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Research Article

Mental workload, situational awareness, and safety culture in high-speed craft navigation: A multidimensional analysis of Turkish bridge officers

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Abstract
This study examines the interrelationship of mental workload (MWL), situational awareness (SA), and safety culture (SC) within high-speed craft (HSC) navigation, focusing on certified Turkish bridge officers. Data were collected between 1 June and 31 December 2024 using purposive and snowball sampling techniques. A total of 38 certified HSC navigators operating under the Turkish flag voluntarily participated in structured, interviewer-assisted surveys, yielding a 100 % response rate. The Revised NASA Task Load Index (RNASA-TLX), the Situational Awareness Rating Technique (SART), and the Nordic Occupational Safety Climate Questionnaire (NOSACQ-50) were employed to assess cognitive and organizational factors affecting navigational performance in high-tempo maritime environments. Descriptive analysis revealed that visual demand constituted the most significant MWL source, while perceived organizational safety- particularly managerial safety justice- scored lowest among SC dimensions. Notably, while SA and MWL were positively correlated in certain subdomains, multinomial logistic regression analysis found no statistically significant predictive relationships among MWL, SA, or SC. These findings suggest that the three core constructs' interdependencies may be non-linear and shaped by context-sensitive or latent variables. The study concludes with implications for human-centered design and organizational safety policies aimed at fostering cognitive resilience in HSC bridge operations.

Nomenclature

AIS	Automatic Identification System
ARPA	Automatic Radar Plotting Aid
ECDIS	Electronic Chart Display and Information System
KMO	Kaiser-Meyer-Olkin measure of sampling adequacy
d	Margin of error
H	Kruskal-Wallis test
M	Mean of a population of scores
Mdn	Median
p	Significance level
r	Pearson's correlation coefficient
SD	Standard deviation in a population of data

U	Mann-Whitney test
W	Shapiro-Wilk test
α	Cronbach's alpha
τ	Kendall's tau-b coefficient
$\chi 2$	Chi-square

1. Introduction

A primary objective in modern maritime transportation is reducing transport time through technological advancements that enable higher vessel speeds. This drive for efficiency has fostered the widespread adoption of high-speed craft (HSC) (Benassai, Piscopo, & Scamardella, 2013); vessels engineered for rapid operations across commercial, military, leisure, and special-purpose domains. Characterized by advanced maneuverability and complex systems, HSCs operate in restricted waters with high traffic density, demanding swift, precise, and safety-critical decisions from bridge crews.
The operational complexities of HSC navigation are shaped by three interrelated human factors: mental workload (MWL), situational awareness (SA), and safety culture (SC). MWL refers to the cognitive effort required to meet task demands and is influenced by both internal and external stressors (Boet et al., 2017). SA captures the crew's ability to perceive, comprehend, and project changes in the navigational environment, playing a vital role in timely decision-making (Skrypchuk et al., 2019). SC represents the collective values and practices surrounding safety, influenced by organizational norms, leadership, and crew behavior (Berglund, 2020).

MWL, SA, and SC are widely acknowledged as key determinants of safety in high-risk industries such as aviation, nuclear energy, and healthcare. Research in these fields has shown that high MWL, inadequate SA, and weak SC can lead to errors and accidents, especially in complex maritime settings (Boughaba et al., 2014; Mišković et al., 2018; Murai et al., 2015; Young et al., 2013). These findings offer valuable insights that are increasingly relevant in HSC navigation, which combines dynamic control demands with rapid decision-making under time pressure.

To build the conceptual foundation for this study, a structured literature review was conducted using the keywords "mental workload," "situational awareness," and "safety culture." The review covered publications from 2010 to 2025, and included journal articles, conference proceedings, book chapters, and technical reports retrieved from multiple scholarly databases such as Scopus and Web of Science. A total of 450 sources were screened, with inclusion criteria prioritizing empirical and conceptual studies related to human factors in safety-critical domains, especially in maritime operations. This review informed the study's conceptual framework and selection of measurement instruments.

Studies on MWL have employed tools such as the NASA Task Load Index (NASA-TLX), electrocardiography, eye-tracking, and other physiological measures to assess cognitive demand (Li et al., 2020; Orlandi & Brooks, 2018; Shkembi et al., 2022; Soto-Castellón et al., 2023). For instance, Murai et al. (2015) used nasal temperature as an indicator and showed it could effectively reflect workload variations of port coordinators. Recent studies further suggest that technological automation may help reduce cognitive load in dynamic control environments (Balta et al., 2024; Causse et al., 2025). Such approaches are applicable to HSC bridge operations, where navigators must process large volumes of data in fast-changing situations, often under adverse environmental conditions.

SA has been studied using methods such as Situation Awareness Global Assessment Technique, Verbal Protocol Analysis, and electroencephalogram (Liu et al., 2023; Rose et al., 2018). Researches indicate that visual distractions, fatigue, and even augmented reality systems can significantly affect SA (Lim et al., 2015; Mallam et al., 2024). In maritime navigation- particularly aboard HSCs, where speed amplifies the need for anticipatory perception- maintaining SA is critical to preventing collisions and navigational errors. However, the connection between SA quality and safe decision-making still warrants further clarification (de Zwart et al., 2025).

Studies across different sectors, including shipping, fishing, and nuclear energy, have used SC maturity models and surveys to examine its impact (Arslan et al., 2016; Dai et al., 2023; Thorvaldsen et al., 2018). Factors such as leadership commitment, communication, and employee engagement have been identified as key drivers of safety performance (Ali et al., 2024; Tappura et al., 2022). Nævestad et al. (2019) further emphasize that SC influences both organizational norms and individual safety behavior. In HSC navigation, the short voyage durations and rapid crew rotations underscore the need for strong SC to ensure consistent operational discipline and cross-role trust.

