



MODERATION EFFECT OF TECHNOLOGICAL INNOVATION ON PSYCHOLOGICAL STATE AND NAVIGATIONAL SAFETY IN TANZANIA MARITIME TRANSPORTATION

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Abstract

This study examines the impact of ergonomic factors, specifically the psychological state (PS) of seafarers, on navigation safety (NS) in Tanzania's maritime transport, with technological innovation (TI) explored as a moderating variable. Despite recent advancements in naval technologies and regulatory reforms, the sector continues to experience navigation-related incidents, which are largely attributed to human error and the inadequate integration of new technologies. Anchored in the Human Factors Analysis and Classification System (HFACS), the study adopted an explanatory research design and surveyed 203 seafarers across five maritime institutions in Dar es Salaam. Using Partial Least Squares Structural Equation Modelling (PLS-SEM), the study assessed the reliability and validity of measurement models and tested hypothesised relationships. Findings reveal that psychological state significantly influences navigation safety ($p < 0.001$), emphasising the role of cognitive, emotional, and attentional factors in maritime operations. Technological innovation not only had a direct positive effect on navigation safety ($p = 0.049$) but also moderated the relationship between PS and NS ($p = 0.013$), suggesting that technology can mitigate psychological limitations and enhance decision-making performance in navigation tasks. The study concludes that navigation safety is a

function of the interplay between human psychological conditions and technological systems. These findings carry critical implications for maritime training, vessel design, and regulatory policy advocating for adaptive, human-centred systems that balance human performance with technological support. Future research is recommended to incorporate longitudinal methods and cross-cultural comparisons to evaluate the evolving role of human-technology integration in global maritime safety.

Keywords: Maritime Technological Innovation, Psychological state, Navigational safety, Maritime transportation

INTRODUCTION

Maritime transportation is vital to the global economy, with approximately 80% of international trade carried by sea (Grech et al., 2019; Chauvin et al., 2021; Lützhöft & Dekker, 2020). Despite significant technological advancements, navigation-related accidents persist, primarily attributed to human error. Studies estimate that between 75% and 96% of maritime incidents are caused by human factors such as poor decision-making, stress, fatigue, and inadequate training (Zagar et al., 2020; Wu et al., 2020; Hetherington et al., 2021). These findings underscore the critical role of ergonomic and behavioural influences on navigational safety across maritime operations.

In Tanzania, maritime transport serves as a key driver of economic activity, supporting trade within East Africa and beyond. However, the country continues to face navigation safety challenges, as evidenced by a recurring pattern of marine accidents. These incidents occur despite the government's regulatory reforms, such as the establishment of the Tanzania Shipping Agencies Corporation (TASAC) in 2018 and the introduction of new maritime safety regulations in 2023 under the Merchant Shipping Act No. 14 of 2017. While these institutional reforms aim to strengthen maritime governance, the persistence of accidents points to underlying issues, particularly those related to human factors and their interaction with evolving technologies.

Ergonomic factors, including both physiological abilities and psychological states, have been widely cited in international literature as root causes of unsafe maritime navigation (Chauvin et al., 2021; Olsen, 2024; Grech et al., 2019). These factors involve the physical and cognitive conditions of seafarers, such as fatigue, reaction time, stress management, and attention levels, all of which directly affect decision-making and performance. In high-risk and dynamic marine environments like those found in Tanzanian waters, characterised by variable

weather, high traffic density, and diverse operational contexts, these human limitations can significantly compromise safety.

Despite global recognition of these issues, limited research has been conducted in the Tanzanian context to examine how physiological and psychological factors influence navigation safety, especially in interaction with modern technological systems. Most existing studies have focused on technical or regulatory challenges, leaving a gap in understanding the human element within maritime safety management. This study addresses that gap by exploring the influence of psychological state and physiological abilities on navigation safety, with a specific focus on how technological innovation moderates these relationships.

