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(Research Article)

Assessing the effects of arctic darkness and extreme cold on seafarers' fatigue and performance to develop resilience techniques

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Abstract

This research analyses the mental and physical effects of prolonged Arctic darkness and severe cold on the fatigue, performance, and resilience of seafarers, considering the increasing maritime activities in polar regions.

The researchers gathered primary data using an extensive questionnaire with 23 questions, shared through the professional networks of 51 individuals, and conducted semi-structured interviews with four seafarers who had experience in Arctic conditions. Quantitative responses were examined with descriptive and inferential statistics, particularly Spearman's correlation tests. Thematic analysis, based on Braun and Clarke's six-phase framework, was utilised on qualitative interview data to recognise patterns and contextual insights.

Primary results show a statistically significant negative correlation between sleep quality and levels of fatigue, as well as a strong positive correlation between concentration in extended darkness and psychomotor decline in severe cold. About 40% of participants reported that Fatigue Risk Management Systems (FRMS) were not available onboard, and the presence of current FRMS did not significantly correlate with decreased fatigue.

The study's results highlight the immediate need for regulatory revisions to ensure the safety and effectiveness of maritime activities in Arctic environments. The research suggests that updated FRMS tailored for the Arctic, improved PPE design, ergonomic modifications, compulsory fatigue training, and the integration of resilience strategies, such as mindfulness, light therapy, and adaptable work-rest patterns, are necessary. Moreover, revisions to the Polar Code and Standards of Training, Certification and Watchkeeping for Seafarers (STCW) convention are proposed to tackle the increasing Arctic challenges and enhance the safety and performance resilience of seafarers.

Keywords: Arctic navigation; Fatigue; Seafarers; Cold environment; Resilience

1. Introduction

1.1. Background and Significance of the Study

Maritime operations have profoundly shaped the development of civilisation and international relations, both explicitly and implicitly, for centuries (Paine, 2015). As the many climates across the world change, the brave men and women who sail the seas are at the mercy of these challenging environments, creating unparalleled pressure on the 'human element' at sea.

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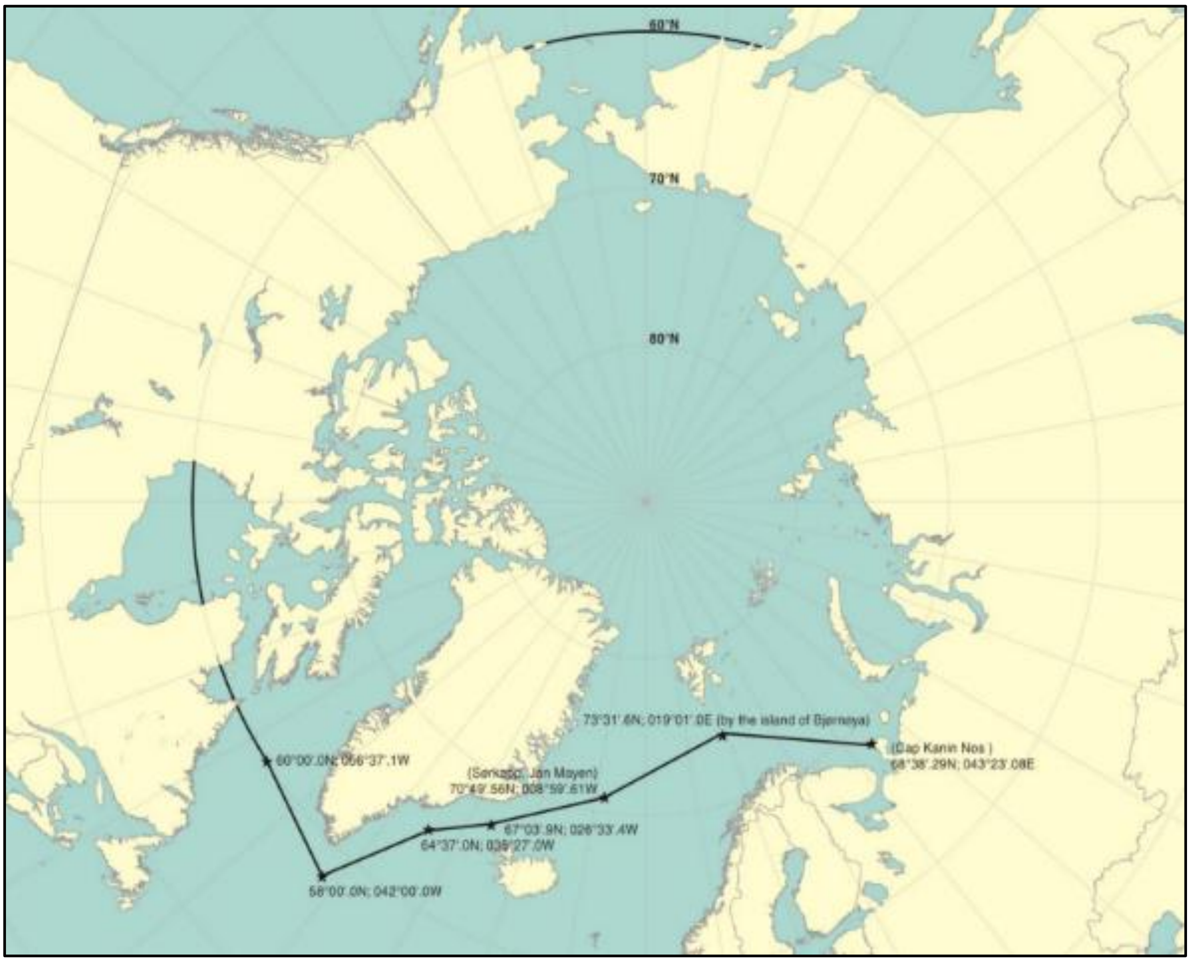


Source: (International Maritime Organisation, 2015)

Figure 1 Maximum Extent of Arctic Waters

In the twenty-first century, rising sea levels due to climate change and global warming remain at the forefront of many news reports. It is alarming the rate at which sea ice is reducing, with one report stating that since 1979, the winter sea-ice maximum extent retreated by 10%, and the summer minimum extent by 38% (Thompson, 2025).

Yet, one silent benefit of the rapid melting of ice due to climate change is that it has opened a unique opportunity for previously inaccessible routes, such as the Northern Sea Route (NSR), to become accessible for vessels to navigate for an extended period of the year (Lynch, Norchi and Li, 2022).

Generating significant economic opportunities, these routes also offer reduced voyage times of up to 30-50% (Faber, Huigen and Nelissen, 2017), a reduction in greenhouse gas emissions of around 24% (Kimball, 2022), and further savings in time and money.

The term 'Polar Silk Road' was coined as a testament to the importance of the trade route (State council information office of the people's republic of China, 2018).

Source: (Fleck, 2023)

Figure 2 The Various Routes of the 'Polar Silk Road'

However, whilst ships have required additional structural arrangements, such as those mandated in the International Code for Ships Operating in Polar Waters (Polar Code) and MGN 637, (IMO, 2016; MCA, 2022), and navigational procedures have become more demanding, the crewing aspect and compensation for human factors have not been adjusted fittingly to the conditions to which the seafarers are exposed in these regions. Seafarers are subjected to extreme stressors induced by the environment, such as sub-zero temperatures, prolonged periods of daylight or darkness, the unique isolation of the Arctic, and fatigue from vigilant ice navigation. These factors may influence potential changes in human performance, well-being and fatigue, the latter of which is consistently being studied and increasingly understood as a contributing factor in many maritime accidents. The missing frontier of legislation, operations and performance measures for seafarers in this situation underscores a dire gap in knowledge regarding the genuine experiences of seafarers in these stressful environments.

2. Literature Review

2.1. Overview and Purpose

The increasing complexity of shipping volume in the Arctic, combined with harsh environmental conditions and remoteness, will harm both shipping and the fragile Arctic environment. The likelihood of a ship accident will increase and is likely to cause severe pollution (Jiacai, Mengjie and Feng, 2025).

Arctic shipping frequently encounters grounding accidents due to the region's unique geographical environment, which features factors such as ice, unpredictable weather, and high latitudes (YU *et al*., 2024).

2.2. The Arctic Maritime Environment: An Overview

2.2.1. Defining the Arctic Operating Environment

The Arctic is defined broadly as the area enclosed by the circle surrounding latitude 66° 33' N heading north toward the North Pole. the region is characterised by a uniquely challenging environment of ice, snow and low temperatures, requiring stringent navigation and vigilance, exceptional planning, and dynamic risk assessment within the relative isolation and poor infrastructure in the area (Arctic council, 2025).

The grounding of the Ocean Explorer in 2023 underscores the importance of an experienced crew, thorough navigational risk assessments, and informed decision-making (The guardian, 2023).

In a less fortunate incident, the sinking of the MV Explorer in 2007, with no loss of life, raised concerns about the structural conditions and the need for ice-strengthened vessels, as well as the eleven deficiencies found on the ship during prior inspections (Orr and Batty, 2007).

Therefore, operations in polar regions require further recommendations and safety measures to ensure compliance and prevent recurrence.