Although each construct- MWL, SA, and SC- has been extensively explored in isolation, few empirical studies have examined their interrelationships in maritime contexts. This gap is especially apparent in HSC navigation, where unique cognitive and organizational challenges make an integrated analysis essential. Therefore, the current study addresses this void by exploring the combined influence of MWL, SA, and SC among HSC bridge officers, drawing on validated tools and domain-specific observations.

The structure of this paper is as follows: Section 2 details the research methodology, including participant characteristics, measurement instruments, and data collection procedures. Section 3 presents the key empirical findings. Section 4 offers a critical discussion of the results in relation to the existing literature, while also addressing the study's methodological strengths and limitations. Section 5 concludes the paper and proposes directions for future research.

2. Materials and methods

2.1 Revised NASA-TLX

To evaluate the MWL experienced by navigators during HSC operations, the Revised NASA-TLX (RNASA-TLX) was utilized. This version is adapted from the original NASA-TLX framework (Hart, 2006), which is widely recognized for its reliability and efficiency in measuring MWL across various safety-critical domains. However, due to the unique sensory and cognitive demands of modern maritime bridge operations, particularly those involving high-speed vessels, certain modifications have been introduced to enhance its contextual relevance (Kartoğlu & Kum, 2017; Kartoglu et al., 2024).

In the RNASA-TLX, the original six dimensions are revised to better reflect the perceptual and operational characteristics of HSC navigation. Specifically, physical demand and performance, which are considered less informative in highly automated bridge settings, are replaced with visual demand and auditory demand, respectively. As a result, the six final dimensions assessed include: mental demand (MD), visual demand (VD), auditory demand (AD), temporal demand (TD), effort (E), and frustration level (FL).

These dimensions were selected to capture the multifaceted nature of workload in fast-paced maritime environments, where decision-making, perceptual vigilance, time pressure, and emotional regulation are highly interdependent. For example, visual demand accounts for lookout duties, interpreting navigation displays, and managing screen glare, while auditory demand addresses communication clarity, alarm detection, and radio traffic, all key elements in dynamic bridge settings. The updated six dimensions and their related questions are detailed in **Table 1**.

The RNASA-TLX maintains the structure of the original NASA-TLX and is administered in two main phases. In the first phase, navigators complete 15 pairwise comparisons among the six dimensions to determine which aspects most significantly influenced their MWL during bridge navigation (**Table 2**). Each time a dimension is selected as more influential in a comparison, it gains one point, which contributes to its weight (W). In the second phase, participants assign a subjective rating (R) to each dimension, using a scale ranging from 0 (no contribution) to 100 (maximum contribution), based on perceived intensity.

Table 1 Questions and descriptions of RNASA-TLX's dimensions.

Dimension	Question	Description
Mental demand	*How much mental and perceptual activity was required in bridge navigation operations?*	Includes cognitive processes such as decision-making, memory recall, observation, and analytical thinking.
Visual demand	*How much visual activity was required in bridge navigation operations?*	Covers visual engagement tasks like lookout maintenance, display interpretation, screen brightness adaptation, and visual cue recognition.
Auditory demand	*How much auditory activity was required in bridge navigation operations?*	Encompasses auditory-based lookout tasks, detection of auditory alarms, and handling communication signals.
Temporal demand	*How much time pressure did you feel in bridge navigation operations?*	Reflects time constraints and urgency, including time-sensitive decision-making and operational pacing.
Effort	*How hard did you have to work (mentally and physically) in bridge navigation operations?*	Measures the intensity of physical and cognitive exertion needed to manage workload and multitask.
Frustration level	*How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel in bridge navigation operations?*	Assesses emotional states ranging from stress and frustration to confidence and calmness.

Table 2 Pairwise comparisons in RNASA-TLX.

Case	Pairwise comparison	
1	Mental demand	Temporal demand
2	Temporal demand	Auditory demand
3	Mental demand	Frustration level
4	Effort	Auditory demand
5	Mental demand	Visual demand
6	Visual demand	Frustration level
7	Temporal demand	Effort
8	Mental demand	Auditory demand
9	Temporal demand	Frustration level
10	Visual demand	Temporal demand
11	Auditory demand	Frustration level
12	Visual demand	Effort
13	Effort	Frustration level
14	Mental demand	Effort
15	Visual demand	Auditory demand

The final step involves computing the adjusted rating (AR) for each dimension by multiplying its W by its R. The weighted rating (WR)- representing overall MWL- is then derived by summing the ARs across all dimensions and dividing the total by 15, as shown in Eq. (1). This final score offers a quantitative representation of the navigator's perceived MWL during bridge navigation operations (Kartoğlu & Kum, 2017; Kartoglu et al., 2024).

$$WR = \left[\begin{matrix} (W_{MD} \times R_{MD}) + (W_{VD} \times R_{VD}) \\ +(W_{AD} \times R_{AD}) + (W_{TD} \times R_{TD}) \\ +(W_{E} \times R_{E}) + (W_{FL} \times R_{FL}) \end{matrix}\right] \Big/ 15 \qquad (1)$$

2.2 Situational awareness rating technique (SART)

SART is a subjective technique for measuring SA, known for its simplicity and broad applicability across sectors (Kartoglu et al., 2023b). It is structured around three core dimensions: attentional demand (DD), attentional supply (DS), and understanding of the situation (DU). These dimensions are assessed using a total of 10 items (Selcon et al., 1991; Taylor, 1996).

- The DD dimension comprises three components: instability of the situation (IS), complexity of the situation (CS), and variability of the situation (VS).
- The DS dimension includes four components: arousal (A), concentration of attention (CA), division of attention (DA), and spare mental capacity (SMC).
- The DU dimension consists of three components: information quantity (IQT), information quality (IQL), and familiarity with the situation (FS).

