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Navigating Mental Workload and Safety Performance in Air Traffic Control: The Mediating Roles of Psychological Safety and Situational Awareness

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ABSTRACT

Purpose – This study aims to elucidate a comprehensive structural framework governing the safety performance (SP) of active Air Traffic Control (ATC) personnel in Indonesia. Specifically, it investigates the underlying mechanisms by examining how psychological safety (PCS) and situational awareness (SA) collectively and concurrently mediate the relationship between operational mental workload (MW) and overall safety performance (SP).
Design/methodology/approach – A quantitative, cross-sectional survey design was deployed, targeting ATCs across three distinct operational sectors: Aerodrome Control Tower, Approach Control Unit, and Area Control Center within high-density traffic ANSP facilities. Data collected from 204 certified personnel were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM).
Finding/Results – Empirical results reveal that MW has a significant negative direct effect on both PCS and SA, whereas both constructs directly enhance SP. Intriguingly, the direct relationship between MW and SP is non-significant. Instead, the results establish an indirect-only (full) mediation model; MW impairs SP entirely through two parallel socio-cognitive pathways: the interpersonal-psychological pathway (via PCS) and the cognitive processing pathway (via SA).
Originality/Value – This study challenges traditional linear models by demonstrating that MW impacts SP solely through mediating mechanisms. By uniquely integrating Cognitive Load Theory and the Job Demands-Resources framework within high-risk ATC operations, this research highlights that mitigating operational risk requires a dual-systemic strategy that simultaneously guards controller cognition and fosters individual psychological fortitude.

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1. Introduction

Global aviation growth is accelerating substantially. The International Air Transport Association (IATA) projects a 4.9% increase in global passenger traffic, with the Asia-Pacific region leading at 7.3% (IATA, 2025). Consequently, managing air traffic safely and efficiently has become a paramount priority. Air Traffic Controllers (ATCs) play a critical role in maintaining required separation minima and responding to abnormal situations within the airspace (B. Liu et al., 2026). Data from the Indonesian National Transportation Safety Committee (NTSC) revealed 48 accidents and 57 serious incidents between 2021 and 2025, signaling an urgent need to enhance safety performance across various dimensions. Notably, four safety recommendations from this data were explicitly directed at the Indonesian Air Navigation Services Provider (ANSP). Across these reports, human **error** remains contributing factor, accounting for 70% of the occurrences ((NTSC), 2025; D. Guo et al., 2025). Rising traffic demand inherently escalates operator workload (Cui et al., 2026). In aviation operations, particularly within the ATC context, task demand serves as a primary determinant of the attention and perception required for effective decision- making (Francisco et al., 2024; B. Liu et al., 2026), Elevated ATC workload demands stricter adherence to separation standards to maintain high safety performance Simultaneously, the surge in flight density increases potential conflicts, thereby intensifying the cognitive demands, known as mental workload (Alaydi & Ng, 2024). Nonetheless, empirical evidence indicates that mental workload is negatively correlated with ATC performance (Pang et al., 2023).

Situational awareness is conceptually defined as the cognitive capacity to process information to predict or anticipate future operational events (ICAO, 2022). Prior empirical evidence indicates that the interplay between situational awareness and workload exerts a substantial influence on the safety performance of air traffic control (Edwards & Field, 2016). Concurrently, psychological safety represents a workplace dynamic wherein a secure environment empowers personnel to execute risk-calculated decisions without fear of negative repercussions (Hata et al., 2026). In the context of ATC operations, establishing psychological safety is critical to optimizing performance, as it effectively mitigates human error while fostering heightened safety standards (Newman et al., 2017). Empirically, psychological safety has been shown to cultivate a robust safety culture, enhance work engagement, and minimize occupational incidents (Hata et al., 2026). Furthermore, it serves as a potent mediator between supportive coaching behavior and overall performance (Sakallı et al., 2026). While academic literature extensively explores the direct relationship between workload and safety performance, scholarly investigations evaluating psychological safety and situational awareness as dual mediators within the nexus of ATC workload and safety performance remain critically scarce.

This study aims to elucidate a comprehensive framework regarding the evolution of Air Traffic Control (ATC) safety performance in Indonesia, specifically examining the underlying mechanisms of mental workload as influenced by psychological safety and situational awareness. To address this objective, the research addresses two overarching questions:

(1) To what extent do mental workload, psychological safety, and situational awareness directly affect safety performance within ATC operations?

(2) How do psychological safety and situational awareness collectively mediate the relationship between mental workload and operational safety performance in the ATC environment?