2.2.2. Climatic Factors: Darkness and Extreme Cold

Arctic Darkness (Polar Night)

Defined by Mulvaney (2024) as the period of night lasting more than 24 hours, Polar Night is a phenomenon occurring at or near the Earth's Polar regions (Mulvaney, 2024).

Those who permanently live in Arctic conditions, such as those in 'Extreme North' settlements, may experience periods where the sun does not rise for up to three months (Leibowitz, 2015).

A study conducted in Tromsø (Norway) by Johnsen, Wynn and Bratlid (2012) investigated the relationship between sleep problems and mental distress during winter. It reported that sleep quality was affected by periods of extended darkness, which were associated with high levels of issues in sleeping patterns and quality.

Extreme Cold

As the body temperature continues to decrease, drowsiness, shivering, poor cognitive ability, and loss of consciousness may occur, and death is likely (Mayo clinic, 2020).

Sub-zero temperatures can indirectly lead to significant safety hazards. One such hazard is the considerable reduction in grip strength. This reduction can be particularly perilous for those who need to maintain a strong grip on equipment, especially during cargo or mooring operations on the deck (Dizmen, MAN and Chan, 2015).

Equipment exposed to low temperatures must be designed to operate safely in these conditions. Challenges for materials in low temperatures include durability, strength, toughness, and brittleness, which may result in material changes in properties as the temperature changes (The crosby group, 2019).

2.3. The Growing Significance of Arctic Shipping

The increasingly navigable Arctic waters, resulting from the melting of sea ice primarily driven by climate change, have sparked economic interest and strategic rivalry in the region (Uryupova, 2024).

This route offers reduced fuel consumption and transit times, providing significant economic benefits to shipowners and operators (Guo, Guo and LV, 2022).

The Arctic, an area rich in resources, plays a significant role in the global supply of fuels, providing the world with 10% of its total oil and 25% of its natural gas. In untapped areas, it is estimated that the Arctic holds 22% of the Earth's oil and gas reserves (WWF, 2025).

In 2024, 1781 unique vessels entered the waters, an increase of almost 500 ships compared to 2013. With this increase in shipping, a growing number of seafarers are exposed on a regular basis to the hazardous conditions of the unique

Arctic environment, such as extreme cold, limited daylight, and ice, as well as the challenges of operations in such a remote location (Muller *et al*., 2023).

2.4. Effects of Arctic Conditions on Seafarers: Fatigue and Performance

2.4.1. Understanding Seafarer Fatigue

Understanding that fatigue is a multi-faceted symptom, this dissertation will use the following definition of 'extreme and persistent tiredness, weakness or exhaustion that could be mental, physical or both' (Hernandez Ronquillo *et al.*, 2011; MCA, 2025). The Maritime and Coastguard Agency (MCA) provide detailed guidance on the causes and risks of fatigue in the Code of Safe Working Practices for Merchant Seafarers, commonly referred to as Code of Safe Working Practices for Merchant Seafarers (COSWP).

2.4.2. Impact of Arctic Darkness on Seafarers

Physiological Effects

Seafarers are subjected to extended periods of darkness in the Arctic, much like permanent residents. One of the key physiological effects of this is the disruption of the circadian rhythm and light-dark cycle due to the lack of natural light exposure during winter. Furthermore, Matre *et al*., (2023) also studied 120 process operators at an industrial plant located at 70 degrees North in Norway. They found that seasonal variation not only impacted sleepiness levels and fatigue, but that natural light variation is strongly related to alertness, regardless of prior symptoms (Matre *et al.*, 2023).

According to a study done by the National Heart, Lung, and Blood Institute (2022), light signals received through optical exposure inform the brain of the body's natural schedule of days and nights, commonly referred to as the 'light-dark cycle', a simplified representation of the circadian rhythm. Melatonin, a hormone produced in the brain to promote sleep, is synthesised during the evening in response to this cycle. In a maritime context, however, the production of melatonin can be disrupted by exposure to artificial lighting, particularly from electronic components such as RADARs and Electronic Chart Display and Information System (ECDIS) on bridge and engine control room monitors. Excessive exposure to artificial light can interfere with the body's natural sleep signals, disrupting the circadian rhythm. Such disturbances in the light-dark cycle may result in insomnia, which is marked by difficulty falling asleep, staying asleep, and waking without feeling rested (National heart, lung, and blood institute, 2022).

Sivertsen *et al*., (2009) determined that insomnia was an independent risk factor for long-term sick leave. Given that "Arctic-qualified but not always experienced crews remain in low numbers", reducing insomnia is essential to ensure vessels are safely manned with experienced personnel (Browne *et al.*, 2021).

Seafarers are subjected to desynchronized internal 'body clocks', leading to further fatigue if maladaptation to the ship's clock occurs and may compromise overall operational safety (Karim *et al.*, 2024).

Dachev and Lazarov (2019) found that seafarers' performance in physical power and labour efficiency on duty is reduced when fatigued, highlighting the dangers to safe operations.

Additionally, limited exposure to natural light in Arctic conditions can reduce vitamin D intake, potentially leading to vitamin D deficiencies. According to the National health Service (NHS, 2020), insufficient levels of vitamin D may result in conditions such as rickets and osteomalacia, which are painful disorders that are further exacerbated by cold environments.

Furthermore, vitamin D deficiency has been linked to changes in mood, including increased feelings of anxiety and depression (Akpınar and Karadağ 2022), which may further impair seafarer performance and wellbeing.

Psychological Effects

The unchanging, monotonous landscape and the lack of daylight can lead to a reduction in mental stimulation. As McLeod (2025) points out in Maslow's Hierarchy of Needs, a person needs a mental challenge or a goal to work toward to achieve 'self-actualisation'.

Deprivation of the senses and isolation can lead to poorer mental wellbeing, contributing to higher levels of stress and the likelihood of developing anxiety or depression (Mofatteh, 2020).

An inability to have a firm visual reference in darkness may impact the seafarer's ability to safely keep watch. For seafarers, the disrupted light-dark cycle, which causes fatigue, has been found to lead to reductions in alertness, vigilance, and slower reaction times (Mcewen and Karatsoreos, 2015).

As Kunasegaran *et al*., (2023) state, fatigue may lead to "irritability, decreased patience and poor reasoning skills," which in turn can hinder effective teamwork. This deterioration in interpersonal functioning increases the risk of communication breakdowns, which are particularly critical in the maritime context. A lack of positive communication may lead to a breakdown of the team onboard, undermining the collaborative effort essential for safe vessel operations (Ermal and Kristofor, 2010).

2.5. Impact of Extreme Cold on Seafarers

2.5.1. Physiological Effects

Acute physiological responses to cold environments include vasoconstriction, whereby blood vessels narrow to reduce heat loss, and shivering, which is caused by involuntary muscular contractions to generate heat (Castellani and Young, 2016).

2.5.2. Psychological Effects

The experience of being outdoors, with wind chill and sub-zero conditions, directly detrimentally impacts the motivation and willingness of seafarers to perform outdoor tasks, such as chipping and painting, associated cargo duties, and mooring (Chan and Ryan, 2009].

Protective clothing helps the seafarer to feel a greater sense of security, as well as being protected from the elements, the employee is also more likely to be productive (SBN, 2025).

Yet, bulky and obstructive PPE may cause physical irritation to the skin, as well as increased discomfort and irritability on a psychological level, leading to lowered morale and adding to the challenge of the task at hand (Lu and Jiang, 2023).

2.5.3. Combined and Cumulative Effects

Solberg (2020) documents the strong correlation between 'loss of cognitive abilities and reduction of body core temperature', which is pertinent to the safe execution of safety-critical tasks.

The Maritime and Coastguard Agency (MCA) recognise the link between fatigue and fitness for duty, developing MGN 505. In terms of maritime safety, this Guidance Note defines a fatigue management plan, stating that fatigue can be prevented or considerably reduced when addressed properly (MCA, 2014).

Research like that of Pickup *et al*., (2025) emphasises the significance of adopting Fatigue Risk Management Plans (FRMP), which encompass elements like fatigue awareness training and 'just culture' reporting systems. FRMP provides a systematic and organised method for recognising and addressing risks associated with fatigue. An effective FRMP typically consists of three main components:

- Predictive (identifying fatigue-related hazards),
- Proactive (implementing preventive measures), and
- Reactive (responding efficiently to fatigue incidents as they occur)

2.6. Existing Approaches to Mitigate Fatigue and Enhance Performance at Sea

Two key documents that form the foundation of legislation surrounding fatigue, providing specific standards and requirements to safeguard seafarer wellbeing and operational safety are shown in Table 1.

Table 1 International Work-Rest Arrangements

International Document	Purpose	Regulation
International Maritime Organisation: The International Convention on STCW 1978, as amended (2010 Manila Amendments)	To provide guidance and legislation for international compliance with seafarer training, certification and fitness for duty. By providing a unified code for international standards, the document is a powerful publication for maritime professionalism and safety.	Section A, Regulation VIII/1 and Section A-VIII/1 minimum rest hour requirements: a minimum of 10 hours of rest in any 24-hour period, which can be divided into no more than two periods (one of which must be at least six hours), and 77 hours in any seven-day period.
International Labour Organisation: Maritime Labour Convention 2006	The Maritime Labour Convention (MLC) (2006) lays out the international maximum working hours, but it must be ratified by each member state through flag state legislation.	Under Regulation 2.3 and Standard A2.3: Maximum Hours of Work: 14 hours in any 24-hour period. 72 hours in any seven-day period. Minimum Hours of Rest: 10 hours in any 24-hour period. 77 hours in any seven-day period.