To ensure contextual relevance, all SART items were tailored specifically for use in HSC navigation. Detailed questions and descriptions for each component are provided in **Table 3**. Participants responded to each item using a 7-point Likert scale, where 1 indicates a low level, and 7 indicates a high level.

Table 3 Questions and descriptions of SART dimensions.

Dimension	Subcomponent	Question	Description
Attentional demand	Instability of the situation	*Were navigational conditions highly unstable and likely to change suddenly (high) or were they very stable and steady (low)?*	Degree of instability in navigational conditions
	Complexity of the situation	*Was navigation complex with many interrelated components (high) or was it simple and straightforward (low)?*	Complexity level of the navigation task
	Variability of the situation	*Were there many changing navigational variables (high) or only a few (low)?*	Number of variable elements affecting navigation
Attentional supply	Arousal	*Were you alert and ready for navigation (high) or did you experience low alertness (low)?*	Navigator's level of arousal and readiness
	Concentration of attention	*Were you able to concentrate on various aspects of navigation (high) or were you distracted (low)?*	Degree of focused attention
	Division of attention	*Were you engaged with many current and potential navigation events simultaneously (high) or only focused on one (low)?*	Distribution of attention across navigation-related tasks
	Spare mental capacity	*Did you have spare mental capacity to handle multiple navigation demands (high) or were you overwhelmed (low)?*	Cognitive flexibility and capacity to manage additional input

Table 3 (continued) Questions and descriptions of SART dimensions.

Dimension	Subcomponent	Question	Description
Understanding of the situation	Information quality	*Was the navigation information accurate, clear, and helpful (high) or vague and unhelpful (low)?*	Quality and usefulness of navigational data
	Familiarity with the situation	*Were you familiar with the problems and dynamic changes during navigation (high) or unfamiliar (low)?*	Familiarity with navigation scenarios and challenges
	Information quantity	*Was the information obtained from navigation sources sufficient (high) or inadequate (low)?*	Quantity of usable navigational data

The scores obtained from individual items are aggregated to form three subtotal scores:

- SDD: the sum of DD scores,
- SDS: the sum of DS scores, and
- SDU: the sum of DU scores.

These subtotal scores are then used to compute the overall SART score using Eq. (2) (Taylor & Selcon, 1994).

$$\text{SART} = \text{SDU} - (\text{SDD} - \text{SDS}) \quad (2)$$

2.3 Nordic occupational safety climate questionnaire (NOSACQ-50)

The NOSACQ-50 is a validated multidimensional tool to assess SC, especially in high-risk industries (Kalteh et al., 2021; Kartoglu et al., 2023a). Developed by a team of Scandinavian occupational safety experts, it contains seven dimensions that represent both managerial and worker perspectives (Kines et al., 2011):

- Management’s safety priority, commitment, and competence (MSPCC),
- Management’s safety empowerment (MSE),
- Management’s safety justice (MSJ),
- Workers’ safety commitment (WSC),
- Workers’ safety priority and risk non-acceptance (WSPRNA),
- Safety communication, learning, and trust in co-workers’ safety competence (SCLT),
- Trust in the efficacy of safety systems (TESS).

The NOSACQ-50 comprises 50 items rated on a 4-point Likert scale ranging from “strongly disagree” (1) to “strongly agree” (4), with 29 items positively worded and 21 negatively worded. The dimension average score (DAS) for each category is computed by summing the individual item scores within that dimension, adjusted according to the polarity of the item, and dividing by the total number of valid responses for that dimension (NAQ). To ensure reliability, dimension scores are only calculated when participants respond to at least 50 % of the items in that dimension (Det Nationale Forskningscenter for Arbejdsmiljø, 2024a). The overall NOSACQ-50 score is derived by averaging the DAS values across all seven dimensions, as shown in Eq. (3)-(10).

$$\text{MSPCC DAS} = \frac{[\text{Q1} + \text{Q2} + (5 - \text{Q3}) + \text{Q4} + (5 - \text{Q5}) + \text{Q6} + \text{Q7} + (5 - \text{Q8}) + (5 - \text{Q9})]}{\text{NAQ}} \quad (3)$$

$$\text{MSE DAS} = \frac{[\text{Q10} + \text{Q11} + \text{Q12} + (5 - \text{Q13}) + \text{Q14} + (5 - \text{Q15}) + \text{Q16}]}{\text{NAQ}} \quad (4)$$

$$\text{MSJ DAS} = \frac{[\text{Q17} + (5 - \text{Q18}) + \text{Q19} + \text{Q20} + (5 - \text{Q21}) + \text{Q22}]}{\text{NAQ}} \quad (5)$$

$$\text{WSC DAS} = \frac{[\text{Q23} + \text{Q24} + (5 - \text{Q25}) + (5 - \text{Q26}) + \text{Q27} + (5 - \text{Q28})]}{\text{NAQ}} \quad (6)$$

$$\text{WSPRNA DAS} = \frac{[(5 - \text{Q29}) + (5 - \text{Q30}) + (5 - \text{Q31}) + (5 - \text{Q32}) + \text{Q33} + (5 - \text{Q34}) + (5 - \text{Q35})]}{\text{NAQ}} \quad (7)$$

$$\text{SCLT DAS} = \frac{[\text{Q36} + \text{Q37} + \text{Q38} + \text{Q39} + \text{Q40} + (5 - \text{Q41}) + \text{Q42} + \text{Q43}]}{\text{NAQ}} \quad (8)$$

$$\text{TESS DAS} = \frac{[\text{Q44} + (5 - \text{Q45}) + \text{Q46} + (5 - \text{Q47}) + \text{Q48} + (5 - \text{Q49}) + \text{Q50}]}{\text{NAQ}} \quad (9)$$

$$\text{NOSACQ-50} = \frac{(\text{MSPCC DAS} + \text{MSE DAS} + \text{MSJ DAS} + \text{WSC DAS} + \text{WSPRNA DAS} + \text{SCLT DAS} + \text{TESS DAS})}{7} \quad (10)$$