2. Literature Review & Hypothesis Development

Air Traffic Controllers (ATCs) bear the operational responsibility for all aircraft within their designated airspace, indirectly safeguarding millions of passengers whose lives depend on optimal safety performance to ensure secure and efficient flights (X. Li et al., 2025). In high-reliability organizations, safety performance is conceptually operationalized as safety behavior, which is further bifurcated into two primary dimensions: *safety compliance* and *safety participation*. Concurrently, mental workload represents a critical determinant of human performance, particularly within complex and highly dynamic socio-technical environments (Khan et al., 2026). The ATC profession is characterized by exceptional operational complexity, requiring simultaneous pilot communications, real-time coordination with adjacent sectors, and continuous traffic analysis to maintain airspace integrity (ICAO, 2016; Muñoz-de-escalona & Leva, 2024). To empirically quantify this construct, the NASA-Task Load Index (NASA-TLX) is widely utilized, capturing load perception and performance across six distinct subscales: *mental demand, temporal demand, physical demand, effort, frustration*, and *performance* (Hao et al., 2025). While traditional ergonomic scholarship frequently relies on multidimensional frameworks like NASA-TLX to quantify operator strain across six generic indicators, contemporary aviation research emphasizes the need for domain-tailored metrics (Alaydi & Ng, 2024; Rubio-valdehita et al., 2017). In safety-critical aviation environments, the nature of task load is predominantly mental and emotional rather than somatic. Air traffic controllers execute duties within a highly automated, sedentary environment where physical workload plays a minimal role in operational success or degradation (Pang et al., 2023).

Consequently, recent empirical paradigms adapt specialized inventories—such as the CarMen-Q metric—to isolate the primary psychological drivers of controller strain. By focusing on cognitive, temporal, performance, and emotional demands, the construct captures the severe information-processing requirements, rapid decision-making windows, error-intolerant environments, and post-shift psychological fatigue without confounding the analysis with irrelevant physical exertion parameters

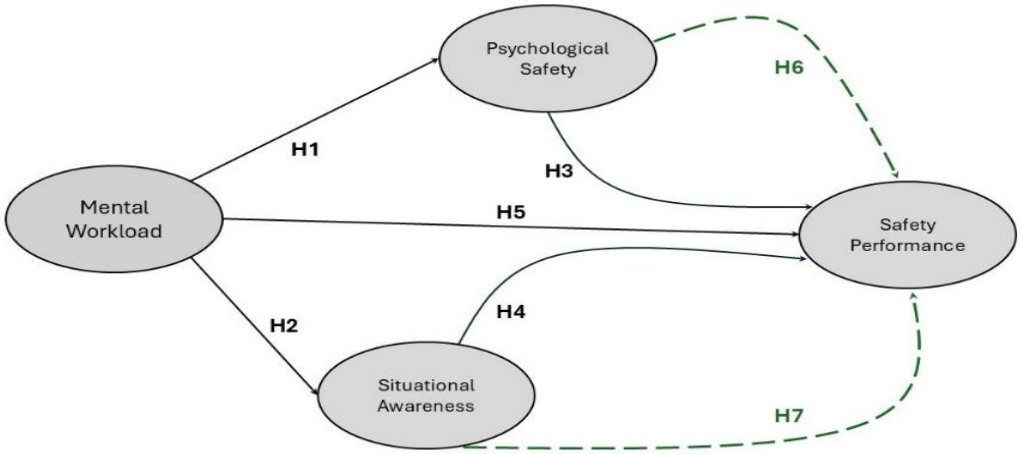
When an ATC's mental workload breaches optimal thresholds, it triggers a severe degradation in working memory capacity. This cognitive saturation directly impairs the *comprehension* and *projection* dimensions of situational awareness, ultimately leading to performance degradation (Muñoz-de-escalona & Leva, 2024). Beyond cognitive limits, organizational climate plays a critical role. Psychological safety is defined as a shared belief that the workplace environment is secure enough to allow interpersonal risk-taking, enabling personnel to voice concerns or admit mistakes without fear of adverse repercussions (R. Li & Zhang, 2026).

While psychological safety can be conceptualized as a collective unit-level climate, this study explicitly focuses on perceived individual-level psychological safety. Grounded in recent high-reliability organization (HRO) and aviation literature (Biedermann et al., 2024; Dong et al., 2024; Read & Charles, 2018) psychological safety fundamentally operates through an individual's cognitive processing of interpersonal risks. In Air Traffic Control (ATC) environments, system safety relies heavily on real-time micro-decisions and immediate error reporting by individual controllers facing variable sector workloads (Gu & Wang, 2026; L. Wang & Zhu, 2026; Xiong et al., 2023) Therefore, operationalizing psychological safety as an individual perception provides a robust and methodologically valid framework to examine how personal psychological states shape individual safety performance (Amoadu et al., 2023; N. Guo et al., 2025; Uddin, 2025).

