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Article

The impact of marine engine noise exposure on seafarer fatigue: A China case

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ABSTRACT

Previous relevant studies have revealed that noise and poor sleep quality are two important risk factors causing seafarer fatigue. However, the relationship between marine engine noise and objective sleep parameters has rarely been studied. Using primary data collected from a 28-day on-board experiment and 1 questionnaire survey during both voyage and berthing periods, this study takes a pioneering step to address this crucial relationship. Energy indicators related to the engine noise for 28 days were estimated and 6 objective sleep parameters were used to measure the degree of seafarer fatigue. The findings reveal that as seafarers want to sleep longer to relieve their anxiety and irritability caused by the increased engine noise, the time in bed (TB) and the total sleep time (TST) increased when the engine noise level increased. Meanwhile, with the growing engine noise levels and the higher number of engine noise events, the total wake time after sleep onset (WASO) and the time for sleep onset latency (SOL) increased, and the sleep efficiency (SE) decreased. Energy indicators were significantly associated with objective sleep parameters. Finally, strengthening the content of psychological adjustment in the seafarer training link and cultivating the seafarers' character strength to improve the ability to face harsh environments are recommended. In maritime management, managers should play the role of social work intervention to

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adjust seafarers' sleep quality and ease fatigue. In the construction of ships, builders should emphatically consider the use of sound insulation materials to reduce noise effect on living areas.

Keywords: Maritime safety, Seafarer fatigue, Engine noise exposure, Logistic regression model, Objective sleep parameters

1. Introduction

Good health and well-being is one of the important sustainable development goals that are attracting numerous research interests worldwide (Zheng et al., 2021), with maritime studies no exception. Research revealed that the confined and isolated environment could induce a negative impact on the physical and psychological functioning of seafarers (Smith et al., 2006; Zhao et al., 2020). Despite the efforts the maritime industry has been made to improve structural stability and reliability through laws, regulations, training forms and technical means, the occurrence rate of maritime accidents still remains at a relatively stable level after a dramatic reduction in the past half of century (Fan et al., 2020; Liu et al., 2021; Shu et al., 2022; Wang et al., 2022b). The ship operation system is designed by incorporation of human behavior, due to the complex socio-technical structure of human factors, it is critical to study the human factor to reduce maritime accidents (Fan et al., 2018). The serious negative effect of human factors on the occurrence of maritime accidents has aroused great attention and heated discussion in the maritime industry.

Human factor can contribute to a disaster or economic losses due to delayed human operations (Fan et al., 2018). According to the latest accidents report of the European Maritime Safety Agency (EMSA), 80% of the incidents were related to human error. The distribution of accidents for 2014-2020 and the relationship between accident events and the main contributing factors for 2014-2020 were reported by EMSA as shown in Fig. 1 and Fig. 2. Although modern ships are equipped with advanced accident prevention systems, the human factors are still acting as one of the main root causes leading to maritime accidents (EMSA, 2021). Fatigue as one of the major human factors has been regarded as the main human-related problems leading to the deterioration of safety consequence in the maritime industry (Akhtar and Utne, 2015). Griffith and Mahadevan (2011) studied the acute fatigue caused by sleep deprivation with the approach of human reliability analysis (HRA). It was found that seafarer fatigue had been measured repeatedly as a factor of human error, therefore, it is needed to include fatigue and sleep deprivation in HRA and in the evaluation of human error probability (Griffith and Mahadevan, 2011). Maritime accident studies reveal the fact that there is a strong relationship between the occurrence of maritime accidents and the crew's sleep quality. Fan *et al.* (2020) selected the maritime reports from TSB (Transportation Safety Board of Canada) and MAIB (Maritime Investigation Agency of British) between 2012 and 2017, to form a database of 161 accident reports through which the most relevant risk factors were identified. The results showed that 13.46% of the accidents were caused by fatigue and sleep. As studies show that sleep deprivation reduces the energy level, and seafarer fatigue leads to otherwise avoidable human errors (Hystad and Eid, 2016). It is the consensus in the maritime industry that exposure to the monotonous noise of the ship's engine can lead to sleep quality problems. Sleep quality problems (e.g., sleep-deprived or time awake) are undoubtedly the most crucial contributor to fatigue (Hystad and Eid, 2016; Oldenburg and Jensen, 2019b). For seafarers, assessing sleep quality is pertinent. Sleep must be taken into account when explaining the influences of circadian rhythms (24-hour biorhythms) on seafarers' task performance and health. Previous studies have shown that most seafarers have sleep quality problems and fatigue-related accidents at sea are closely linked to sleep-deprived caused by disrupted circadian rhythms (Arendt et al., 2006; Gander et al., 2008; Harma et al., 2008). Questionnaire surveys among seafarers also found that engine noise is the main cause of sleep quality problems (Azimi Yancheshmeh et al., 2020; Hystad and Eid, 2016). A study about noise and sleep on-board in the Royal Norwegian Navy found that the number of noise events, noise level, watch systems, day-to-day variation, nicotine use and coffee drinking are associated with seafarers' sleep quality (Sunde et al., 2016).

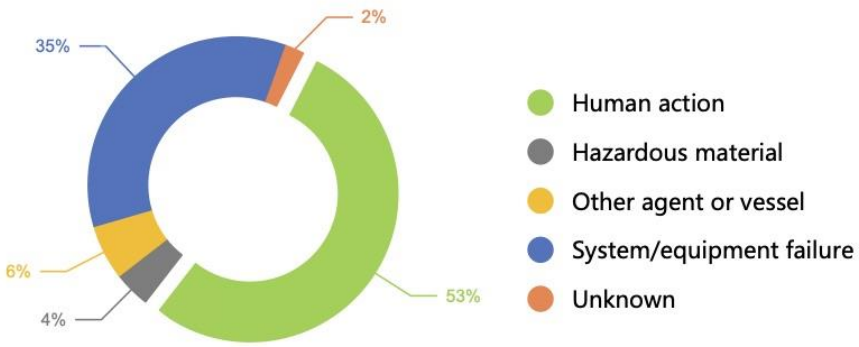

Fig. 1. Distribution of accident events for 2014-2020.
（EMSA, 2021. Annual overview of marine casualties and incidents 2021, pp. 1–175.）