2.4 Data collection

This study employed purposive (intentional) and snowball (chain-referral) sampling techniques to recruit certified HSC navigators operating under the Turkish flag. Invitations were distributed via professional maritime networks and institutional contacts. The inclusion criteria required participants to hold active certification and possess recent operational experience in HSC navigation. Data collection was conducted between 1 June and 31 December 2024. A total of 38 navigators were invited, and all accepted the invitation to participate, resulting in a 100 % response rate. Prior to data collection, participants were informed of the study’s purpose and voluntarily provided informed consent. Participants were scheduled for interviews by the research team and did not self-select the response mode.

To ensure consistency in data collection, all navigators responded to the same structured web-based questionnaire. The researcher conducted the interview and simultaneously entered the participants’ responses directly into the digital form. This approach ensured that all data, regardless of collection circumstances, were recorded through the same online instrument, eliminating methodological discrepancies. All participants used the same structured web-based form under the supervision of the researcher, ensuring methodological consistency across the sample. Therefore, no comparison between subgroups was required.

An official request was submitted to the Communication Center of the Presidency of the Republic of Türkiye in an effort to estimate the population size (PS) and calculate the necessary sample size (NSS) for the study. The request aimed to obtain the number of shipmasters and deck officers certified to operate HSCs within the Turkish Merchant Fleet. However, it was confirmed that such specific data were not available in the national registry. As an alternative, the number of HSCs in the Turkish Merchant Fleet was used as a proxy for estimation. According to official records, the fleet comprises 37 HSCs. Assuming that each vessel employs navigators across three operational shifts and one reserve shift, the total estimated population size was calculated as 148 navigators.

The NSS was determined using Eq. (11) (Krejcie & Morgan, 1970), with the population proportion (PP) assumed at 99 %, a χ^2 value of 3.84 corresponding to a 95 % confidence level, and a margin of error (d) set at 0.05 (Field, 2018). The sample size was determined to estimate MWL, SA, and SC perceptions with a high expected agreement rate (PP = 0.99), using a 5 % margin of error as the minimal relevant difference. Under these parameters, the minimum required sample size was calculated to be 14. A total of 38 Turkish HSC navigators participated in the study, thus exceeding the minimum sample size and providing a representative sample of the estimated population within the Turkish Merchant Fleet.

$$\text{NSS} = \frac{\chi^2 \times \text{PS} \times \text{PP} \times (1 - \text{PP})}{[d^2 \times (\text{PS} - 1)] + [\chi^2 \times \text{PP} \times (1 - \text{PP})]} \quad (11)$$

3. Results

Data analysis was performed using IBM SPSS Statistics version 25.0. All raw data are openly accessible on Mendeley Data (https://doi.org/10.17632/hm6c9b8y5v.2), supporting transparency and reproducibility.

3.1 Validity and reliability analysis

Construct validity for the RNASA-TLX was not assessed via exploratory factor analysis, as each dimension corresponds to a single item. However, internal consistency was examined, yielding a Cronbach's α of 0.58 for weightings and 0.88 for ratings. While the alpha value for weightings is relatively low, it remains within the acceptable range for exploratory studies employing brief scales, and the rating dimension demonstrates strong reliability consistent with psychometric standards in behavioral research (Field, 2018).

For the SART, exploratory factor analysis with varimax rotation yielded satisfactory sampling adequacy (KMO = 0.73; Bartlett's χ^2 (45) = 259.13, p = 0.00), revealing three factors that explained 77.23 % of the total variance. The item structure remained consistent with previous validations (Bolton et al., 2022; Chen et al., 2023). The Cronbach's α values for the three dimensions-DD, DS, and DU-were 0.86, 0.77, and 0.93, respectively, demonstrating strong psychometric robustness (Field, 2018).

The NOSACQ-50 retained its seven-factor structure, accounting for 72.35 % of variance. Despite the non-positive definite matrix limiting KMO/Bartlett testing, internal consistency across dimensions remained robust (**Table 4**), with minor variations attributed to sample homogeneity (Field, 2018).

Table 4 Cronbach's α values for NOSACQ-50 dimensions.

Dimension	Cronbach's α
Management's safety priority, commitment, and competence	0.80
Management's safety empowerment	0.83
Management's safety justice	0.77
Workers' safety commitment	0.88
Workers' safety priority and risk non-acceptance	0.70
Safety communication, learning, and trust in co-workers' safety competence	0.90
Trust in the efficacy of safety systems	0.91

3.2 Descriptive statistics

All respondents held oceangoing master (unlimited) certifications and were actively serving as shipmasters on board HSCs at the time of data collection. A summary of their demographic characteristics is provided in **Table 5**.

Table 5 Descriptive statistics of demographic variables.

Demographic variable		Frequency	%
Gender	Male	38	100
Age	30-39	8	21
	40-49	27	71
	≥ 50	3	8
Marital status	Married	35	92
	Single	3	8

Table 5 (continued) Descriptive statistics of demographic variables.