Within ATC operations, psychological safety serves as a cornerstone for cultivating a robust safety culture; it creates a supportive atmosphere that eliminates fear when human errors occur

during separation management, thereby fostering proactive safety participation. However, empirical evidence indicates that escalating mental workload induces acute occupational stress, which conversely erodes psychological safety, establishing a significant negative correlation between the two constructs (Han, 2026). Consequently, when a controller experiences excessive cognitive overload, their psychological safety is heavily compromised, constructing a barrier that inhibits open communication and obstructs continuous safety performance optimization.

Figure 1. Conceptual Framework



Based on the theoretical framework developed above, the following hypotheses are proposed based on Figure 1 :

H_1: MW exerts a significant negative effect on PCS.
H_2: MW exerts a significant negative effect on SA.
H_3: PCS exerts a significant positive effect on SP.
H_4: SA exerts a significant positive effect on SP.
H_5: MW exerts a significant negative effect on SP.
H_6: PCS significantly mediates the relationship between MW and SP.
H_7: SA significantly mediates the relationship between MW and SP.

3. Methodology

This study employs a quantitative approach utilizing a cross-sectional survey design, which was administered via an online survey platform. To empirically evaluate the proposed hypotheses, Partial Least Squares Structural Equation Modeling (PLS-SEM) was adopted as the primary statistical method for data analysis and structural estimation (Gonzales et al., 2026). The analytical procedure was executed sequentially. Initially, the measurement model was assessed to determine the predictive capabilities and psychometric properties of the safety performance constructs in alignment with the other latent variables. Subsequently, the analysis focused on validating the structural paths to ascertain the specific mediating mechanisms exerted by psychological safety and situational awareness within the established framework. Finally, the comprehensive PLS-SEM estimation was performed to conduct sample-specific path analysis grounded in the pre-defined theoretical configuration (Batuhan et al., 2026).

Data were collected using a purposive sampling technique. To ensure data quality and relevance, specific inclusion criteria were established: participants had to be active, fully

licensed air traffic controllers currently assigned to operational duty (TWR, APP, or ACC), trainees and administrative-only personnel were excluded from the target population. Utilizing Google Forms, the questionnaire was disseminated nationwide across high-traffic ANSP facilities. The final sampling process yielded 204 active personnel who completed the survey, representing a net effective response rate of **91.48%** (sample target's 223 using Slovin's formula at a 5% margin of error) (Holtom et al., 2022; Wu et al., 2022), the characteristics of whom are thoroughly detailed in Table 1. To determine whether $N = 204$ was adequate for PLS-SEM estimation, Using GPower 3.1 with an effect size of 0.15, alpha level of 0.05, power of 0.80, and 3 predictors, the minimum required sample size was calculated to be 119. **Since the** final sample (N=204) exceeds this threshold, the study possesses adequate statistical power to detect meaningful structural effects.

Table 1. Demographic character of Sample

Criteria	**Character**	**Total**	**%**
Gender	- Male	118	57.8 %
	- Female	86	42.2 %
Age	- 21-30 Years old	78	38.2%
	- 31-40 Years old	66	32.3%
	- 41-50 Years old	49	24%
	- > 50 Years old	11	5.39%
Unit	- Tower	87	42.6%
	- APP	62	30.3%
	- ACC	55	26.9%
Working Experience	- 1 – 10 Years	75	36.7%
	- 11- 20 Years	68	33.3%
	- 21-30 years	45	22.05%
	- > 30 Years	16	7%

All constructs in this study were operationalized using established multi-item scales adapted from validated aviation and organizational literature. Responses were captured using a 5-point Likert scale, ranging from 1 (Strongly Disagree) to 5 (Strongly Agree), categorized into two distinct directional orientations to ensure response validity and mitigate common method variance. Specifically, the measurements for safety performance, psychological safety, and situational awareness deployed a *favorable* (positively anchored) and the mental workload construct utilized an *unfavorable* (reverse-anchored or negatively phrased scaling configuration. Conversely, Safety Performance (6 items): This variable was measured based on the dimensions of *safety compliance* and *safety contribution*, adapted from the framework established by (X. Li et al., 2025). Mental Workload (4 items): This construct evaluated the operational pressure on controllers across four core indicators: *cognitive demand, temporal demand, performance demand*, and *emotional demand*, drawing from validated scales by (Alaydi & Ng, 2024; Pang et al., 2023). Psychological Safety (4 items): Adapted from (Edmondson & Bransby, 2023), this scale captured the workplace interpersonal climate through four specific behavioral indicators: *getting things done, learning behaviors, improving the work experience*, and *perceived leadership*. Situational Awareness (3 items): This cognitive metric was operationalized based on the three chronological

dimensions of aviation situational awareness—*perception, interpretation*, and *projection*—adapted from (Kim et al., 2022; Samardžić et al., 2022) (see Table 2).