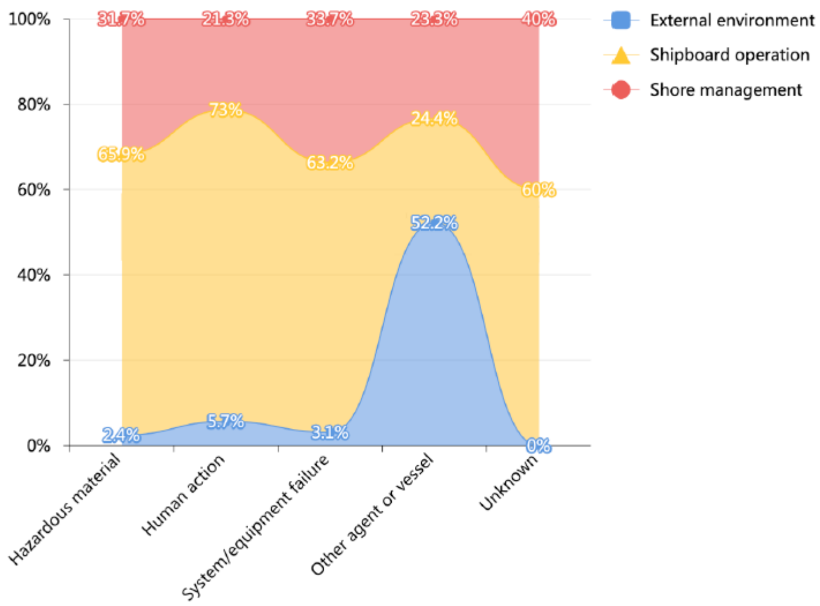

Fig. 2. Relationship between accident events and the main contributing factors for 2014 – 2020.
（EMSA, 2021. Annual overview of marine casualties and incidents 2021, pp. 1–175.）

This study sought to shift the seafarer fatigue research into a new paradigm in which the negative impacts of engine noise on objective sleep quality caused by disrupted circadian rhythms in on-board environment can be quantitatively measured. It is no doubt that data collected from on-board environment are more reliable. However, due to the particularity of work on-board and the restrictions of some rules and regulations, there were few studies on noises and sleep quality conducted in an actual ship environment. In this study, with the strong support of a world leading maritime university and the permission of the captain of its training ship "*Yukun*", research on noise decibel level and objective sleep parameters was carried out on-board. IMO specifies maximum noise limits for various areas of vessels, ranging from 55 dB(A)/60 dB(A) in cabins for vessels more than/less than 10,000GT (Sunde et al., 2016). However, a study in Norway found that noise levels range from 44 dB(A) to 78 dB(A) in cabins depending on ships type (Sunde et al., 2016). Although IMO proposed the noise level standard, IMO did not regulate the noise level in the bedroom when seafarers sleep, and poor sleep quality on-board is still very common. So, it is meaningful to conduct a case study in China. In addition, this study combined descriptive basis and quantitative analysis to examine the negative impacts of engine noise decibel levels on sleep quality problem.

In terms of practical application value, a ship operating system is a system incorporating human behavior, so it is meaningful to study the seafarers' sleep problem, because it is closer to the human factors that lead to maritime accidents. This study is helpful to improve the safety awareness of seafarers, reduce the human error caused by seafarers' sleep quality during the navigation, and avoid the occurrence of unsafe behaviors, so as to ensure the navigation safety. Meanwhile, the results of this study will provide data support for shipping companies and maritime regulatory authorities to relieve seafarers' fatigue, and provide empirical support for reducing human errors during the navigation, protecting and safeguarding seafarers' health and legitimate right. The experiment was conducted on the training ship and the participants are all good educated college students, the result of this study can also provide experience cases for teachers about how to improve seafarers' sleep quality and reducing fatigue from an educational perspective.

2. Literature review

Working on-board faced with many occupational challenges and risks. Seafaring is undoubtedly ranked as one of the most hazardous occupations (Fan et al., 2018; Shu et al., 2022; Zhao et al., 2020). According to the fatigue guideline published by the

International Maritime Organization, fatigue is primarily caused by poor sleep quality and sleep depriviation (caused by the disrupted circadian rhythms) (Main and Chambers, 2015; Zhao et al., 2020). As seafarers work and live in the same on-board environment for a prolonged period of time, engine noise and sleep quality present in seafaring have negative effect on seafarers' health. Studies have also found that being exposed to the on-board environment for a prolonged time leads to great stresses (Hystad and Eid, 2016). Since seafaring is an inherently stressful environment, helping seafarers to relieve their fatigue are meaningful.

Noise on-board are receiving increased attention. The current maritime research on fatigue usually focused on the external stressors such as shift-work, workload, scheduling, isolation and remoteness (Harma et al., 2008; Hystad and Eid, 2016; Lutzhoft et al., 2010). In addition to the factors mentioned above, sleep quality and engine noise should be highlighted. Engine noise and sleep quality that seafarers facing are prolonged and chronic, and of course lead to fatigue (Hystad and Eid, 2016). Seafarers have suffered from insomnia, waking up often and hard to fall asleep. These problems reduce the restorative of sleep quality, which no doubt contributes to fatigue and creates an aggressive climate in the shipboard environment.

Engine noise as a form of environmental noise is recognized as a main physical stressor onboard, the monotonous engine noise, vibration and weather condition can lead to fatigue and sleepiness of all the seafarers on-board, some previous researches have found that 80.6% seafarers reported psychological stress due to vibration (Oldenburg et al., 2020; Oldenburg and Jensen, 2019b). In addition, the nature of work on-board, watch systems, day-to-day variation in operational requirements and activities are likely to cause variation between seafarers' sleep periods on-board (Oldenburg et al., 2020; Sunde et al., 2016). The major effect of environmental noise is sleep disturbance (WHO, 2018). Poor sleep quality caused by engine noise is considered to be one of the main risk factors for fatigue and accidents at sea, as environmental noise has been linked to cognitive impairment in distress and depression. A reduction in subjective sleep deprivation and a worsening of human performance and mood were observed at a subjective level in the previous maritime study (Hassel et al., 2011). In the cross- sectional study about the sleepiness of seafarers on-board, it was found that the monotonous noise of the ship's engine led to sleepiness during the day of all the seafarers on-board and high levels of exposure to engine noise increased sleep troubles when they are exposed to the noise throughout the day (Oldenburg and Jensen, 2019a). High levels of noise pollution can increase the awakenings during sleep periods, and decrease the duration of sleep, thereby reducing the sleep quality. It degrades the sleep quality at both objective and subjective levels. Due to the particularity of work, seafarers on-board are constantly exposed to engine noise. Therefore, a sleep quality problem is a common phenomenon among seafarers.

Noise is often loosely defined as "unwanted sound" and it is a variation of pressure which can be detected by reporter cells in the ear of human (Ohrstrom and Skanberg, 2004). Engine noise as an undesirable environmental noise presents in all motor vessels. Environmental noise standard is the noise tolerance range stipulated to ensure population health and living environment. Each country has its own basic environmental noise standards. According to the sleep guidelines of World Health Organization (WHO), noise levels exceeding 40 dB(A) outside the bedroom are identified to disturb sleep quality (Sunde et al., 2016). The associations between sleep disturbance and levels of noise have been found in road traffic. Belgrad's residents living in noisy urban areas reported lower sleep efficiency than residents living in other areas (de Kluizenaar et al., 2009). de Kluizenaar *et al.* (2009) indicated that road noise increased the likelihood of insomnia in the nearby residents. A study investigating the influences of nighttime railway and road noise found that nighttime noise definitely led to poor sleep quality and fatigue (Ohrstrom and Skanberg, 2004). Aircraft noise exposure has also been investigated. Europe has conducted many pieces of research on large airports to study the negative effects on the sleep quality of nearby residents. Most of them confirmed that exposure to aircraft noise also contributes to physical fatigue when waking up (Perron et al., 2012).