Demographic variable		Frequency	%
Educational background	Bachelor's degree	33	87
	Master's degree	3	8
	Doctorate	2	5
Total seafaring experience	5-9 years	2	5.3
	10-14 years	9	23.7
	15-19 years	8	21.1
	≥ 20 years	19	50.0
Experience with current certificate of competence	< 5 years	7	18.4
	5-9 years	11	28.9
	10-14 years	11	28.9
	15-19 years	6	15.8
	≥ 20 years	3	7.9
Experience at current company	< 5 years	14	36.8
	5-9 years	11	28.9
	10-14 years	8	21.1
	15-19 years	2	5.3
	≥ 20 years	3	7.9
Type of HSC operated	Only HSC catamaran passenger ship	29	76.3
	Both HSC catamaran passenger ship and ferry	9	23.7
Experience on HSC catamaran passenger ship	< 5 years	18	47.4
	5-9 years	12	31.6
	10-14 years	5	13.2
	15-19 years	3	7.9
Experience on HSC catamaran passenger ferry	No experience	29	76.3
	< 5 years	5	13.2
	5-9 years	2	5.3
	10-14 years	1	2.6
	15-19 years	1	2.6

The mean overall score for MWL was 82.27 (*SD* = 21.14). Across the six subdimensions of the RNASA-TLX, the highest mean was observed in VD, followed by MD, FL, TD, and E. The lowest mean score was recorded for AD (**Figure 1**).

The average score for SA was 22.21 (*SD* = 8.73). Among its three components, DS showed the highest mean value, followed by DU and DD (**Figure 2**).

SC yielded a mean score of 2.87 (*SD* = 0.41). Among the seven SC dimensions, TESS had the highest average score, while MSJ had the lowest (**Figure 3**).

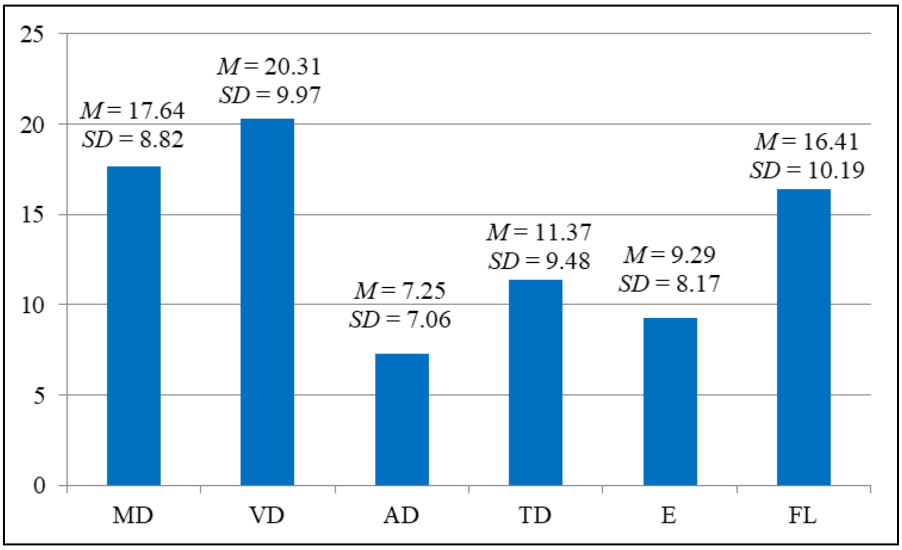

Figure 1 Average scores across RNASA-TLX dimensions.

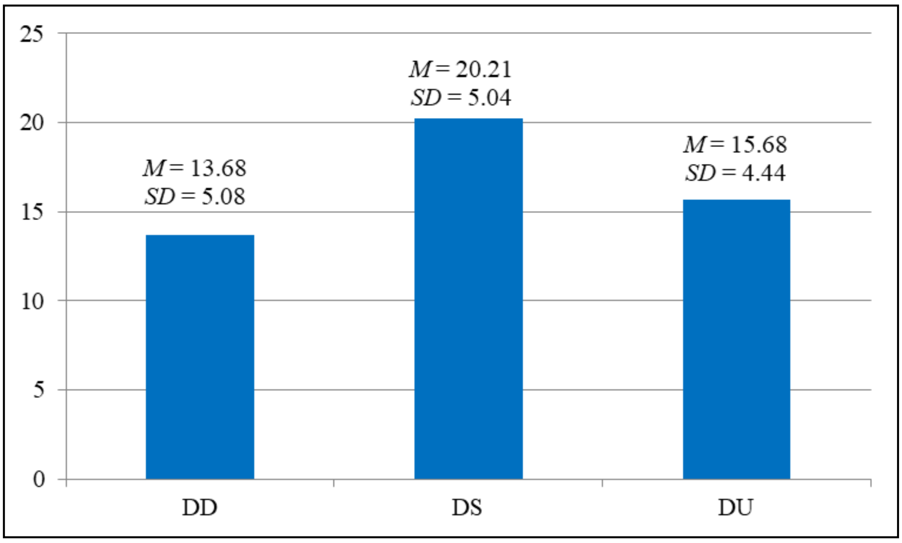

Figure 2 Average scores across SART dimensions.

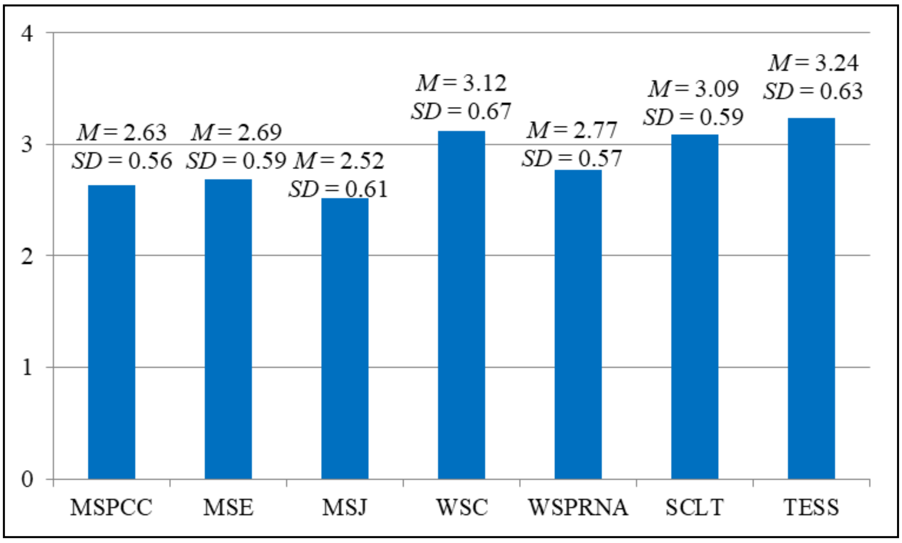

Figure 3 Average scores across NOSACQ-50 dimensions.