Source: IMO, 2017

Ships must keep a log of every seafarer's work and rest periods to ensure adherence, which is to be signed by both the seafarer and the master (ILO, 2006).

2.6.1. Management of Operations

Marine Guidance Note 505 (MGN 505) outlines the various risks associated with fatigue, working hours likely to induce fatigue, a checklist to recognise fatigue, and suggests a framework for FRMPs, tailored to the vessel and circumstances. The IMO's guidance on fatigue, in MSC.1/Circ.1598, should be incorporated into the FRMP (IMO, 2019).

However, while a holistic set of guidelines recognising that fatigue exceeds work-rest allowances is in place, the Circular is not mandatory. It does not address the commercial pressure that affects seafarers, which may be a contributing factor to forged work-rest documentation (Baumler, Bhatia and Kitada, 2021).

2.6.2. PPE effectiveness and design

It is likely due to the body's response to these extremes, including elevations in blood pressure, blood viscosity, cholesterol, platelet and red blood cell counts, dehydration, as well as rhinorrhoea and bronchoconstriction (Fischer *et al*., 2024).

PPE design also needs 'rethinking' from a safety aspect; the condensation from breath leaves the balaclava wet, crystallising the moisture and reversing the intended effect of the protective item. the use of a balaclava or other facial coverings, may lead to miscommunication, which is essential for safe operations (Storr-Mathis, 2021).

2.7. Polar Code

The Polar Code was established under Chapter XIV of the Safety of Life At Sea (SOLAS) Convention, making it mandatory to regulate ships operating in polar waters, with national implementation through MGN 637. While it mandates ice navigation certification and the inclusion of a Polar Waters Operations Manual, the Code falls short in addressing the human element, leaving notable gaps in mitigation tools and support for seafarers in these extreme environments (MCA, 2022).

3. Methodology

3.1. Research Methods

A mixed-methods strategy was employed, facilitating the simultaneous collection and analysis of qualitative and quantitative data to provide a comprehensive understanding of the effects of Arctic stressors and to inform the development of effective resilience strategies. Data collection specifically focused on seafarers who had at least one week of experience in Arctic waters.

3.2. Data Collection

3.2.1. Questionnaire

Quantitative data collection was primarily based on a questionnaire of twenty-three questions that was distributed through social media.

3.2.2. Interviews

The authors collected Qualitative data through interviews with four professional seafarers, selected to provide a range of perspectives based on their rank, experience, and operational environments. The interviewees were as follows:

- Interviewee 1: Engine Cadet (LNG), with 2 years of sea service.
- Interviewee 2: Third Officer (LNG), with 6 years of sea service.
- Interviewee 3: Master Mariner with 16 years of sea service, including experience as an Ice Pilot and as an instructor on Polar Code training courses.
- Interviewee 4: Lieutenant Commander in the Royal Navy, with 12 years of sea service as an Air Warfare and Principal Warfare Officer.

The interview guide included a mix of open- and closed-ended questions, covering the following key areas:

- Self-reported fatigue experienced while onboard.
- Perceived impact of cold environments on personal performance.
- Strategies and techniques used to mitigate the effects of cold and operational stress.
- Awareness and application of company-specific procedures and guidance.

3.3. Ethics

Ethics approval for this research was granted in April 2025 by the Southampton Solent University Ethics Board.

3.4. Data Analysis

The results involved triangulating qualitative and quantitative aspects identified in maritime safety, personal accounts, academic and theoretical frameworks, self-reported seafarer fatigue, environmental conditions and analysing these to form evidence-based, practical, accessible techniques in the mixed-methods approach.

3.5. Constraints

A range of constraints as discussed in the proposal are detailed below:

- Limited seafarers with Arctic experience
- Limited research timeframe
- Participant availability
- Lack of physiological data collection
- Privacy concerns

4. Discussion

4.1. Survey Respondent Demographic

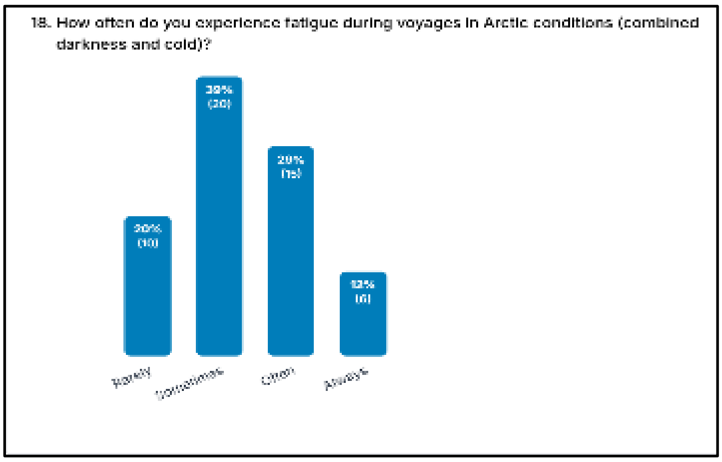
The survey had 51 participants, including four inspiring individuals who were former seafarers and are now in governmental or shore-based roles. The rank dispersion ranged from Able Seaman (AB) to Master, Motorman to Chief Cook, and Cadet to Deputy Harbour Master.

Collectively, Junior Deck Officers of the Watch formed 31.3% of the overall participants, whilst Chief Mates and Masters corresponded to 19.6% of the participants. Vessel types spanned seven categories, with most respondents having experience on tankships (45%), followed by passenger vessels, superyachts, or expeditionary vessels, which accounted for 27.4% of participants.

Moreover, a notable 9.1% of participants reported sailing in the challenging Arctic waters on these ship types. The average experience of each participant sailing in the Arctic region was 6-12 months, with the median being 1-2 years. The average voyage length was reported as 2-4 weeks (34% of respondents).

4.2. Overall Levels of Fatigue and Insomnia

4.2.1. Fatigue Levels

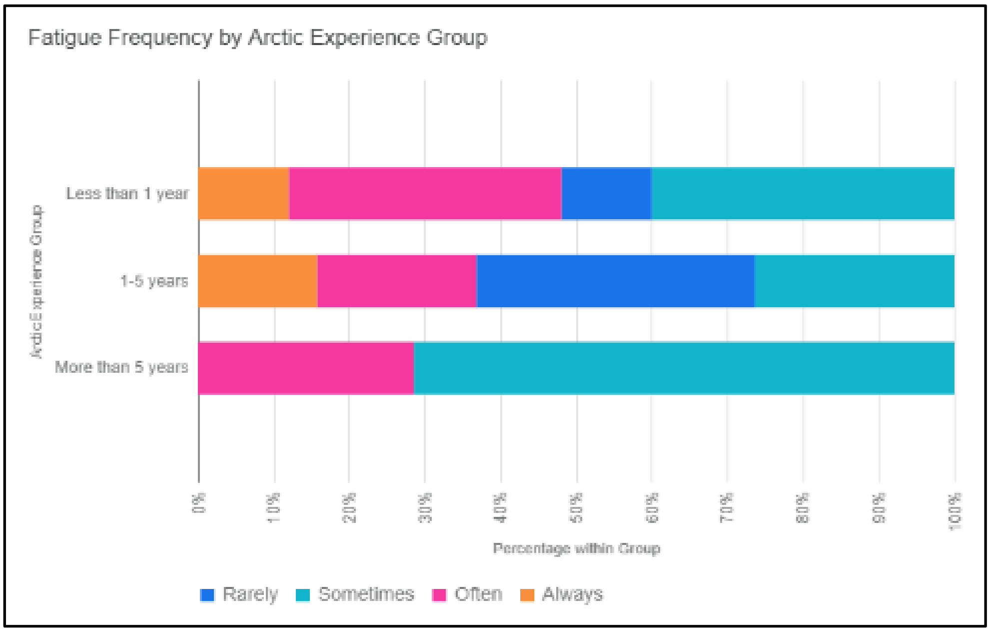


Source: Author's compilation

Figure 3 Levels of Fatigue Experienced in Arctic Voyages

Significantly, 80.4% of participants reported experiencing fatigue at a frequency of 'Sometimes', 'Often' or 'Always when underway in Arctic waters, and 12% of participants reported 'Always' feeling fatigued (Figure 3).