In the study of evaluating crew fatigue as a PSF (performance shaping factor) using the Petro-HRA method (a HRA developed for the petroleum industry), Rasmussen and Laumann cited sleep deprivation as one major factor that caused fatigue.

However, they discussed two issues as to 1) whether sleep deprivation affected the performance of the driver, and 2) whether the operator was suffering sleep deprivation (Rasmussen and Laumann, 2020). Poor sleep quality and sleep disturbance on-board among seafarers have frequently been reported in maritime studies (Arendt et al., 2006; Gander et al., 2008; Lutzhoft et al., 2010). In an investigation about offshore fleet workers, noise on-board was found to be the main factor leading to sleep deprivation at sea (Smith et al., 2006). However, in the very few available studies on monitoring noise and sleep quality on-board through field investigation, the results of the relationship between noise and sleep quality were ambiguous. Under the pre-conditions for unsafe act level, environmental factors are assessed as latent factors. In the formation of unsafe acts, environmental factors play an important role in all high-risk industries. Engine noise as an on-board environmental noise has negative effects on the task being performed by seafarers. Being exposed to noise for a prolonged period will cause changes in the body, such as digestive disorders (ulcers or colitis), cardiovascular disorders (hypertension or heart disease) or endocrine and biochemical disorders. Though negative physiological influences are hard to detect, their impacts on human performance are considerable and make them the critical human factors leading to sleep quality and fatigue (Calhoun, 2006).

The maritime industry is a twenty-four-hour industry. Seafarers have to work under hectic activities and time pressure. Watch-keeping, cargo-handling and maintenance during the night take place around the clock and cause the occurrence of irregular work hours. Besides, being exposed to engine noise during sleep is a common phenomenon. Therefore, regular sleep patterns and the circadian rhythm of seafarers might be disturbed, which will definitely lead to fatigue and poor sleep quality. Some maritime studies have investigated seafarers' sleep quality. For instance, Oldenburg *et al.* (2020) designed a cross-sectional survey to evaluate the prevalence of seafarers' sleepiness on duty. Sleepiness on duty was found to be prevalent on-board. Hystad and Eid (2016) studied if sleep duration had negative influences on insomnia at sea. However, the results showed that sleep duration has minor influence on insomnia. Fahad *et al.* (2020) used the Pittsburgh Sleep Quality Index (PSQI) to examine the seafarers' subjective sleep quality. The result showed that seafarers' sleep quality remained to be a severe problem and poor sleep quality played a negative role in Psychomotor Vigilance Task (PVT) performance. Some studies found that sleep quality had often been interrupted by engine noise (WHO, 2018). A research involved 11 Norwegian ships aimed to identify harmful risk factors to seafarer's health, and it was found that 46% of seafarer reported noise from engine as a serious risk factor leading to sleep problems (Song et al., 2021). Sleep insomnia deriving from constantly noise exposure contributes to annoyance, and the percentage of annoyance is the crucial health endpoints for health environmental assessment (de Kluizenaar et al., 2009). Seafarers staying with high levels of noise were easily annoyed and consequently, reduced the cognitive resources (Hystad and Eid, 2016). Sleeplessness derived from engine noise can also contribute to anxiety. Anxiety affects central nervous system, which in turn reduces performance on vigilance tasks performance (Warm et al., 2008).

A few maritime studies have taken objective sleep parameters into account and most of them separated the noise level and the objective sleep parameters. However, in aviation, many studies have been conducted around the big airports to examine the relationship between the aircraft noise and the objective sleep parameters of the nearby residents (Franssen et al., 2004; Kwak et al., 2016; Nassur et al., 2019). Aircraft noise studies which considering the sleep objective parameters found that exposure to aircraft noise definitely led to mental fatigue when wake up in the morning and poor self-reported sleep quality (Lutzhoft et al., 2010; Rasmussen and Laumann, 2020; Smith et al., 2006). Because of the particularity of working and living environment, such as isolation from shore-based life, inconvenient work hours and high workload, seafarers are more sensitive to noise and sleep quality than the residents nearby the airports (Fan et al., 2021). In addition, the noise on-board ship is constant, but the aircraft noise is intermittent. Therefore, it is supposed that the sleep quality of the seafarers could be worse than the residents nearby the airports. In the maritime industry, the updated International Maritime Organization Code on Noise Levels on Board Ships is the latest noise standard (Hirshkowitz et al., 2015; Main and Chambers, 2015). The new code required to establish mandatory noise limits for the seafarers' dormitories on the basis of experiences. Nevertheless, these noise limits are defined only to prevent seafarers from hearing loss, the associated impacts of engine noise on human performance and sleep quality of the seafarers have yet been addressed in the current literature. Different from the previous studies, this study focused on the relationship between noise and sleep quality as well as seafarers' subjective feeling of fatigue. This study will provide the stakeholders of the shipping industry and the fatigue risk management system with objective and reliable quantitative empirical data for the mitigation and management of seafarer fatigue. This experiment was under the good supervise of the teachers on-board, the result of this study will be more accurate than the previous studies. This study will also use the collected data to provide experiences and case for navigation education. Education is often one the best ways to avoid human errors.

3. Method

3.1 Ship profile and experimental conditions

A training ship of a world leading maritime university was chosen to conduct the research. “*Yukun*” is a training ship that integrates teaching and research tasks. It sails in the coastal areas of China and always encounters all kinds of sea conditions, which helps us to test the variation of engine noise due to various practical conditions that the ship may encounter during the experiment. About 800 cadets from the university will participate in a four-week internship from September to December every year in batches. Table 1 presents the basic information of “*Yukun*” (Wang et al., 2021a; Wang et al., 2021b). During the experiment, the ship navigated for 14 days and stayed in port for 14 days. When the ship sailing off the coast of China, it encountered different waves and wind, which caused impact on the hull, and generated noise and vibration. At the same time, in order to better provide cadets with a real practice training scene. The ship berthed at Dalian Port for 14 days, and there were other merchant ships nearby for cargo loading, unloading, sailing and berthing. The dormitories of “*Yukun*” are mainly distributed on the main deck and the tween deck. The location distribution diagrams of the dormitories are shown in Fig. 3. All cadets lived in fixed dormitories during their 28 days of internship life on the ship. Therefore, the distance between their dormitories and the engine room remains constant. Five bedrooms on the main deck was chosen to compare the noise levels on the same floor. At the same time, three bedrooms on the tween deck with the same longitudinal position as the three bedrooms on the main deck were also chosen to measure the noise between different decks.