3.3 Analysis of difference

To assess group-level differences, preliminary normality tests were performed using the Shapiro-Wilk test. The variables FL ($W(38) = 0.95$, $p = 0.11$), SART ($W(38) = 0.98$, $p = 0.59$), NOSACQ-50 ($W(38) = 0.98$, $p = 0.60$), MSPCC ($W(38) = 0.95$, $p = 0.10$), MSJ ($W(38) = 0.98$, $p = 0.64$), and WSPRNA ($W(38) = 0.97$, $p = 0.45$) followed a normal distribution. However, the remaining variables, including all categorical data, violated the assumptions of normality ($p < 0.05$ for all). Therefore, the Kruskal-Wallis H test, a non-parametric alternative to Analysis of Variance, was employed to examine differences across groups. Where statistically significant differences were found, Mann-Whitney U tests were conducted as post hoc analyses, with Bonferroni correction applied to adjust for multiple comparisons (Field, 2018).

To aid interpretability and align with recent methodological recommendations (Det Nationale Forskningscenter for Arbejdsmiljø, 2024b), continuous scores for RNASA-TLX (MWL), SART (SA), NOSACQ-50 (SC), and their respective dimensions were recoded into ordinal categories based on threshold-based classification criteria, as shown in **Table 6**.

Table 6 Recoding of RNASA-TLX, SART, NOSACQ-50, and dimension scores.

Data	Score range	Level	Description
MD, VD, AD, TD, E, FL	0.00-8.33	1	Very low
	8.34-16.66	2	Low
	16.67-24.99	3	Optimum
	25.00-33.33	4	High
RNASA-TLX	0-24	1	Very low
	25-49	2	Low
	50-74	3	Optimum
	75-100	4	High
DD, DU	3-7	1	Very low
	8-12	2	Low
	13-17	3	Good
	18-21	4	Very good
DS	4-9	1	Very low
	10-15	2	Low
	16-21	3	Good
	22-28	4	Very good
SART	-14-0	1	Very low
	1-15	2	Low
	16-30	3	Good
	31-46	4	Very good
MSPCC, MSE, MSJ, WSC, WSPRNA, SCLT, TESS, NOSACQ-50	1.00-2.69	1	Very low
	2.70-2.99	2	Low
	3.00-3.30	3	Good
	3.31-4.00	4	Very good

The results revealed a significant difference in MWL levels across groups defined by DU ($H(3) = 8.87$, $p = 0.031$). Further analysis indicated that navigators with very good DU levels ($Mdn = 4.00$) experienced significantly higher MWL compared to those with low DU levels ($Mdn = 3.50$,

$U = 21.00$, $p = 0.005$, $r = -0.62$). However, no significant differences were detected in the other DU-based pairwise comparisons ($p > 0.008$).

A significant effect was also observed in the influence of MSPCC levels on SA ($H(3) = 13.36$, $p = 0.004$). Post hoc comparisons revealed that participants with very low MSPCC ($Mdn = 3.00$, $U = 4.00$, $p = 0.000$, $r = -0.68$) and low MSPCC ($Mdn = 3.00$, $U = 0.00$, $p = 0.007$, $r = -0.89$) demonstrated significantly higher SA than those with very good MSPCC levels ($Mdn = 2.00$). No significant differences emerged between other MSPCC level combinations (all $p > 0.008$).

3.4 Analysis of correlation

Given that the majority of variables did not satisfy the assumptions of normality, Kendall's tau-b correlation coefficient was utilized to evaluate the strength and direction of associations between MWL, SA, and SC, as well as their respective dimensions (Field, 2018). The analysis identified multiple statistically significant correlations.

A positive correlation was found between overall MWL and the SA subdimensions DS ($\tau = 0.198$, $p = 0.044$) and DU ($\tau = 0.267$, $p = 0.011$). MD was also positively associated with DU ($\tau = 0.243$, $p = 0.022$), while VD correlated positively with DS ($\tau = 0.271$, $p = 0.011$). Additionally, TD exhibited a positive correlation with overall SA scores ($\tau = 0.293$, $p = 0.006$).

Conversely, multiple negative correlations emerged between SC perceptions and MWL dimensions. Specifically, MSPCC was negatively associated with overall MWL ($\tau = -0.306$, $p = 0.005$), MD ($\tau = -0.249$, $p = 0.020$), and FL ($\tau = -0.220$, $p = 0.033$). MD was also inversely correlated with WSC ($\tau = -0.208$, $p = 0.047$), In addition, higher overall MWL was associated with lower MSJ ($\tau = -0.235$, $p = 0.024$). A similar negative relationship was observed between MSE and MD ($\tau = -0.222$, $p = 0.035$), as well as between MD and overall NOSACQ-50 scores ($\tau = -0.228$, $p = 0.026$).

Positive correlations were observed between SA and two key SC dimensions: WSC ($\tau = 0.293$, $p = 0.008$) and SCLT ($\tau = 0.264$, $p = 0.013$). Both WSC and SCLT demonstrated significant positive associations with the SA subdimension DS ($\tau = 0.293$, $p = 0.008$; $\tau = 0.224$, $p = 0.031$, respectively). Lastly, a positive correlation was observed between SART and TESS ($\tau = 0.245$, $p = 0.021$).