By adopting the Human Factors Analysis and Classification System (HFACS) as its theoretical framework and utilizing Partial Least Squares Structural Equation Modelling (PLS-SEM), the study aims to generate empirical insights that support safer maritime practices. The findings are expected to inform training, policy, and design strategies that better align human capabilities with modern navigation technologies, thereby enhancing overall safety and efficiency in Tanzanian maritime operations.

LITERATURE REVIEW

Theory of Human Factors Analysis and Classification System (HFACS)

This study is grounded in the Human Factors Analysis and Classification System (HFACS), developed by Dr. Scott Shappell and Dr. Doug Wiegmann in the 1990s. Originally designed to investigate aviation accidents, HFACS identifies human error as a leading cause responsible for approximately 80% of incidents, particularly in military aviation. Over time, its applicability has expanded to other safety-critical sectors, including maritime operations.

HFACS emphasizes the interaction between humans and systems, focusing on how individual conditions (e.g., psychological and physiological states), organizational factors, and technology affect safety outcomes. The model categorizes human error into key domains such as unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences.

This study adopts HFACS as a guiding framework, specifically focusing on psychological state, physiological abilities, and technological innovation—all of which are embedded within the system's preconditions for unsafe acts. By examining these variables, the study aims to understand how human performance and technological tools interact to influence navigation safety in Tanzania's maritime sector.

Psychological state is a critical component of ergonomics in maritime operations, directly influencing human error and navigation safety. Research by Hetherington, Flin, and Mearns (2021) and studies in China confirm that poor psychological conditions, such as stress, fatigue,

or emotional instability, increase the risk of human error. Scholars such as Fan et al. (2023) and Moreno et al. (2022) emphasise that psychological health supports essential cognitive functions, including decision-making, situational awareness, and hazard detection.

Distorted psychological states can impair emotional regulation, communication, and risk perception, leading to unsafe behaviour such as ignoring navigational protocols or hesitating in emergencies. Despite measures like mental health screenings, support systems, and stress management training, psychological factors still significantly affect mariners' decisions, especially under high-pressure conditions.

Technological innovation has significantly transformed the maritime industry, enhancing navigation accuracy, operational efficiency, and safety. As Usluer (2024) notes, global technological advancements affect all sectors, including maritime transport, through tools that improve monitoring and control. Okafor et al. (2024) further highlight that African maritime security remains vulnerable, but technology enables better surveillance and operational oversight.

Studies such as those by Yuhao et al. (2023) and Cao et al. (2023) confirm that innovations like GPS, AIS, radar, sonar, and AI systems reduce human error, enhance situational awareness, and support emergency response efforts. Popoola et al. (2024) found that automation has empowered navigators with real-time data, collision avoidance systems, and advanced route planning tools, thereby lowering accident risks.

Despite these advancements, human error remains a persistent cause of navigational incidents. In Tanzania, challenges in the implementation of technologies like ECDIS (Ojode, 2021), power inconsistencies, and poor system integration limit the benefits of automation. Although new regulations and institutions such as TASAC aim to improve safety, maritime accidents still occur, underscoring the need for improved human-technology integration and infrastructure upgrades.

Despite extensive literature on human factors in maritime navigation safety, significant research gaps remain, particularly in the African context. Most existing studies have focused on general human error or training aspects, with limited emphasis on the specific roles of psychological state and physiological abilities of seafarers in ensuring navigational safety. Furthermore, little attention has been given to how technological innovation moderates these relationships.

While studies by Xu and Xue (2024), Hetherington et al. (2021), and Fan et al. (2023) highlight the importance of physical and mental readiness in navigation, they are largely based in non-African settings. Similarly, technological studies by Usluer (2024), Yuhao et al. (2023), and Popoola et al. (2024) examine innovations like automation and remote-controlled ships but do not address their moderating effects on human performance. Even within Africa, few studies,

such as Ojode (2021) in Tanzania, focus on technology application challenges without linking them to human factors.

This study addresses these gaps by investigating the influence of psychological and physiological factors on navigation safety in Tanzania, while also examining the moderating role of technological innovation, offering a novel and context-specific contribution to maritime safety literature.