4.2.2. Fatigue Frequency

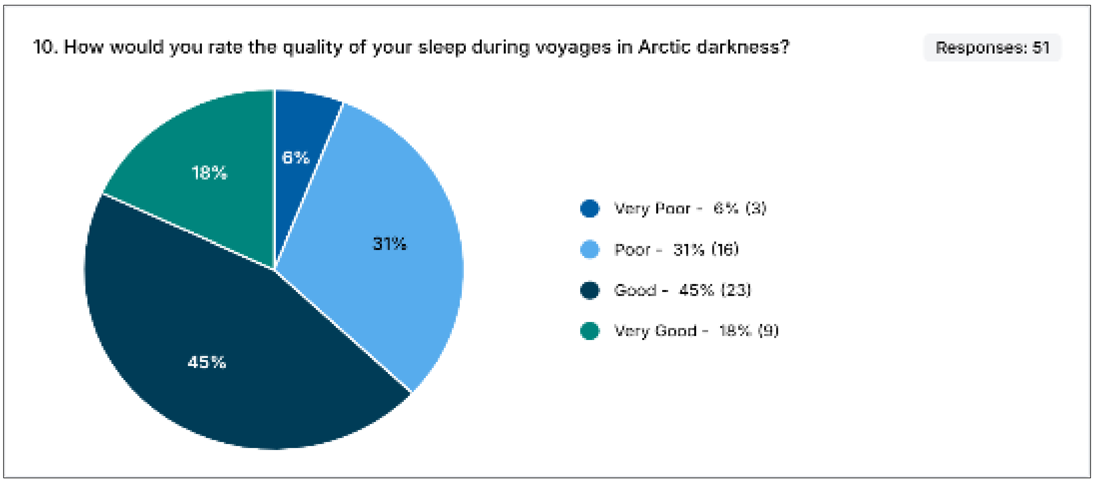


Source: Author's compilation

Figure 4 Fatigue Frequency by Cumulative Experience in the Arctic

Figure 4 illustrates that those with less than one year of experience in the Arctic were much more likely to report being fatigued 'Often' or 'Always', in comparison to those with over 5 years of experience, who found they were fatigued 'Sometimes'.

4.2.3. Insomnia and Sleep Disturbances



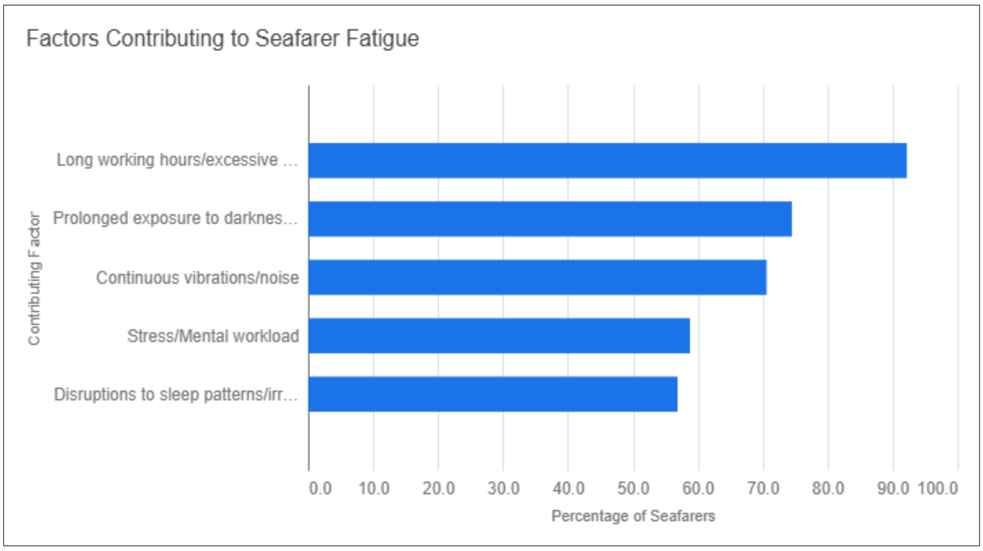
Source: Author's compilation

Figure 5 Reported Sleep Quality During Arctic Darkness

Regarding sleep quality, as Figure 5 shows, a majority, 62.7% of participants, reported 'Good' or 'Very Good' during periods of Arctic darkness, while 37.3% of participants felt their sleep quality was 'Poor' or 'Very Poor'.

4.3. Factors Contributing to Fatigue and Sleep Disturbances

4.3.1. Factors Contributing to Seafarer Fatigue

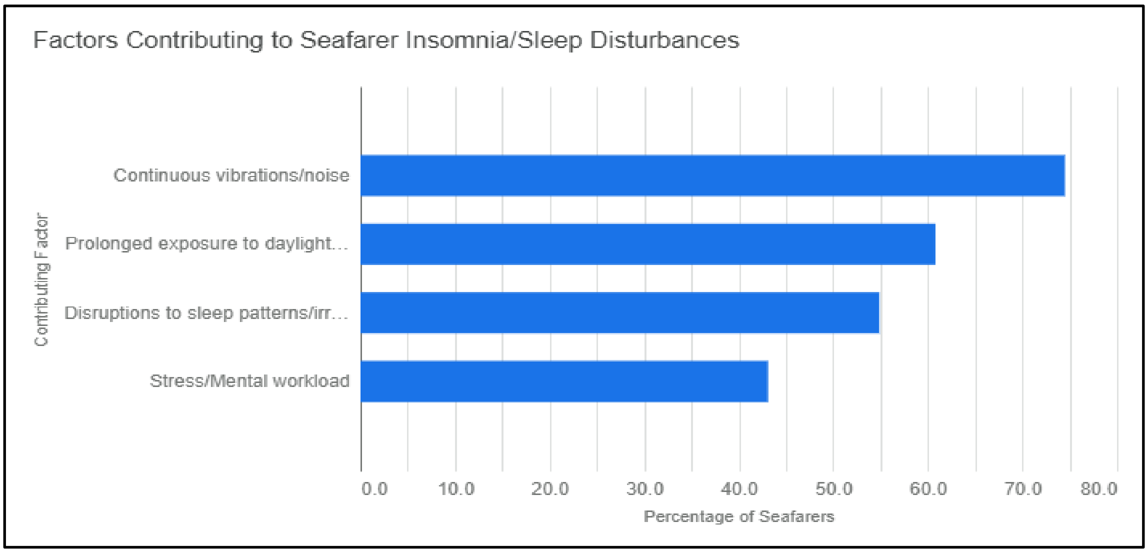


Source: Author's compilation

Figure 6 Reported Factors Contributing to Seafarer Fatigue

According to Figure 6, ninety two percent of participants believe that long working hours and excessive duty periods play a more negative role in fatigue. Prolonged exposure to darkness or a lack of light was reported by 74.5% of respondents, as well as continuous vibrations or noise (70.6%), stress or mental workload (58.8%), and disruptions to sleep patterns and irregular working schedules in 56.9% of responses.

4.3.2. Factors Contributing to Sleep Disturbances/ Insomnia

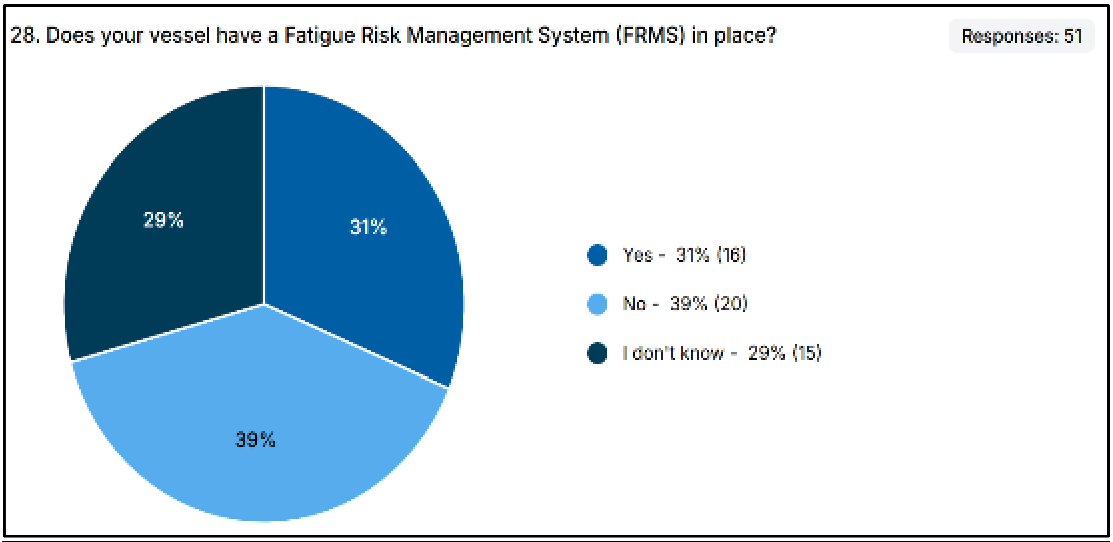


Source: Author's compilation

Figure 7 Factors Contributing to Sleep Disturbances/ Insomnia

Participants reported various factors, with 74.5% citing noise or vibrations as a cause, 60.8% citing light pollution or exposure to daylight, and 54.9% reporting disruptions to sleep patterns or irregular work arrangements as a cause. Stress and mental workload were reported by 43.1% of participants as causing sleep issues.