Table 1

Basic information of the training ship "*Yukun*".

Category	Information
Ship Name	Yukun
Type of Ship	Special Purpose Ship
LOA	116.0 m
LBP	105.0 m
Max. breadth	18.0 m
Max. height	11.10 m
Main engine	4440kw*173rpm
Service Speed	16.7 knots
Capacity	23 seafarers, 17teachers, 196 cadets
Navigation route	Coastal area of China

3.2 Participants information

All participants are junior students of the university who have to finish their internships on "*Yukun*". The age distribution of the cadets is between 19-21 years old and they are all males in good physical condition. All cadets worked on "*Yukun*" for 28 days during September to December. During the four-week internship, these cadets were divided equally into four groups. Each group of cadets took the same training schedule on the ship. The days on board were divided equally into three groups, in which all cadets worked as first, second and third officers in each group. All of the participants took the same 4 on/8 off rotation. Nevertheless, for each cadet, the schedule was the same and their dormitories did not change during the internship. The participants and the officers have the same work and rest time and the participants were on duty in the shift.

3.3 Experimental design and procedure

To investigate the relationship between engine noise and sleep quality, an experiment was conducted to measure noise level in the living area of the training ship "*Yukun*". The experiment was conducted in the dormitories of the training ship "*Yukun*". The relevant ethical clearance has been approved by the university's Human Research

Ethics Committee and the captain of "*Yukun*". DELIXI ELECTRIC noise decibel meters were used to measure the noise level. The measurement range of the noise decibel meters is from 30 dB(A) to 130 dB(A), and the frequency response is from 30 Hz to 8 kHz. The resolution of the noise decibel meters is 0.1 dB(A) and the accuracy is ±1.5 dB(A).

Based on the distance from the engine room, 8 dormitories were selected to place decibel meters to measure noise, as shown in Fig. 3. The port and starboard sides of the ship are symmetrical, and the noise levels at the corresponding positions on the port side and starboard side are the same. Therefore, all the noise decibel meters were placed at the starboard side, and 5 dormitories were selected on the main deck and 3 dormitories on the tween deck. At the same time, to compare the difference of noise between different decks on sleep quality, selected dormitories on the tween deck are perpendicular to the selected dormitories on the main deck. One decibel meter was placed in every dormitory, parallel with the ship engine, to detect the variation of the noise in the dormitories associated with the engine noise. Noise was measured by energy indicators (related to the sound energetic average for a given period). According to the actual working situation of the ship, during the berthing period, the ship only has auxiliary machinery to work; during the voyage, the ship's main engine and auxiliary engine work simultaneously. Therefore, the engine noise during berthing is mainly caused by auxiliary engine, and the engine noise during sailing days is caused by the main engine and auxiliary engine together, as well as the propeller. In this study, energy indicators notably included equivalent continuous engine noise pressure level during berthing and sailing period at the main deck (LAeq, main deck for engine noise) and at the tween deck (LAeq, tween deck for engine noise) of the dormitory, respectively. Cadets in each dormitory measured the decibel once before going to bed and once when they woke up. Cadets would ensure that there was not any noise other than engine noise in the dormitory while performing noise measurement. At the same time, the cadets in charge of recording clearly marked whether the ship was sailing or berthing at the port when the decibel was measured because that the engine noise decibel was definitely different when the ship sailed or not.

Fig. 3. The dormitory layout of the main deck and the tween deck.

Before the experiment, participants were informed to be the subjects selected for the experiment. They were also told that they could quit the experiment as long as they felt uncomfortable with the experiment or changed their mind.

3.4 Measurement

The measurement mainly consists of three parts. The first part involves energy indicators that measured by decibel meter before going to bed and when they woke up in each dormitory, such as age, major and the room number of the dormitory. The second part is designed to investigate the seafarer's sleep quality which consists of a series of objective sleep parameters to show their objective sleep quality. The third part is the assessment of subjective emotions, in which a combination of the SAM (Self-Assessment Manikin) scale and five- point-Likert-type scale were used to reflect the cadets' subjective emotions, emotions were coded as 1 to 'smiling' to 'frown' as 5.

According to the time recorded by the wrist actigraph, cadets filled out the same questionnaires once during the voyage period and the other time during the berthing period. The wrist actigraph records the sleep-wake rhythm. To achieve the aim of collecting real objective sleep parameters which were representative of normal daily life, cadets were asked to behave as usual to collect more realistic data.

- Total Sleep Time (TST): the duration between fall asleep to wake up, reduced by the awakenings;

- Wake After Sleep Onset (WASO): the duration of awakenings;

- Total Sleep Period (TSP): the duration between fall asleep to wake up, and TSP = TST+WASO;

- Sleep Onset Latency (SOL): the duration between turn off the lights to fall asleep;

- Time in Bed (TB): the duration staying in bed between turn off the lights to get up, and TB = SOL+TSP;

- Sleep Efficiency (SE): TST/TSP.

According to the third edition of the International Classification of Sleep Disorders (ICSD-3) (Perron et al., 2012), SOL$\geqslant$30 min should be judged as insomnia. TB >8h was the character of long duration in bed. On work days, sleep fewer than 6 h per night (TSP<6h or TST< 6h) is treated as short sleep (Lutzhoft et al., 2010; Smith et al., 2006). The duration of being awake more than 30 min (WASO$\geqslant$30) is treated as sleep maintenance insomnia. SE < 90% is judged as insomnia (Cappuccio et al., 2010; Kurina et al., 2013).

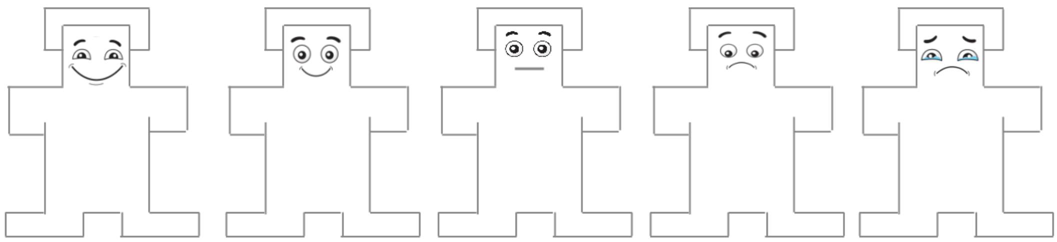

Fig. 4. The SAM (Self-Assessment Manikin) scale.

As shown in Fig. 4, the SAM scale was used to reflect the cadets' subjective feeling during the assessment. Correspondingly, the Likert scale, the smile state was mapped to fully control one's emotion under the influence of engine noise, and coded as 1, a frown state was mapped to completely unable to control one's emotion under the influence of engine noise, and coded as 5.

