer	44.48	32.75	56.21	42.92	29.64	56.20	58.07	47.05	69.09
Marine pilot	95.05	84.12	106.00	103.76	91.34	116.18	86.03	71.21	100.85
Age									
Young	64.10	48.84	79.35	82.01	63.71	100.30	62.46	47.31	77.61
Mature	75.43	61.10	89.77	64.67	47.37	81.98	81.64	69.31	93.97
Navigational experience									
Less experienced	81.24	69.99	92.48	74.26	61.25	87.26	82.37	72.74	92.01
Experienced	58.230	44.30	72.29	72.42	56.53	88.31	61.72	50.87	72.57
Professional level									
Level 1	61.84	43.99	79.70	59.74	40.33	79.14	49.91	31.14	68.68
Level 2	60.20	49.05	71.34	85.34	72.97	97.71	58.22	43.95	72.48
Level 3	87.26	68.87	105.70	74.94	57.71	92.17	108.02	87.76	128.28
Time									
0	60.06	45.62	74.51	74.96	60.20	89.73	65.22	52.34	78.09
1	71.47	57.03	85.92	68.70	53.94	83.46	76.35	63.48	89.23
2	70.42	55.83	85.00	80.25	65.48	95.01	72.78	59.90	85.65
3	70.28	55.70	84.87	71.74	56.97	86.50	69.29	51.02	74.87
4	76.60	62.15	91.04	71.05	55.63	86.47	70.25	57.56	82.94