METHODOLOGY

This study adopted an explanatory research design to assess the causal relationships between human factors (psychological state and physiological abilities), technological innovation, and navigation safety. A survey strategy was employed to collect quantitative data from a large sample, facilitating statistical analysis through a deductive approach.

The study targeted a population of 450 experienced seafarers, those with at least six months of sailing experience, drawn from five key maritime institutions in Dar es Salaam: TPA (133), TASAC (40), KFF-Azam (180), DMI (22), and ZFF (75). Dar es Salaam was selected as the study area due to its strategic maritime position and concentration of marine professionals.

A probability random sampling technique was used to ensure equal selection opportunity and minimize researcher bias. This methodological framework supports the reliability and generalizability of the findings within the Tanzanian maritime context.

To determine the representative sample size, the study applied Slovin's formula, using a 95% confidence level and a 5% margin of error. Given a total population of 450 seafarers, the formula:

$$n = \frac{N}{1 + N(e^2)}$$

Where, N Number Total population=450 seafarers

n= Number Sample size

e=Error Tolerance (which is 05%). The study confidence level was 95% which gives a margin of error of 0.05

Hence,

$$n = \frac{450}{1 + 450(0.05)^2}$$

$$n = \frac{450}{2.125} = 211.765 \approx 212$$

The study sample size was 212 seafarers.

This study employed structured drop-off questionnaires to collect primary data from seafarers, allowing respondents ample time to respond. The questionnaire, adapted from prior validated studies, included sections on demographics, psychological state (PS), physiological abilities (PA), marine safety (NS), and technological innovation (TI), using a 5-point Likert scale.

FINDINGS

Data preparation involved cleaning and coding to ensure quality and accuracy. The process included identifying errors, duplicates, and missing data, with all questionnaires checked for completeness and consistency before being coded and entered into IBM SPSS 27.

For missing data, only 7% of the total responses were incomplete—well below the 10% threshold (Hair et al., 2023), allowing the analysis to proceed. After cleaning, 203 questionnaires (95.75%) were deemed usable, while 9 (4.25%) were discarded. Outliers were assessed using the acceptable range of 1–5 for Likert scale responses. No outliers were detected, confirming the dataset's suitability for analysis under structural equation modelling (SEM) assumptions.

To assess multicollinearity, VIF values were calculated for all indicators. All values were below the acceptable threshold of 3.3 (Hair et al., 2021), with the highest being 2.445 (NS1) and 1.975 (TI4), indicating no serious multicollinearity. Interaction terms (TI × PA and TI × PS) recorded ideal VIFs of 1.000, confirming statistical independence. Thus, the model meets the assumption of multicollinearity and is suitable for further structural analysis.

The model's quality was evaluated through measurement model analysis to confirm the reliability and validity of the constructs. Reliability was assessed using factor loadings, Cronbach's Alpha, and composite reliability, with acceptable thresholds ≥ 0.70 . Validity was established through convergent and discriminant validity, utilizing the Average Variance Extracted (AVE) and the Heterotrait-Monotrait Ratio (HTMT), ensuring that the indicators accurately represented their respective constructs (Hair et al., 2021; Saunders et al., 2019).

The study confirmed the reliability and validity of all measurement constructs. Cronbach's Alpha values ranged from 0.775 to 0.890, exceeding the 0.70 threshold and indicating strong internal consistency. Composite reliability scores for all constructs were above 0.80, satisfying recommended standards. Additionally, the Average Variance Extracted (AVE) values surpassed the 0.50 threshold, establishing convergent validity. Navigation Safety (NS) demonstrated the strongest psychometric properties, with the highest Cronbach's Alpha (0.890) and AVE (0.609), confirming that its indicators effectively represent the underlying construct.

Table 1: Construct Reliability and Validity

	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
NS	0.890	0.903	0.915	0.609
PS	0.808	0.837	0.859	0.507
TI	0.775	0.866	0.838	0.583

The study confirmed discriminant validity among the constructs using the Heterotrait-Monotrait Ratio (HTMT) approach. All HTMT values were below the recommended threshold of 0.85, with the highest being 0.710 between the interaction terms (TI × PS). This indicates that each construct, Navigation Safety (NS), Psychological State (PS), and Technological Invention (TI) is distinct and not overlapping with others. These results validate the structural model's constructs for further analysis, reinforcing the overall measurement model's reliability and integrity.