Sleep quality as a combination of physiological function and subjective perception makes the measurement complicated, so the questionnaire includes both the objective parameters and the subjective feelings. The sleep quality and subjective emotions during the voyage period and the berthing period were investigated, and compared with each other.

3.5 Statistical analyses

Logistic Regression is a classification model and is often used for binary classification or ordered regression model. Logistic regression is always used to estimate the occurance of an effect (Wang et al., 2021c; Wang et al., 2020; Weng et al., 2019). Objective and subjective sleep parameters were treated as dependent variables and acoustic index as independent variables, logistic regression was used to evaluate the effect of engine noise exposure on seafarer's sleep quality and emotion in this study.

3.5.1 Binary logistic regression model

Binary logistic regression refers to the regression analysis when the explained variable is a binary variable of 0/1 (Weng and Yang, 2015). At this time, the theory and idea of establishing linear multiple regression model can also be used to model the probability with the explanatory variable value of 1, as shown in Eqs. (1)-(2).

$$y_i = \alpha + x_i \beta_i + \varepsilon \tag{1}$$

$$\text{logit}\, p = \ln \frac{p}{1-p} = \alpha + x_i \beta_i + \varepsilon = x_i \beta_i + \beta_0 \tag{2}$$

where y is the internal tendency of the observed object, p is the probability of explained variable, α is the intercept term of the model, β is the parameter to be estimated, x is the explanatory variable, i.e., noise acoustic index variable, ε is the error term, β_0 is the sum of intercept term and error term.

The binary logistic regression is shown as Eq. (2), and it can be further translated into Eqs. (3)-(4) to better explain the nonlinear relationship between probability p and explanatory variables (Wang et al., 2020; Weng et al., 2019).

$$\frac{p}{1-p} = \exp(x_i \beta_i + \beta_0) \tag{3}$$

$$p = \frac{1}{1+\exp[-(x_i \beta_i + \beta_0)} \tag{4}$$

In this study, SOL<30 min, TB≤8h, TSP<6h, TST<6h and WASO<30min were coded as 0; SOL≥30min, TB>8h, TSP≥6h, TST≥6h and WASO≥30min were coded as 1.

3.5.2 Ordered regression model

Ordered Regression is a model that solves a certain order relationship between categories. In addition to considering the classification loss, the model also considers the order relationship between different categories, so that the loss of misjudgments closer to the true label ranking is smaller than the loss of misjudgments far away from the true label (Chang et al., 2022; Wang et al., 2022a; Xu and Witlox, 2022). The subjective sleep parameter as the dependent variable, i.e., emotions, is a categorical variable and the number of the classification is more than 2, and there is an ordered relationship between the dependent variable categories, an ordered logistic regression model can be used. Seafarers' emotion evaluated by SAM scale were treated as dependent variables and were classified into 5 categories, coded as 1, 2, 3, 4 and 5 respectively, p_1, p_2, p_3, p_4, p_5 are the probability of corresponding categories respectively, and $p_1 + p_2 + p_3 + p_4 + p_5 = 1$. Therefore, four ordered logistic regression models as Eqs. (5)-(8) can be derived from Eq. (2).

$$\text{logit}\frac{p_1}{1-p_1} = \text{logit}\frac{p_1}{p_2+p_3+p_4+p_5} = \beta_1 + \beta_1 x_1 + \ldots + \beta_i x_i \quad (5)$$

$$\text{logit}\frac{p_1+p_2}{1-(p_1+p_2)} = \text{logit}\frac{p_1+p_2}{p_3+p_4+p_5} = \beta_2 + \beta_1 x_1 + \ldots + \beta_i x_i \quad (6)$$

$$\text{logit}\frac{p_1+p_2+p_3}{1-(p_1+p_2+p_3)} = \text{logit}\frac{p_1+p_2+p_3}{p_4+p_5} = \beta_3 + \beta_1 x_1 + \ldots + \beta_i x_i \quad (7)$$

$$\text{logit}\frac{p_1+p_2+p_3+p_4}{1-(p_1+p_2+p_3+p_4)} = \text{logit}\frac{p_1+p_2+p_3+p_4}{p_5} = \beta_4 + \beta_1 x_1 + \ldots + \beta_i x_i \quad (8)$$

In ordered logistic regression model, the test of proportionality hypothesis condition (also known as "parallel line test") should be carried out first. If the test significant result *p*-value of parallel line test is larger than 0.05 (p>0.05), indicating that the assumption can be accepted, and the proportional odds assumption is true for all logits (Wang et al., 2021c; Weng et al., 2019).

3.5.3 Odds ratios

In logistic regression models, regression coefficients are often explained by odds ratios (OR). OR is a measurement of the change of a variable due to the increase of another variable by one unit while all other variables are kept unchanged (Wang et al., 2021c; Weng et al., 2019). In this study, OR can be calculated by Eq. (9), and used to indicate the degree of influence of the given noise acoustic indexes.

$$OR\ (odds\ \text{ratio}) = \frac{e^{\beta_0+\beta_1(x_1+1)+\beta_2 x_2}}{e^{\beta_0+\beta_1 x_1+\beta_2 x_2}} = e^{\beta_1} \tag{9}$$

It can be seen Eq. (9), the exponential transformation of the regression coefficient indicates that for one unit increase in the occurrence rate of the explanatory variable, if the OR is greater than 1, indicating that the greater the probability that the objective sleep quality parameter and emotion change with the change of the noise acoustic index.

4. Results

Data from 150 cadets were collected in this study. Table 2 shows that 33% of participants slept less than 6 h per day (TST< 6h), 35% of participants in this study have difficulties in sleep maintenance (WASO ≥ 30 min) and 42% of participants have sleep onset insomnia problem (SOL ≥ 30min). The participants slept less than 6 hour per day also suffered from sleep maintenance problem and sleep onset insomnia problem.

Table 2

Description of the objective sleep parameters of the participants.

		Sailing days		Berthing days	
		Number of participants	Percentage of participants	Number of participants	Percentage of participants
SOL	<30min	87	58	102	68
	≥30min	63	42	48	32
TB	≤8h	118	79	107	71
	>8h	32	21	43	29
TSP	≥6h	105	70	115	77
	<6h	45	30	35	23
TST	≥6h	101	67	104	69
	<6h	49	33	46	31
WASO	<30min	98	65	110	73
	≥30min	52	35	40	27
SE	≥90	131	87	137	91
	<90	19	13	13	9

Fig.5 presented the number of awakenings per night due to noise events. The results showed that most of the participants waked up three times per night.