4.4. Fatigue Management/ Fatigue Risk Management Systems

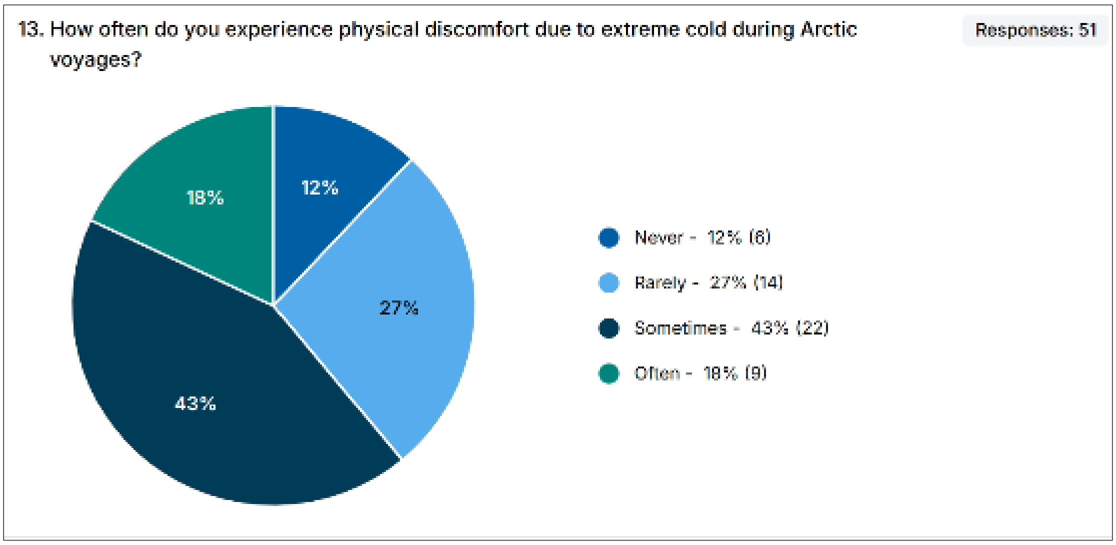


Source: Author's compilation

Figure 8 Reported Presence of FRMS

When rating the effectiveness of the FRMS, Figure 8 shows that 34% of respondents reported it as 'Very Effective' or 'Moderately Effective', while 29% were uncertain about the presence of an FRMS. Nearly 40% reported the lack of an FRMS onboard.

4.5. Physiological and Psychomotor Effects



Source: Author's compilation

Figure 9 Frequency of Reported Physical Discomfort in Extreme Cold

Physical discomfort was experienced by 18% of participants, by just under half (43%) of participants at times, and by 27% of participants rarely. Only 6 of 51 participants reported feeling 'never' uncomfortable because of the cold.

4.5.1. Psychomotor Effects

Concentration and Decision-Making Ability

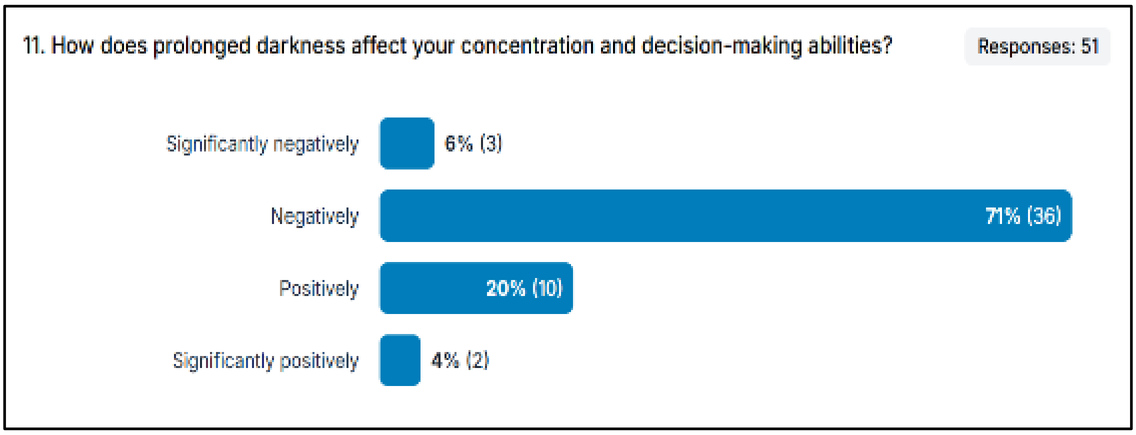


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Figure 10 Effects of Prolonged Darkness on Concentration and Decision-Making Ability

Most participants reported that prolonged darkness negatively affected their concentration and decision-making capability, accounting for 71% of the responses. A minority of respondents reported extreme values at either end of the selection, indicating either 'significantly negatively' or 'significantly positively', accounting for 10% of the overall responses (Figure 10).

Manual Dexterity in Extreme Cold

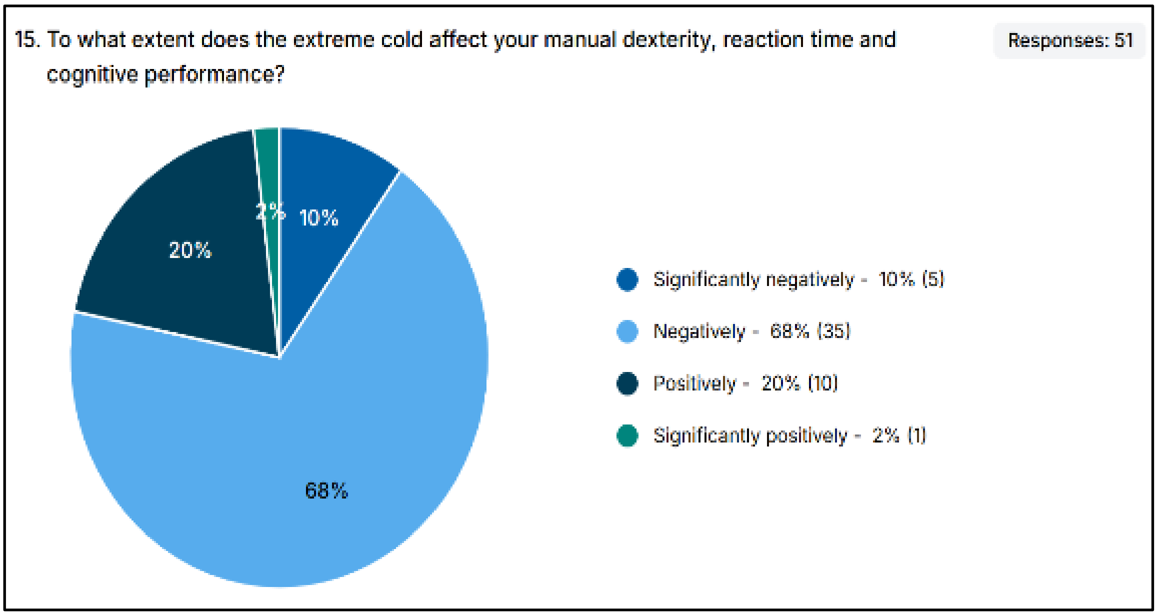

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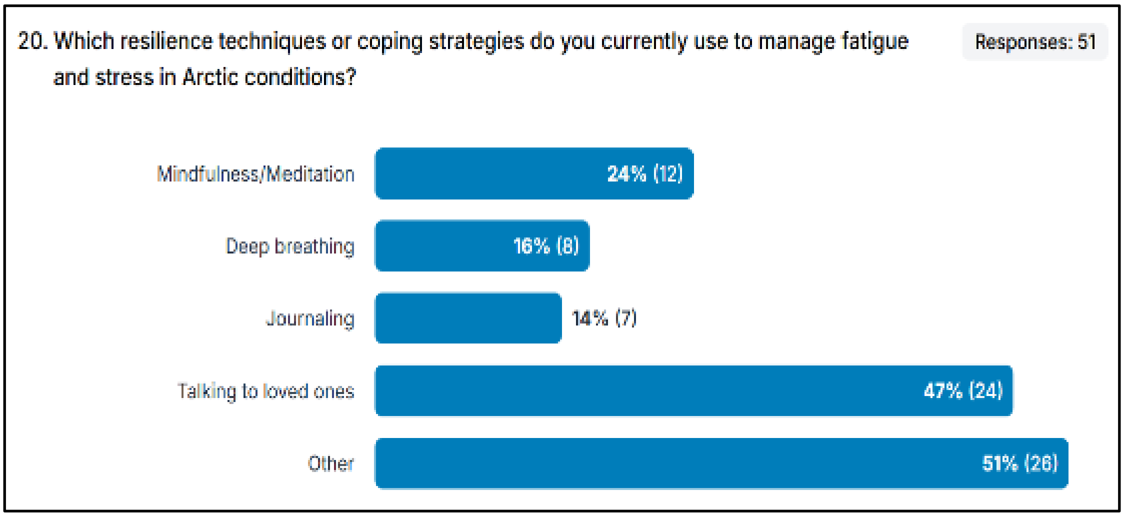
Figure 11 Extreme Cold Impact on Manual Dexterity, Reaction Time and Cognitive Performance

As shown in Figure 11, Like the immediately previous findings, manual dexterity in extreme cold was found to be ‘negatively’ affected by 68% of participants, and ‘significantly negatively’ by a further 10%, forming 80% of the participants with adverse psychomotor reactions among the overall respondents.