Although the regression analyses did not yield statistically significant predictive relationships between MWL, SA, and SC, the bivariate analyses, encompassing both correlation and group-difference tests, offer valuable exploratory insights into their interrelationships. Rather than aiming to establish causality or prediction, these analyses help visualize trends, detect covariation patterns, and identify group-level distinctions based on categorical variables. In high-demand operational contexts such as HSC navigation, where cognitive, situational, and organizational factors interact in complex ways, such exploratory techniques are essential for mapping the structure of underlying relationships. Additionally, the results from these analyses provide empirical grounding that supports and contextualizes the subsequent regression modelling. Accordingly, both correlation- and difference-based analytical stages were retained to ensure a thorough and multidimensional examination of the constructs.

3.5 Analysis of regression

To explore the potential explanatory relationships among MWL, SA, and SC, a multinomial logistic regression analysis was performed using recoded ordinal values of RNASA-TLX (MWL), SART (SA), and NOSACQ-50 (SC), as outlined in **Table 6**. Given the ordinal structure of the data and the absence of distributional normality, this approach was deemed appropriate for capturing potential multivariate associations (Field, 2018).

A set of regression models was tested, assessing both bivariate and trivariate relationships between the variables. The results of the model fitting procedures and associated goodness-of-fit statistics are presented in **Table 7**, including *p*-values from Pearson and deviance tests where applicable.

Table 7 Summary of *p*-values for "Model Fitting Information" and "Goodness of Fit".

Dependent variable	Predictor(s)	Model fitting (*p*)	Goodness of fit	
			Pearson (*p*)	Deviance (*p*)
NOSACQ-50	RNASA-TLX and SART	0.227	0.542	0.410
SART	RNASA-TLX and NOSACQ-50	0.368	0.543	0.410
RNASA-TLX	SART and NOSACQ-50	0.750	0.890	0.805
RNASA-TLX	SART	0.723	-	-
RNASA-TLX	NOSACQ-50	0.406	-	-
SART	RNASA-TLX	0.723	-	-
SART	NOSACQ-50	0.125	-	-
NOSACQ-50	SART	0.125	-	-
NOSACQ-50	RNASA-TLX	0.406	-	-

The statistical analysis yielded no significant relationships between the variables across all model configurations. The *p*-values associated with model fitting and goodness-of-fit tests exceeded conventional significance thresholds, indicating that MWL, SA, and SC lack predictive or explanatory power over one another in the context examined.

4. Discussion

The mean overall MWL was high, suggesting significant cognitive demands placed on HSC navigators during bridge operations. A positive association between visual demand and attentional supply underscores the reliance of HSC navigators on visual cues, both external (e.g., other vessels, weather conditions) and internal (e.g., ARPA, ECDIS, AIS), for maintaining environmental awareness and resolving navigational complexity. This is in line with findings from maritime ergonomics studies that emphasize the centrality of visual processing in time-sensitive bridge operations (Mallam et al., 2024; Stopa, 2024).

Self-perceived SA yielded a relatively high overall mean score, indicating that participants generally perceived themselves as situationally aware during HSC navigation. SA was positively correlated with temporal demand, suggesting that time pressure, often associated with traffic density or adverse weather, may intensify navigators' cognitive engagement. This reflects a trade-off frequently reported in the literature, where heightened time awareness contributes to SA (Tan & Zhang, 2025; Tang et al., 2024), although prolonged exposure can impair decision-making quality.

The low mean NOSACQ-50 score is a critical finding, indicating potential areas for improvement. Mental demand was negatively correlated with both management's safety justice and overall NOSACQ-50 scores, implying that fairness perceptions and strong SC are linked to reduced mental burden. This pattern aligns with evidence that trust in leadership and transparent safety procedures buffer against psychological strain in operational environments (Hayes-Mejia & Stafström, 2023; Kaya & Yorulmaz, 2023).

Further analysis of group-level differences revealed that navigators with exceptionally strong situational understanding reported notably higher MWL. This interpretation is supported by recent studies demonstrating that high SA, particularly in data-rich and high-tempo environments such as HSC navigation, can elevate mental effort unless appropriately mitigated by supportive system design (Loft et al., 2025; Lopes et al., 2024; Nizar et al., 2024).

Converging with this, correlation analyses revealed positive associations between MWL and both understanding of the situation and attentional supply. These findings reinforce the view that sustained vigilance and the continuous integration of dynamic information impose a considerable cognitive burden on navigators. Similar patterns have been documented across various safety-critical domains, including maritime operations, aviation, and clinical environments, where elevated situational demands are often linked to increased MWL (Múller-Plath et al., 2023; van de Merwe et al., 2024). In this context, operational strategies such as suppressing non-essential auditory and visual stimuli during peak workload periods- aligned with IMO human element principles- are crucial for mitigating cognitive overload and preserving decision-making capacity.

Conversely, a paradoxical inverse relationship emerged between perceived management safety priority and SA levels. Navigators perceiving lower managerial safety commitment reported higher SA, suggesting that reduced oversight may trigger greater personal alertness and accountability. This finding aligns with recent evidence in leadership and safety commitment research, demonstrating that when managers' safety commitment is perceived as weak, frontline workers often heighten their own situational vigilance to compensate (Levovnik et al., 2024; Xi et al., 2025).

At the same time, a clear protective function of perceived safety leadership was evident in its negative correlations with MWL, mental demand, and frustration level. These results emphasize the mitigating role of safety-oriented leadership in reducing mental strain, anxiety, and fatigue (Huang et al., 2024; Tawfik et al., 2023). Furthermore, mental demand was inversely related to both workers' safety commitment and management's safety empowerment, underscoring the cognitive relief provided by open dialogue, shared responsibility, and participatory practices in safety-related decisions.