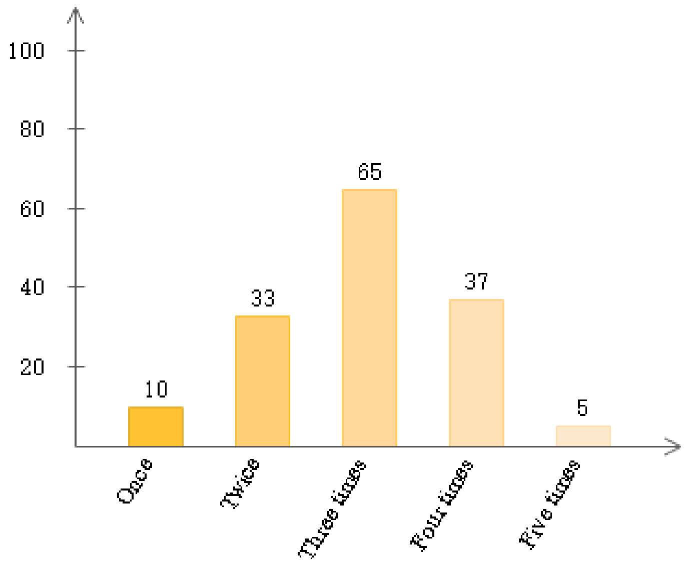

Fig. 5. The number of awakenings per night due to noise events

Table 3 describes the differences of the noise indicators on the main deck and the tween deck during berthing days. According to the Table 3, it was showed that the noise decibel level is closely related to both horizontal and vertical distances. On average, the equivalent noise when falling asleep were 63.09 dB(A) on the main deck and 57.29 dB(A) on the tween deck. The equivalent noise on average when waking up were 62.28 dB(A) on the main deck and 57.13 dB(A) on the tween deck. The standard deviations when waking up and falling asleep on the main deck were both higher than on the tween deck.

Table 3

Description of noise indicators on the main deck and the tween deck.

Noise indicators	Mean	SD	F	P
LAeq. main deck (dB(A)) when wake up	62.28	7.22	39.23	<0.001
LAeq. tween deck (dB(A)) when wake up	57.13	5.34		
LAeq. main deck (dB(A)) when fall asleep	63.09	7.16	41.30	<0.001
LAeq. tween deck (dB(A)) when fall asleep	57.29	5.33		

Table 4 presents the difference of the noise indicators during sailing days and berthing days. The reason for performing these tests during sailing days and berthing days were the differences of the noise and sleep atmosphere the seafarers are exposed to. During the sailing days, the equivalent noise on average when falling asleep and when waking up were 64.68 dB(A) and 64.43 dB(A). During the berthing days, the equivalent noise on average when going to bed and when waking up were 57.20 dB(A) and 57.00 dB(A). Besides, the standard deviation when waking up in berthing days was higher than in sailing days. The standard deviation when falling asleep in sailing days was higher than in berthing days.

Table 4

Description of noise indicators in sailing days and berthing days.

Noise indicators	Mean	SD	F	P
LAeq. sailing days (dB(A)) when wake up	64.43	5.43	83.46	<0.001
LAeq. berthing days (dB(A)) when wake up	57.00	6.49		
LAeq. sailing days (dB(A)) when fall asleep	64.68	6.68	85.66	<0.001
LAeq. berthing days (dB(A)) when fall asleep	57.20	5.36		

Table 5 presents the objective sleep parameters on different decks. TST on the main deck was on average 6 h 57 min and on the tween deck was 6 h 48 min. SOL were 37 min on the main deck and 36 min on the tween deck. The participants' total sleep period (7 h 33 min) on the main deck was longer than the tween deck (7 h 16 min). The participants on the main deck spent more time in bed (8 h 29 min) than the participants on the tween deck (8 h 24 min), with higher SE on the tween deck (94% vs. 92%).

Table 5

Description of objective sleep parameters.

	Main Deck		Tween Deck	
	Mean	SD	Mean	SD
SOL (h: min)	00:37	00:39	00:36	00:39
TB (h: min)	08:29	01:32	08:24	01:32
TSP (h: min)	07:33	01:28	07:16	01:25
TST (h: min)	06:57	01:23	06:48	01:21
WASO (h: min)	00:28	00:20	00:27	00:20
SE (%)	92	2	94	4

With objective sleep parameters as dependent variables and noise acoustic indexes as independent variables, Eqs. (2)-(4) and (9) were used to establish a series of binary logistic regression models, and the results are shown in Table 6 and Table 7. Table 6 describes the likelihood ratio test of binary logistic regression model. All test *p*-values in the model are less than 0.05, indicating that the model is valid, and binary logistic regression analysis can be performed on.

Table 6

The likelihood ratio test of binary logistic regression model.

Sleep parameter	Chi-square	df	*p*-value
SOL	55.461	1	< 0.001
TB	49.954	1	< 0.001
TSP	30.539	1	< 0.001
TST	54.197	1	< 0.001
WASO	28.138	1	< 0.001
SE	46.131	1	< 0.001

Table 7 presents the results of binary logistic regression between the noise decibel value and objective sleep quality parameters. At the 99% confidence level, the effect of noise decibel level on objective sleep quality parameters is statistically significant. The regression coefficients of SOL, TB, WASO and SE are all positive, indicating that the decibel values will have positive impacts on them. It is important to point out that, unlike previous studies, the reason for the larger TB with louder noise is that seafarers want to spend more time in bed to get more sleep to recover from fatigue. The regression coefficients of TSP and TST are negative, which mean that the decibel values will have negative impacts on TSP and TST. It means that for every unit increase in decibel value, TSP will decrease by 0.606 time and TST will decrease by 0.629 time.

Table 7

The results of binary logistic regression of the relationship between the noise decibel value and objective sleep quality parameters.

	Coefficient	Standard error	Wald	*p*-value	OR (95%CI)
SOL	0.434^{***}	0.094	21.288	< 0.001	1.544 (1.284 ~ 1.856)
TB	0.395^{***}	0.088	20.296	< 0.001	1.485 (1.250 ~ 1.764)
TSP	-0.500^{***}	0.14	12.842	< 0.001	0.606 (0.461 ~ 0.797)
TST	-0.463^{***}	0.112	17.194	< 0.001	0.629 (0.505 ~ 0.783)
WASO	0.284^{***}	0.073	15.233	< 0.001	1.329 (1.152 ~ 1.532)
SE	0.232^{***}	0.076	18.979	< 0.001	1.090 (1.000 ~ 1.180)

Note: *** $p < 0.001$ (two-tailed), statistically significant at the confidence level of 99%.

In order to more intuitively reflect the relationship between emotions influenced by noise on-board, Fig. 6 is created, showing that 46.8% of the participants were annoyed by the noise and 10.1% of the participants were extremely annoyed.