4.6. Resilience Techniques/ Resilience Techniques Used

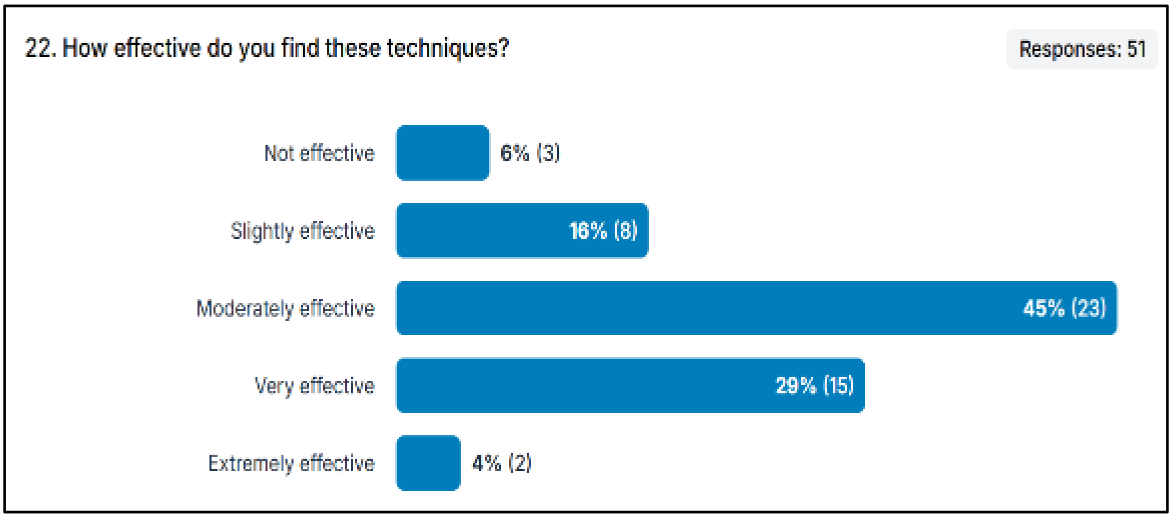


Source: Author’s compilation

Figure 12 Resilience Techniques Employed by Seafarers in Arctic Conditions

Half of the 51 participants use ‘talking to loved ones’ as a technique for maintaining resilience. One quarter of respondents reported using ‘Mindfulness’ or ‘meditation’ as a strategy, and ‘Deep Breathing’ formed almost a fifth of the overall responses, with eight reports (Figure 12).

4.6.1. Effectiveness of Resilience Techniques in Use



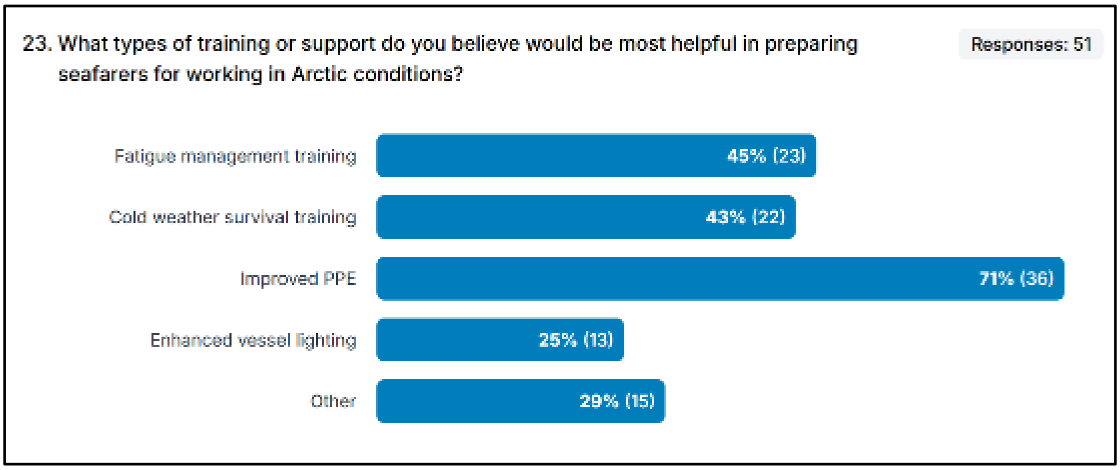
Source: Author's compilation

Figure 13 Self-Reported Effectiveness of Seafarers' Resilience Techniques

Figure 13 illustrates the range of personal resilience techniques employed by seafarers, revealing that while these strategies are widely used, their perceived effectiveness varies. Notably, 45% of respondents rated their chosen techniques as only 'moderately effective', and 6% found them 'not effective' at all. However, it's reassuring to note that 78% of participants reported experiencing at least some positive impact, indicating that while there is room for improvement, the current methods do offer some relief. It underscores the need for developing more effective, evidence-based resilience tools tailored to the unique challenges of Arctic operations.

4.7. Training and Support

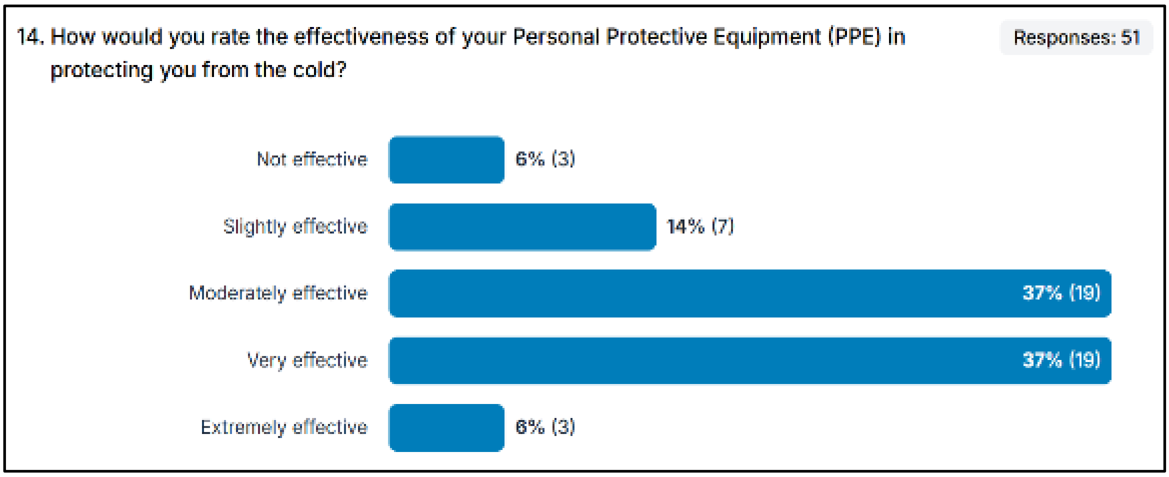
4.7.1. Pre-Voyage Training Recommendations



Source: Author's compilation

Figure 14 Reported Pre-Voyage Training and Support Measures Supporting Arctic Working

4.7.2. Support

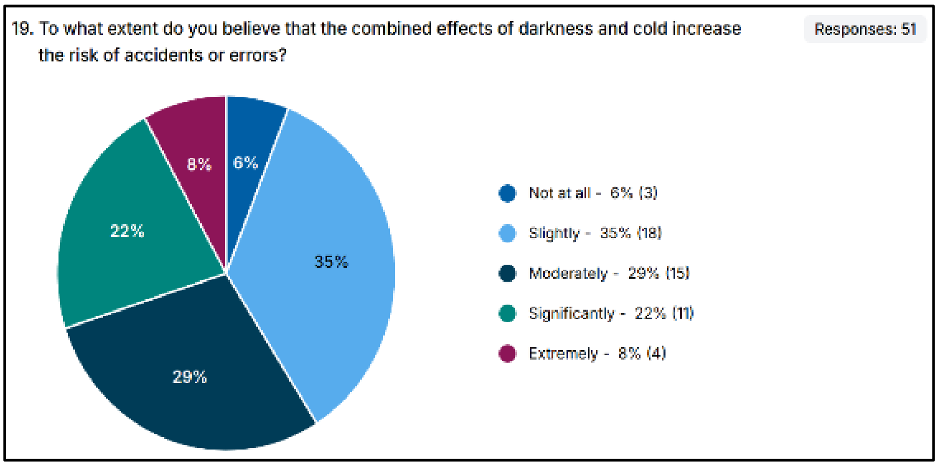


Source: Author's compilation

Figure 15 Rated Effectiveness of PPE

As depicted in Figure 15, PPE was found to be effective to some extent by 94% of respondents, with 80.4% rating it as 'moderately' to 'extremely effective'. When juxtaposed with the self-reported effectiveness of personal resilience techniques in Figure 13, where only 45% found their methods 'moderately effective' and 6% deemed them ineffective, it becomes evident that PPE consistently plays a reliable role in mitigating the challenges of Arctic conditions. This reliability should reassure us about the effectiveness of PPE and the need to supplement it with more structured, evidence-based psychological resilience strategies to support overall seafarer wellbeing.