The findings also indicate that positive SC perceptions- particularly regarding safety communication, learning, trust in co-workers' safety competence and workers' safety commitment- are associated with higher SA and attentional supply. These associations support the argument that trust-based and cooperative bridge environments foster better awareness and responsiveness to navigational complexity (Chubala et al., 2023; Misas et al., 2024). Notably, trust in electronic safety systems also positively correlated with SA, suggesting that confidence in human-machine interaction enhances cognitive readiness, a view consistent with recent research advocating for robust system design and user training (Walters, 2023; Westin & Lundberg, 2025).

However, despite these observed bivariate associations, the regression analyses yielded no statistically significant predictive relationships among MWL, SA, and SC. Across all model configurations- whether considering composite indices or inter-variable predictors- the *p*-values consistently exceeded conventional significance thresholds. This outcome implies that while MWL, SA, and SC are meaningfully interrelated at a correlational level, they do not serve as reliable predictors for one another when modeled using multinomial logistic regression.

Such an outcome points to the complex, potentially non-linear nature of cognitive and cultural influences on navigation performance. As HSC navigation involves rapidly evolving operational conditions, context-sensitive behavioral responses, and latent organizational variables, it is possible that traditional regression models are insufficient to fully articulate these multifaceted relationships. Future studies employing longitudinal or simulation-based data and using advanced multivariate techniques may better delineate the causal pathways between these constructs. Similar perspectives have been adopted in domains such as air traffic management and nuclear plant operations, where systemic interactions and latent human factors are more accurately modeled using holistic frameworks (Dai et al., 2023; Krasnopevtseva et al., 2025).

These results collectively demonstrate that bridge crew performance in HSC operations is influenced not only by task design and system interaction, but also by deeper organizational and psychosocial dynamics. Understanding and optimizing this interplay is essential for improving resilience, situational effectiveness, and, ultimately, navigational safety.

This study offers several methodological strengths. Domain-specific adaptations of established tools (RNASA-TLX, SART, and NOSACQ-50) improved construct validity and ensured relevance to HSC operations. The multidimensional focus on MWL, SA, and SC enabled a holistic assessment of bridge crew performance. The structured, interviewer-assisted data collection approach promoted response consistency and mitigated interpretation-related variability.

Nonetheless, some limitations should be noted. Reliance on self-reported data may introduce subjectivity and limit real-time accuracy. The sample, limited to Turkish HSC navigators, constrains generalizability, and the focus on high-speed passenger vessels reduced operational variability. Finally, the cross-sectional design prevents causal inference.

5. Conclusions

This study underscores the multifaceted nature of bridge crew performance in HSC operations, highlighting how mental workload, situational awareness, and safety culture co-exist within complex cognitive and organizational ecosystems, using a combination of descriptive, correlational, and regression-based analyses. Rather than seeking singular causality, the findings prompt a broader recognition that safe navigation emerges from the alignment of human, technological, and managerial systems.

The interplay between visual demand and attentional engagement illustrates that information-rich environments require not only perceptual acuity, but also thoughtful system design, to mitigate overload. Similarly, perceptions of organizational safety priorities were shown to influence situational responsiveness, suggesting that cultural conditions on board, though often intangible, hold tangible consequences for real-time decision-making.

These insights advocate for a shift toward more dynamic models of navigational performance assessment that transcend linear cause-effect assumptions. Enhancing bridge safety in HSC contexts may require more than training or system upgrades; it necessitates fostering resilient safety cultures, designing cognitively ergonomic interfaces, and promoting collaborative crew dynamics.

As maritime operations continue to evolve with increasing digital complexity and time pressure, future research and practice must consider how to sustain cognitive readiness and trust in safety-critical systems. A deeper understanding of the interconnected drivers of operator performance can support not only safer voyages, but also more adaptive and human-centered navigation systems.

To advance this objective, future research should expand the sample to include navigators from diverse nationalities, vessel types, and operational settings, thereby improving the generalizability of findings. Longitudinal designs and simulation-based observations, supported by real-time behavioral and physiological data, would offer deeper insight into the dynamic nature of navigation. Triangulating subjective assessments with objective indicators, such as eye-tracking or performance logs, would enhance measurement validity. Moreover, advanced analytical methods, including structural equation modelling or machine learning, could more effectively capture the complex, non-linear relationships among MWL, SA, and SC. These approaches would support the development of adaptive, evidence-based strategies to improve bridge crew safety and performance in high-speed maritime contexts.

Subsequent investigations should aim to broaden the sample scope by including diverse vessel types and multicultural crews. Incorporating objective physiological or behavioral metrics alongside subjective assessments would provide a richer and more triangulated understanding of cognitive and organizational performance. Finally, applying advanced multivariate techniques, such as structural equation modeling, or machine learning, could better capture the nonlinear dynamics and mediating effects that characterize high-risk maritime operations. Such efforts would contribute to the development of evidence-based interventions aimed at optimizing navigator performance and safety in high-speed maritime operations.

Ethical standards

All procedures involving human participants were conducted in accordance with institutional and national ethical standards, as well as the ethical principles outlined in the Declaration of Helsinki.

Ethical approval for the study was granted by the Humanities and Social Sciences Committee of Human Research Ethics at Istanbul Technical University (Approval No: 193).

CRediT author statement

Cem Kartoglu: Conceptualization; Methodology; Software; Validation; Formal analysis; Investigation; Writing-Original Draft; Visualization. **Yunus Emre Senol**: Resources; Data Curation; Writing-Review & Editing. **Serdar Kum**: Supervision; Project administration.

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