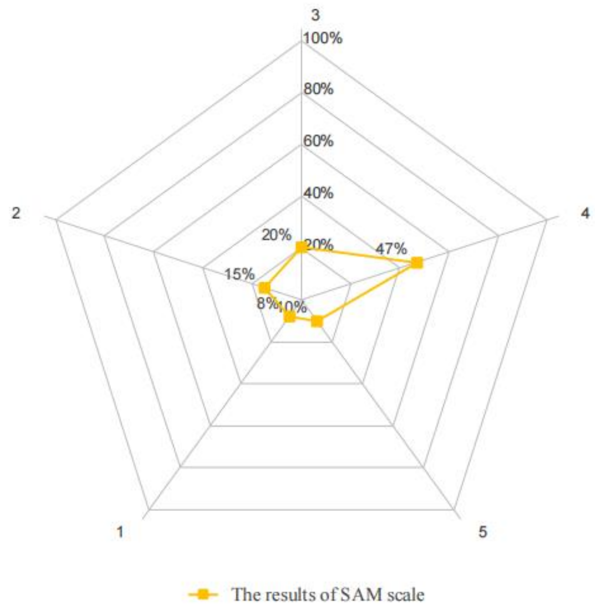

Fig. 6. The results of the SAM scale.

With subjective sleep parameter as dependent variables and noise acoustic indexes as independent variables, Eqs. (5)-(9) were used to establish an ordered logistic regression model, and the results are shown in Tables 8-10. Table 8 presents the result of parallel line test of the relationship between noise and emotion. Since the obtained *p*-value of parallel line test is 0.052, which is greater than 0.05, it indicates that the assumption of parallelism is accepted, and the ordered regression model process can be used to analyze the effect of noise decibel on emotion changes.

Table 8
The result of parallel line test of the relationship between noise and emotion.

Chi-Square	df	*p*-value
15.378	8	0.052

Table 9 presents the results of ordered logistic regression of the relationship between the noise decibel value and emotion changes. The model is valid since the *p*-value of model validity is less than 0.05.

Table 9
The likelihood ratio test of ordered logistic regression model.

Chi-square	df	*p*-value
49.842	1	< 0.000

In Table 10, the results of the ordered logistic regression analysis of the relationship between noise and emotion are presented. At the 99% confidence level, the effect of noise decibel level on emotion is statistically significant. The regression coefficients are all positive, indicating that as the decibel level of noise increases, the emotion of the seafarer gets worse.

Table 10

The ordered logistic regression analysis results of the relationship between noise and emotion.

	Coefficient	Standard error	Wald	p-value	OR(95%CI)
45 dB(A)~50 dB(A)	3.205^{***}	0.808	15.73	< 0.001	0.041 (0.008 ~ 0.198)
50.1 dB(A)~55 dB(A)	4.369^{***}	0.881	24.59	< 0.001	0.013 (0.002 ~ 0.071)
55.1 dB(A)~60 dB(A)	6.026^{***}	1.008	35.75	< 0.001	0.002 (0.000 ~ 0.017)
60.1 dB(A)~65 dB(A)	8.126^{***}	1.133	51.402	< 0.001	0.001 (0.000 ~ 0.003)
65.1 dB(A)~70 dB(A)	3.196^{***}	0.759	14.99	< 0.001	0.032 (0.006~0.184)

Note: *** p <0.001 (two-tailed), statistically significant at the confidence level of 99%.

5 Discussion and implications

5.1 Discussion

To our knowledge, this study is for the first time to use a quantitative method to investigate the relationship between engine noise exposure and objective sleep quality in an on-board ship environment. The results of sleep quality parameters in this study were compared and discussed with a wider epidemiological research program called DEBATS (Discussion on the health effects of aircraft noise) (Nassur et al., 2019). Table 2 presents that 33% of participants slept less than 6 h per day (TST< 6h), 35% of participants have difficulties in sleep maintenance (WASO ≥ 30 min) and 42% of participants have sleep onset insomnia problem (SOL ≥ 30min), while the ratios of DEBATS study are 18%, 45% and 35% respectively. The sleep efficiency were both 13% in the two studies (SE score < 90%). The present studies which take the objective sleep parameters into account found that exposure to aircraft noise caused a significant increase in SOL (Nassur et al., 2019; Smith et al., 2006). This study also found that since the noise decibel of the engine during the voyage period was higher than that during the berthing period, the SOL and WASO in the voyage period were longer than that berthing period. The participants in this study were the individuals who were most concerned about engine noise and sleep quality. The percentage of participants having poor sleep was 72% in our study, the DEBATS study was 32% (de Kluizenaar et al., 2009). In this study, 49% of participants feeling fatigue when getting up, compared to 18% in the DEBATS study. 64% of the participants in this study were annoyed by engine noise and the percentage in the DEBATS study was 24%. Oldenburg and Jensen (2019a) found that seafarers with a 4 on/8 off rotation have great difficulty in getting a TST of 7 hours. In this study, a TST of 6 hour 57 min on the main deck and a TST of 6 hour 48 min on the tween deck also confirmed their findings. In another study related stress and strain among pilots, Oldenburg et al. (2021) also found that 68.1% of the subjects had sleep disorders, including have difficulty in falling asleep, wake up at least once per night and lie awake several times a night. A study showed that the fatigue level of seafarers at the end of voyage was different from it in the middle of the sea-going (Azimi Yancheshmeh et al., 2020). Thus, a slight selection bias may probably interpret the results of our sleep quality study. In this study, the voyage was in coastal waters of China and the overall period of voyage was 28 days. The ship type of "*Yukun*"is a training ship, so its structure and sound insulation equipment are different from normal ships. This study also found that participants in this study were more concerned about sleep and noise problems than those in previous studies. This study suggests that the reason for this gap was that the participants had received professional education before they boarded the ship, and they had a certain understanding of the poor sleep quality caused by noise on-board. In the research of investigating the factors of seafarers' fatigue, Zhao *et al.* (2020) concluded that seafarers have strong negative emotions about the influence of on-board noise on sleep. This study however found that the participants had fewer negative emotions than the ones in the previous study because that they had learned how to regulate mood swings caused by sleep problems before they boarded the ship in psychology course.