4.8. Safety (Extreme Cold and Darkness' Impact on Risk)

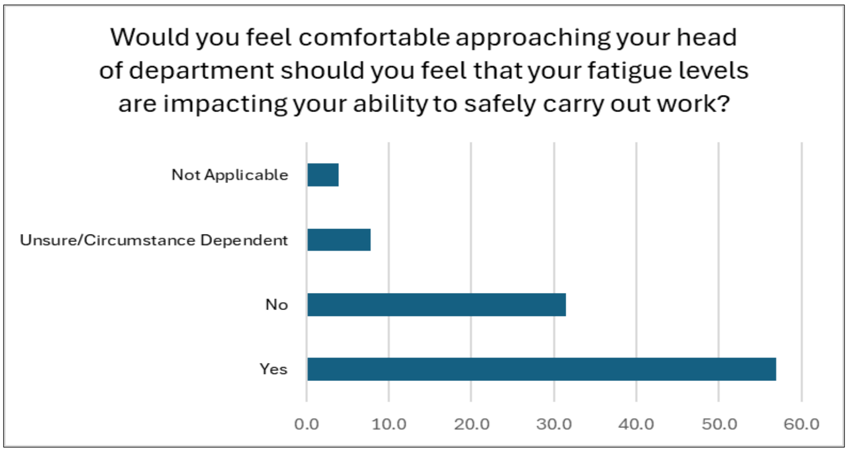


Source: Author's compilation

Figure 16 Perceived Risk of Darkness and Cold in Maritime Accidents and Errors

The survey findings underscore the importance of understanding and mitigating maritime risks. A significant 94% of participants identified darkness and cold as risk factors in maritime accidents, with 8% considering them 'extremely' likely to increase the likelihood of an accident or error. The median response fell within the 'moderate' bracket, reinforcing the strong belief in the potential correlation between these Arctic stressors and accident prevention (Figure 16). 15.7% of respondents recommended amending existing work and rest hour regulations, emphasising that the physical demands of Arctic conditions impose an "additional toll" on seafarers beyond standard operational fatigue. It highlights the inadequacy of current regulatory frameworks in addressing environmental extremes. Additionally, 13.7% of participants identified the need for improved nutrition and vitamin supplementation, particularly Vitamin D, as essential support measures, reinforcing the physiological challenges posed by cold climates and limited sunlight. Together, these findings highlight a pressing need for policy adjustments that holistically address both operational and health-related stressors in polar maritime environments.

4.9. Reporting Fatigue Risk



Source: Author's compilation

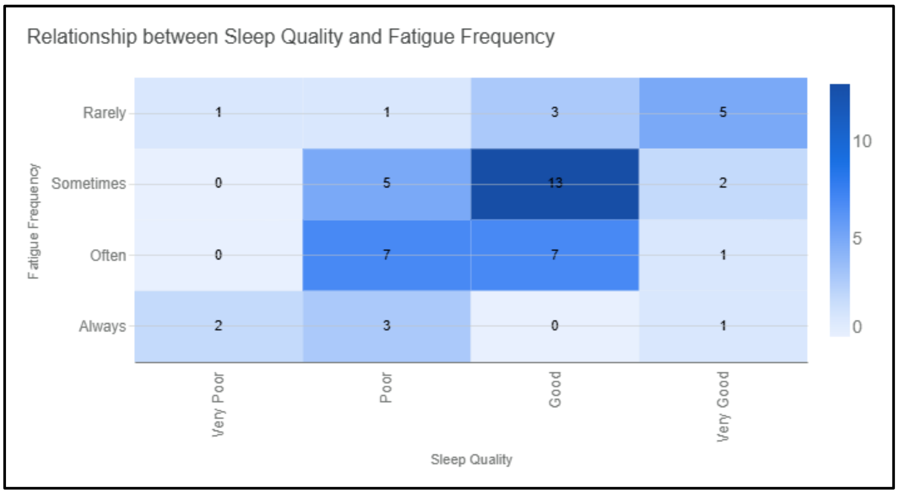
Figure 17 Reporting Fatigue Risk

As illustrated in Figure 17, while a slight majority of respondents (29 out of 51) felt comfortable approaching their Head of Department (HoD) to report fatigue-related concerns, a significant portion, over 30%, indicated reluctance or conditional willingness to do so. This hesitancy aligns with the broader concerns reflected in Table 10, where respondents advocated for amended work-rest regulations (15.7%) and improved nutritional support (13.7%) to manage the unique demands of Arctic operations better. The combined data underscore the urgent need for regulatory reforms to address these concerns. It highlights the need not only for regulatory reforms but also for cultivating a more transparent and supportive safety culture onboard.

4.10. Key Statistical Findings

4.10.1. Fatigue and Sleep Quality

Using data collected from the survey, the reported frequencies of fatigue and sleep quality in the Arctic were plotted on a heatmap to provide a clear and strong visual representation of the overlap. A Spearman's Correlation Coefficient test was conducted, yielding a 'ρ' value of -0.407. It suggests a moderate to strong inverse correlation between sleep quality and fatigue frequency; as seafarers found their sleep quality was 'good' or 'very good', they experienced less frequent fatigue.

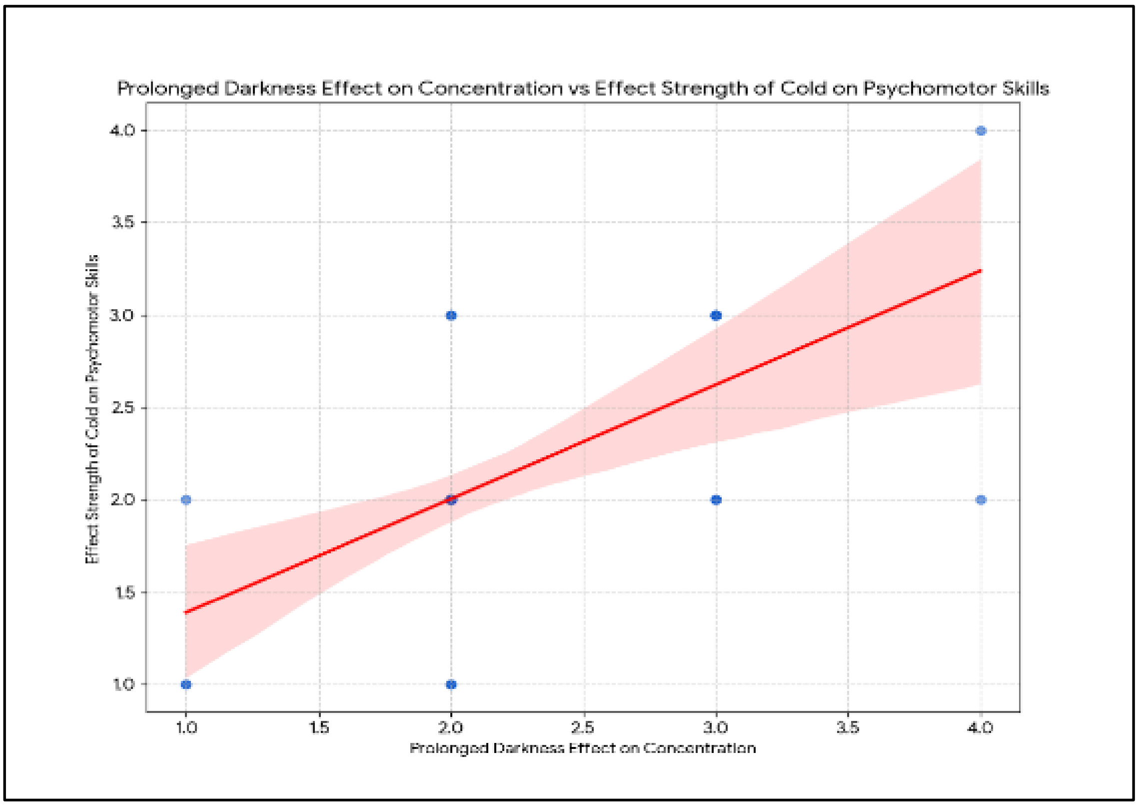


Source: Author's compilation

Figure 18 Heatmap of Reported Sleep Quality and Fatigue Frequency

For further reliability, a Probability Value (P-value) was calculated. The P-value was found to be 0.003, meaning the P-value < 0.05, rejecting the null hypothesis that there is no correlation between the two variables. Therefore, current sleep and rest practices and requirements need intervention to mitigate fatigue.

4.10.2. Concentration in Prolonged Darkness and Psychomotor Skills in Extreme Cold



Source: Author's compilation

Figure 19 Scatter Plot of Effects on Concentration in Prolonged Darkness and the Effect Strength of Cold on Psychomotor Skills

It was found that the correlation coefficient 'ρ' value = 0.626. It indicates a strong and direct relationship, as seen clearly by the plotted line of best fit on the scatter plot, where concentration becomes more affected, and so do psychomotor skills.

For reliability, the 'P-value' was calculated and found to be 0.000. It means it is doubtful that these variables are unrelated, thereby improving confidence in the 'ρ' value.

4.10.3. Fatigue Risk Management Systems and Fatigue Levels

The relationship between fatigue risk management systems and reported levels of fatigue was statistically analysed. The Spearman's correlation coefficient was found to be very weak, ranging from -0.148 to 0.184, indicating a very weak relationship. The P-value found ranged from 0.195 to 0.955 and thus does not reject the null hypothesis of no significant relationship between the variables. Whilst no significant relationship was found, this may indicate that the presence of an FRMP does not mitigate the levels of reported fatigue, suggesting either poor implementation of an FRMS or the need for revised guidance on FRMPs to reduce fatigue levels.