Table 2: Heterotrait-Monotrait Ratio Result

	NS	PA	PS	TI	TI x PS
NS					
PA	0.329				
PS	0.360	0.132			
TI	0.201	0.251	0.406		
TI x PS	0.273	0.261	0.283	0.263	

The structural model was assessed using PLS-SEM with bootstrapping in SmartPLS to test the study's hypotheses. This method enabled the simultaneous evaluation of direct, indirect, and moderating effects.

The hypotheses tested included the positive influence of physiological abilities and psychological state on navigation safety, as well as the moderating role of technological innovation on both relationships. The bootstrapping approach confirmed significant associations, supporting the hypothesised relationships and reinforcing the model's predictive validity.

Path Coefficients and Moderation Effects

Path coefficient analysis revealed significant direct effects of PS on NS. The results also confirmed that TI positively moderates the relationship between PS and NS, strengthening its impact on navigational safety.

The findings underscore the importance of human factors and technological advancement in enhancing maritime safety.

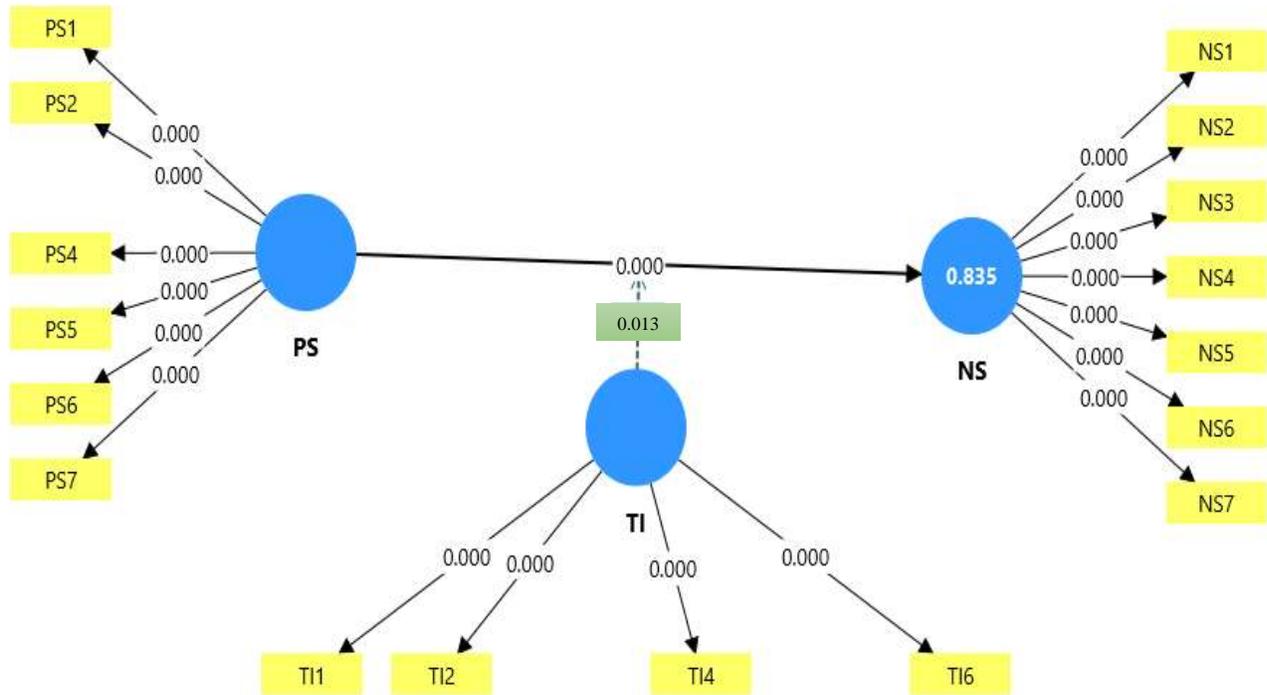


Figure 1: Path Coefficients

Table 3: Interaction among Study Variables

	Original sample (β)	T statistics (O/STDEV)	P values	Interpretation
PS -> NS	0.402	4.223	0.000	***
TI → NS	0.537	1.969	0.049	*
TI x PS -> NS	0.079	3.120	0.013	**