Depending on the distances from the noise source, the noise level at the interior of the bedroom near the airport is compared with the noise level on the main deck, and the noise level at the exterior of the bedroom is compared with that on the tween deck. The results of this study were the same as DEBATS. Both studies showed that the closer to the noise source, the greater the noise level was. Due to the noise level on the main deck was higher than the tween deck, the objective sleep parameters on the main deck (except SE) were higher than the tween deck. The main reason for this result was that the main deck was closer to the engine and participants on the main deck were more anxious than those on the tween deck. It was also found that during the sleep period, the engine noise in the dormitories ranged from 57.00 dB(A) to 64.68 dB(A). However, the level recommended by the WHO to keep health inside bedrooms is no more than 30 dB(A) (WHO, 2018). Everyday participants were exposed to more than 30 dB(A) inside their dormitories. Participants on the main deck would like to sleep more to relieve their anxiety and irritability. The National Sleep Foundation issues new recommendations on sleep time duration (Hirshkowitz et al., 2015) and clearly indicates that young adults and adults need to sleep at least 7-9 hour per night. In maritime industry, similar sleep and rest recommendations have been made by the marine insurer Skuld who recommends that seafarers have to sleep 7-8 hours per 24 hours (Hystad and Eid, 2016). Objective sleep parameters as quantitative measurement standards play a crucial role in measuring sleep quality. According to the results, the average TST of the participants (6 h 57 min on the main deck and 6 h 48 min on the tween deck) which was below 7 h recommended by the National Sleep Foundation. Although not much lower than the recommended total sleep time, the participants of this study reported that they were always fatigue and their sleep quality was poor.

Contrary to the majority of previous noise studies in transportation showed that exposure to road noise or aircraft noise reduced TST (Pirrera et al., 2010), this study found TST and total sleep TB had increased when the engine noise decibel was higher. TST and TB of the participants on the main deck were also higher than the tween deck. WASO increased when the engine noise increase and SE became poorer. These could be the result of behavioral adaptation issues and psychological problems to sleep deprivation. Participants would like to spend more time in bed to recuperate and sleep more. They hope they could relieve their anxiety and irritability caused by the increased engine noise by this way. The noise level on the main deck is higher than the tween deck. The reason why TST and TB of the participants on the main deck is longer than the tween deck can also explained by the same result. The participants on the main deck were more anxiety by the noise than the tween deck, so they would like to sleep more than the participants on the tween deck. A laboratory aircraft study and the DEBATS study (the filed study) also showed an increase in TST and TB after being exposed to aircraft noise (Nassur et al., 2019). The study showed that the founding was an adaptation to sleep deprivation in the sleep duration when the participants were exposed to increased road noise (Pirrera et al., 2010). Subjects would, therefore, stay longer in bed in order to sleep more and recuperate. Nevertheless, uncontrolled or residual confounding could also explain this finding. A road traffic noise study also found a significant reduction in TST and TB, as measured by actigraphy, after a reduction in road traffic at night. They explained this reduction as the result of long wake times and by the fact that the individuals were probably much less tired after the reduction in nocturnal traffic (Frei et al., 2014).

Furthermore, the regression analyses revealed that engine noise was positively related to poorer sleep quality. According to the different vessel types and the different conditions of the seafarers of each flag country, the specific situation should be analyzed in detail, and different protective measures should be implemented according to the actual situation to ensure the sleep quality of the seafarers and relieve fatigue (Sunde et al., 2016).

5.2 Implications

In the study about how to train seafarers to deal with stress on-board, Jensen and Oldenburg (2020) suggest that to integrate stress management in the higher education of future superiors on-board. The previous noise study has found that sleep may improve further into tour due to habituation to noise (Burke et al., 2002). Character strengths can improve the habituation to noise and help seafarers to help the seafarers remain psychologically happy and comfortable. There is no doubt that working and living on-board is inherently stressful. So it is meaningful to cultivate character strength of seafarers who are not as susceptible to the negative impacts of stressful environments. Character strength shows the positive cognition, emotion and behavior of the individual. Individuals use positive cognitive schemas to interpret information from their internal and external environment. Cognitive theory emphasizes the role of cognition in anxiety experience (Martoni et al., 2012). Fredrickson's extension-construction theory suggests that cognitive factors play a role in cardiovascular responses, and that "*individuals with Psychological resilience can recover quickly from negative emotions"*. This positive cognitive model helps individuals construct physical, social, and psychological resources to cope with stressful situations. The ability of high-quality individuals to recover quickly when both heart rate and blood pressure rise during periods of stress is a sign of both character strength and cognitive resilience (Fan et al., 2021). The benefits of humor, hope, and gratitude have been found to help individuals reduce stress, anxiety, and sleep problems in both clinical and practical settings (Ghandeharioun et al., 2016). In short, this research perspective provides a new way of thinking for positive personality to effectively deal with sleep problems.

Current studies have demonstrated that, in various cultural contexts, character strengths are protective factors for individual psychological responses (eg, life satisfaction, depression, anxiety) and physiological responses (eg, physical health, disease symptoms) (Gander et al., 2020; Proctor et al., 2011). For the seafarers, in addition to the safety pressure of the ship during the voyage, the quality of sleep caused by the ship's noise makes the seafarer's thoughts and feelings in a high state of tension, it affects the emotional, work enthusiasm and physical and mental health of seamen all the time. If the sleep pressure exceeds the ability to bear without taking any measures, it is easy to cause the seafarer's own physical and mental diseases, the light will develop autonomic nervous system syndrome, a serious threat to driving safety. Therefore, seafarers not only need to have a strong physique, professional skills and knowledge, but also have a good psychological quality, a strong ability to adapt to the environment. Therefore, it has become an urgent task to understand the training form of seafarers, improve the level of navigation education and training, and rebuild the training system of seafarers. In this situation, it is very urgent and necessary to intervene the psychological crisis of seafarer. Using strength-based interventions (SBIs) to evaluate and intervene seafarers' character strength can improve their ability of coping with crisis, enable them to show physical and psychological adaptability in stressful situations. Although SBIs has universal applicability, the specific performance of protection and promotion function will be different according to different social context. Therefore, such intervention training must also be designed in the context of a seafaring culture and the professional characteristics of seafarers. Maritime psychological education should not only aim to cultivate and develop the general psychological qualities of individuals, but also focus on developing a higher level of sound personality that can meet the needs of maritime occupation, intervention training should integrate new psychological resources at a higher level or level.

6. Conclusion

This study investigated the relationship between the objective sleep quality of seafarers on-board and exposure to engine noise assessed by quantitative analysis at the dormitories. The results of the study confirmed that being exposed to engine noise negatively affected the objective sleep parameters, with a reduction in SE and an increase in duration of SOL and WASO. Being exposed to higher engine noise level also increases TST and TB which could be a serious matter of behavioral adaption to sleep deprivation.

This study had some limitations. Firstly, the experiment was conducted on the training ship and lasted only 28 days. The navigating period of this study was shorter than merchant ship and it is well known that that over time, the effects of stress develop in an increasing manner and worse sleep quality. Secondly, under the supervise of the teachers on-board, with the strengths of the young and good educated participants, the result of this study will be a little bit better than the actual results. Finally, the extent to noise affecting sleep have not been taken into account in detail.

In order to improve the research on the relationship between noise and sleep quality, under the premise of not affecting the daily work of the seafarers and ensuring the safety of the ship's navigation, the research will be carried out using the seafarers of different types of ships such as container and bulk carriers. Furthermore, vibration, weather and the extent to noise affecting sleep quality will be the focus of future research and are worth addressing in the following research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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