5. Conclusion

5.1. Interpretation of Key Quantitative Findings

The qualitative data, enriched by the insights of Interviewees, has underscored the importance of distinguishing between 'tiredness' and 'fatigue.' This deeper understanding equips us with the necessary knowledge to manage these states effectively, with fatigue being escalated to management as a risk mitigation issue.

Interviewee 3 reported that extended watch durations, up to 12 hours within a 24-hour period, were sufficient to induce fatigue. They explained that post-watch recovery was often hindered by being "overtired," making it difficult to fall asleep.

Further compounding fatigue, Interviewee 3 described the impact of "Polar Checks," which added cognitive and physical strain through an increased number of daily responsibilities, often performed outdoors in extreme environmental conditions. During winter operations, their vessel typically engaged in short voyages with port calls every 10 days, leading to continuous operational demands, extensive pilotage, and cargo watches. These factors significantly contributed to persistent fatigue. These circumstances lead to what the IMO defines as "sleep debt"—that is, insufficient cumulative sleep over consecutive 24-hour periods (IMO MSC.1-Circ.1598, 2019). This debt contributes to a gradual, sustained onset of fatigue that persists until substantial rest is achieved.

One interviewee commented, "everyone is fatigued; you just want to be part of the team," highlighting the internal pressures to conform and perform, even when experiencing fatigue. Supporting this, over 80% of survey respondents reported experiencing fatigue "Sometimes," "Often," or "Always" during Arctic voyages (Figure 6). These findings suggest that revisions to the STCW Convention (IMO 2017) may be necessary to offer more precise guidance on fatigue management under Arctic operational conditions, where existing maximum work-hour limits may not sufficiently account for the additional stressors present.

Finally, Interviewee 3 noted that, at the management level, the workload remains consistently high, as environmental conditions do not reduce the need for maintenance tasks. Furthermore, the demands of vigilant navigation in challenging Arctic waters were identified as a significant contributor to fatigue.

5.2. Organisational Perceptions of Fatigue

Interviewee 4 observed that although fatigue is still not fully understood, there has been a notable shift in organisational attitudes over the past decade. In their organisation, fatigue is no longer viewed solely as a reflection of individual weakness or a lack of personal resilience. Instead, it is increasingly recognised as a critical safety concern, with direct implications for the well-being of the vessel, crew, and cargo. The interviewee highlighted that the organisation has drawn on lessons from near miss incidents and engaged in the study of fatigue to prevent maritime accidents proactively.

Interviewee 2 reported the policy of 'Care Culture' growing to understand fatigue as a 'duty of care' matter. This organisational safety culture therefore shows the importance of recognising fatigue and mitigating its effects on a fleet-wide basis, moving beyond the individual and a 'blame culture' to one that supports its crew in maintaining a safe vessel.

5.3. PPE Provision, Necessity and Effectiveness

The importance of PPE was strongly emphasised by Interviewee 2, who stated that it is "impossible to function without it. It underscores the essential role of practical and protective clothing in extreme environments. However, PPE was not consistently or adequately provided. Interviewee 4 noted that winter jackets had to be "requested rather than intrinsically provided," while Interviewee 3 reported inadequacies in the supplied gear. As a result, Personal Survival Kits (PSKs) often lacked the necessary PPE required for emergencies.

Although PPE is critical for safety, it can also impede operational effectiveness. Interviewees 2 and 3 highlighted that items such as thick gloves reduce manual dexterity, a crucial skill for tasks conducted on deck. This not only prolongs task execution, particularly problematic when minimising exposure to extreme conditions is essential but also compromises precision.

Additionally, protective eyewear such as goggles was reported to fog up due to condensation, impairing vision and situational awareness. Interviewee 2 noted that such issues are rarely accounted for in formal written risk assessments, despite their potential to increase danger during deck operations.

Navigation and Operations Practices in the Arctic

Interviewee 3 highlighted the issue of the constant need for dynamic risk assessment, particularly in icy conditions. While there is no specific regulation that explicitly mandates a training course for dynamic risk assessment, its implicit necessity within the company's SMS, as per the ISM Code and Polar Code training under STCW and SOLAS, is a serious matter.

5.4. Watchkeeping and Manning Levels

One interviewee suggested that 'double watches help to prevent overreliance on one specific navigational tool', a practical strategy that could enhance communication and shared responsibility. This 'Junior-Senior split' allows each member to be allocated a specific piece of equipment, providing a practical solution to the problem of information overload during times of stress.

Another helpful suggestion, from interviewee 3, was to consider a dedicated navigational officer for day work. This could provide additional support for the watchkeeping officers without disturbing their rest periods, a practical way to ease the Master's workload and enhance crew safety without compromising the vessel's operations.

5.5. Training and Experience

A lack of the appropriate may lead to situations such as the grounding of the Ocean Explorer in 2023, which had an inexperienced but deemed competent crew (The Guardian 2023).

Interviewee 1, an Engineer, highlighted the impacts of implementing training and the need for briefings from the bridge team at the start and end of each watch. This provides engineers with the necessary information when working on deck, including wind direction and subsequent wind chill effects. None of the interviewees had previously communicated the concept of wind chill, which indicates a lack of adherence to company procedure and may lead to the risk of frostnip or frostbite due to ill-informed PPE donning.

5.6. Summary

The findings of this study urgently highlight the significant challenges that the unique stressors in the Arctic pose to seafarer fatigue and performance. These challenges directly impact operational safety and resilience, underscoring the immediate need for our research to influence policy and operational practices in the maritime industry.

While individual measures and efforts to mitigate fatigue symptoms have proven valuable, there is a compelling need for further integrated and comprehensive solutions at all levels, from the organisational to the international.

Building a safer and more resilient maritime workforce is achievable by taking the following vital steps:

- Addressing deficiencies in FRMS construction and implementation,
- Improving the design and efficiency of PPE,
- Revising training standards, particularly for ice navigation, and
- Optimising manning levels and navigational procedures.

These solutions not only address the current challenges but also pave the way for a safer and more efficient maritime industry in the increasingly transited Arctic waters. This study calls for continued research and proactive, rather than reactive, measures to safeguard life, cargo and vessel in the challenging operational sphere of the Arctic.

Recommendations

Based on the findings of this study, recommendations for improvements are made considering the identified gaps.

- *Organisational Policy and Regulatory Recommendations*
    - The STCW revision for Polar training focuses on enhancing the competence and confidence of Arctic-going navigating officers, including the requirement for mandatory ice navigation experience. It sets higher standards for gaining practical experience and competence beyond theoretical knowledge.
    - Companies should strengthen watchkeeping protocols, reinforce training standards, and provide realistic, practical SOPs for Arctic operations, ensuring that all crew members are well-prepared for the challenges ahead.
    - Revisions to Work and rest regulations, with caution to the effects of these conditions to address psychological and physiological impacts.
    - Anticipate a potential increase in the manning for vessels operating in Arctic waters, a change that could prove beneficial, particularly in ice conditions.
    - The mandatory development of FRMS guidance under the ISM Code is adapted to address the challenges of polar operations.

    - Companies should foster a 'Care Culture', where crew are trained on the use of FRMS, as well as ensuring environments onboard are conducive to proper rest by reviewing noise, vibration and lighting arrangements.
    - Strict Compliance with PPE mandates under the Polar Code and ensuring compliance with requirements and sufficient provisions in the event of vessel abandonment.
    - Providing techniques, adequate recreation facilities, and tools to foster community building onboard, as well as nutritious food and reliable communication with loved ones.
    - Implementing policies to enable each seafarer to report any violation of safety procedures, policies and practices, and feel comfortable doing so.
    - Implement rigorous pre-employment screening and carefully select the crew before embarkation. Adopt a back-to-back crewing system with rotational assignments.
    - Enhance cross-departmental communication between the Deck and Engine departments, particularly during engineer-led operations conducted on deck.
- *Recommendations for Future Research*
    - The potential for long-term investigations into the combined Arctic stressors to provide a clearer understanding of how to mitigate the human-environmental reaction more effectively is a reason for optimism.
    - There is an urgent need for further in-depth study of FRMS effectiveness in the Arctic environment, building on the results of this study.
    - Conducting Studies into innovating new versions of PPE that are sufficient, efficient, and ergonomically designed.
    - Investigating various artificial lighting systems and selecting those that promote the best performance in terms of sleep quality, circadian rhythms, and cognitive functions.
    - Strategic planning and regular rest breaks may enhance the willingness to complete these tasks and promote compliance with safety policies and regulations.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflicts of interest.

Statement of informed consent

Informed consent was obtained from all subjects involved in the study.

Author Contributions

"Conceptualization, A.T; methodology, A.T; software, A.T; validation, A.T; formal analysis, A.T; investigation, A.T; resources, A.T; data curation, A.T; writing—original draft preparation, A.T; writing—review and editing, A.T and M.B; visualization, A.T; supervision, M.B; project administration, A.T and M.B; funding acquisition, NA.

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Data are available from the corresponding author.

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