Note: $p < 0.05$ (Weak significant, *), $p < 0.01$ (Moderate, **), $p < 0.001$ (Strong, ***)

The interaction term $TI \times PS \rightarrow NS$ demonstrated a stronger and statistically significant moderating effect ($t = 3.120, p = 0.013$). This result supports the proposition that in high-technology environments, psychological factors such as alertness, emotional regulation, and cognitive clarity become less critical for navigation safety.

These moderation effects were further visualized using interaction plots which clearly illustrate that the slope between PS and NS is steepest when TI is low and flattest when TI is high.

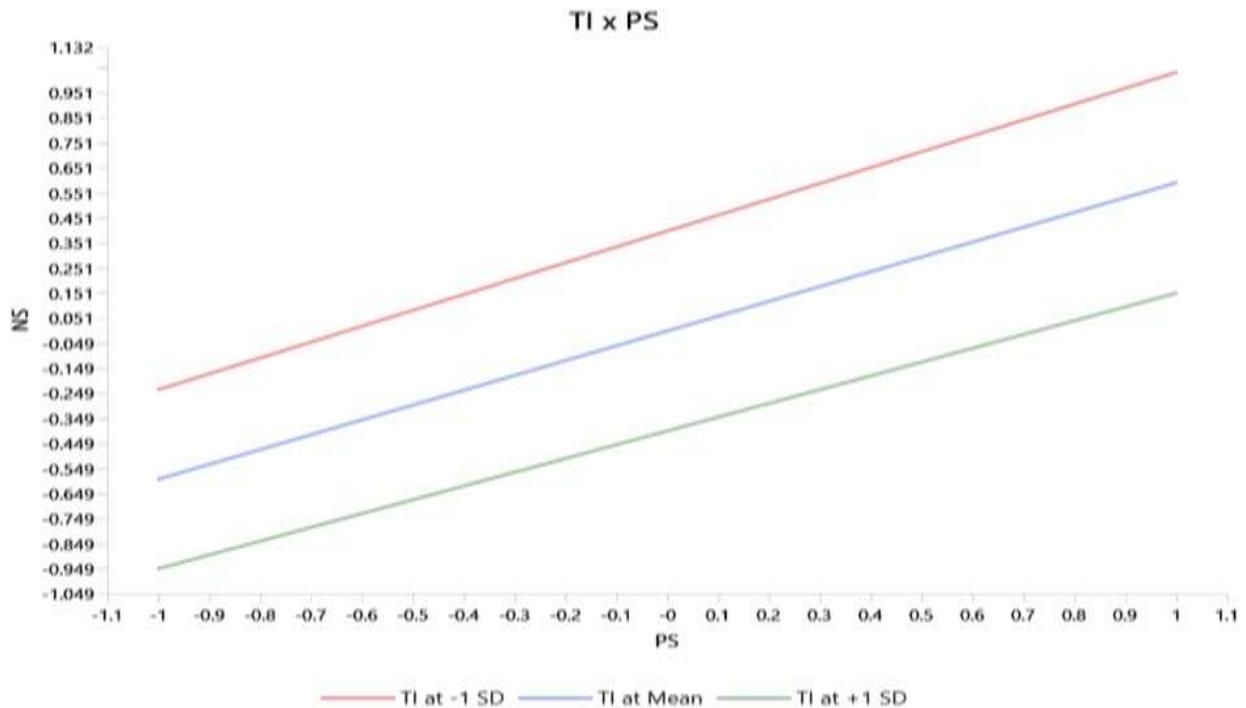


Figure 2: Technological Innovation Interaction with Psychological State.

The figure above reveals that $(TI \times PS \rightarrow NS)$; X-axis: PS (Psychological State), Y-axis: NS (Navigation Safety). Red: TI at (Low Technological Innovation), Blue: TI at Mean (Average Technological Innovation), Green: TI at (High Technological Innovation).

This means better psychological conditions (e.g., focus, alertness, mental stability) are associated with improved navigation safety. The slope is steepest when TI is low (red line), and flattest when TI is high (green line). This suggests that the effect of PS on NS weakens as technological innovation increases.

When technology is less advanced, psychological state plays a bigger role in ensuring navigation safety. As technology improves, its systems likely compensate for psychological variability, reducing reliance on mental sharpness or emotional stability.

This graph reveals a buffering (moderating) role of technological innovation. High TI reduces the dependency of NS on PS. In other words, technology serves as a safeguard against the risks posed by poor psychological conditions, which is especially valuable in high-stress or demanding environments.

DISCUSSIONS

Fajnerová et al. (2018) document how externalising navigation via AR glass technology as a technological innovation can alter psychological navigation processes, effectively

moderating the relationship between navigators' psychological state and their navigation performance. Generally, these studies support the idea that advanced navigation technologies (AR glasses, VR headsets, adaptive robots) moderate how psychological state translates into navigation safety outcomes.

Studies such as Zhou, Zhang, & Luo (2023) and Chatziannakis, Mylonas, and Tzovaras (2021) conclude that augmented virtuality (AV) displays technological innovation, such as the use of sensor fusion and anomaly detection techniques, augmented virtuality (AV) displays significantly improves maritime navigation systems.

By integrating multi-source navigation data and advanced detection algorithms, the framework enhances the system's ability to identify spoofing, tampering, or data inconsistencies in real-time. This approach strengthens operational security and reliability, especially in autonomous or digitalized maritime environments, hence complementing human psychological states that have led to maritime navigation safety.

Moreover, Mohamed & Hosny (2024) advocate for collaboration between maritime academies and ship operators to incorporate advanced, scenario-based ECDIS training into curricula, ensuring officers are well-prepared for real-world navigation challenges highly integrated with technological innovation, as maritime operations pace into that.

Also, studies such as Bilen et al. (2024), which studied social robot navigation with adaptive proxemics based on emotions, conclude that technological innovation, when used by physically fit mariners, improves navigation safety. Also, Kourtesis et al. (2021) state technological competence is a precondition for the effective implementation of virtual reality head-mounted displays in human neuroscience.

CONCLUSIONS

This study explored the relationships among Psychological State (PS), Navigation Safety (NS), and Technological Innovation (TI), addressing both direct and moderating effects. The findings reveal that technological innovation significantly enhances navigation safety, not only directly, but also by moderating the influence of human factors. While physiological and psychological attributes remain essential, their impact on safety is shaped by the technological context. The observed interaction effects underscore the role of technology in compensating for human limitations, especially in high-demand maritime environments. These insights have practical, policy, and theoretical implications, providing a basis for future research focused on optimising human–technology integration in maritime operations.

RECOMMENDATIONS

To enhance maritime navigation safety, it is crucial to strike a balance between the roles of humans and technology. Technological systems should be designed to support, not replace, human performance, with training programs emphasising effective human-machine interaction. Given the observed positive direct effect of technological innovation on navigation safety, there is a need for improved simulation-based training to help seafarers adapt to advanced systems. Future technologies should be user-centred and responsive to the operator's physical and psychological conditions. Moreover, routine monitoring of crew readiness, including fatigue and stress levels, should be institutionalised. Finally, continuous evaluation of automation policies is essential to ensure that increasing system autonomy does not compromise human oversight or operational safety.

SCOPE FOR FURTHER STUDIES

This study highlights how technology moderates the impact of human factors on navigation safety. Future research should adopt longitudinal designs, explore cross-cultural and industry-specific differences, and evaluate policies and training to ensure effective integration of technology with human oversight.

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