Table 2. Questionnaire

Variable	Questioners
Mental Workload *(cognitive demand, temporal demand, performance demand*, and *emotional demand)*	1. The task of monitoring and processing intricate airspace data forces me to exert excessive mental effort to maintain situational awareness. 2. The rapid operational pace mandated by dense flight schedules frequently exceeds my capacity to perform tasks comfortably 3. The absolute zero tolerance for operational errors in my position, creates intense pressure regarding the precision of my decisions 4. Managing high-risk traffic events consistently leaves me with severe mental fatigue that leaks into my personal life after shifts
Psychological Safety *(getting things done, learning behaviors, improving the work experience*, and *perceived leadership)*	1. I feel comfortable voicing operational safety concerns to my team during heavy air traffic conditions without fearing that my input will be dismissed 2. Within our ATC unit, I can openly report minor communication lapses (e.g., readback/hearback errors) or seek guidance without feeling judged by my peers 3. The interpersonal atmosphere in the control facility allows me to feel genuinely valued and comfortable collaborating with fellow controllers 4. Operational supervisors actively listen to my feedback regarding control procedures and support proactive solutions without taking a defensive stance
Situational Awareness *perception, interpretation*, and *projection*	1. I consistently maintain a complete visual and mental tracking of all aircraft positions, movement vectors, and environmental parameters within my assigned sector. 2. I swiftly synthesize incoming radar and communication data to understand how current flight dynamics impact overall airspace traffic flow 3. I accurately anticipate potential loss of separation, trajectory conflicts, and future traffic bottlenecks well before they occur.
Safety Performance *safety compliance* and *safety contribution*	1. I strictly adhere to standard operating procedures (SOPs) and separation minima during routine and unexpected air traffic scenarios. 2. I ensure that all readback/hearback verifications and phraseology protocols are executed flawlessly to maintain operational integrity 3. I consistently utilize mandatory safety equipment, automation tools, and checklist routines without taking shortcuts under time pressure. 4. I proactively report potential hazards, system vulnerabilities, and near-miss events to help prevent future operational risks.

	5. I actively share safety-related insights and lesson-learned operational practices with fellow controllers during shift handovers and debriefs 6. I voluntarily participate in safety initiatives, training refinements, and unit discussions aimed at elevating overall airspace safety standards.

Empirical data were processed and analyzed utilizing SmartPLS 3 software (Ammad et al., 2025a) through a rigorous two-stage analytical approach. The first stage involved the measurement model assessment to evaluate construct reliability and validity. Internal consistency and reliability were determined based on Cronbach's alpha and Composite Reliability (CR), with a threshold set at greater than 0.7 (Kiruthika & Geetha, 2026). Convergent validity was verified using the Average Variance Extracted (AVE), requiring values > 0.5, while discriminant validity was established using the Heterotrait-Monotrait (HTMT) ratio with a conservative criterion < 0.9 (Henseler et al., 2015).

The second stage comprised the structural model evaluation to test hypotheses H_1 through H_7. Potential multicollinearity issues among the latent constructs were monitored using the Variance Inflation Factor (VIF), applying a strict threshold < 5 (Hair Joe F. et al., 2016). The structural models strictly referred to as in-sample explanatory variance was determined via the coefficient of determination (R^2). To test the significance of both the direct paths and the specific mediating effects, a non-parametric bootstrapping procedure was executed with 5,000 resamples, with statistical significance determined at p < 0.(Batuhan et al., 2026; Kiruthika & Geetha, 2026).

The research protocol underwent ethical evaluation and received official clearance (NO. 111/Pus-PPM/IX/2026) from the Research and Community Service Center (PPM) of Politeknik Penerbangan Indonesia Curug on Sept 14, 2026. Because this study involved a survey of air traffic control personnel with negligible risk to participants, it strictly adhered to institutional ethical guidelines. To safeguard privacy, all responses were fully anonymized and kept strictly confidential.

4. Results and Discussion

4.1. Measurement Model Assessment

The initial step in evaluating the measurement model involves assessing data reliability and convergent validity against established threshold criteria, specifically requiring outer loadings > 0.70, Cronbach's alpha (α) > 0.70, and an Average Variance Extracted (AVE) > 0.50. As illustrated in Table *3*, the vast majority of indicators successfully met these statistical criteria. Although indicators Y_1 and Y_2 exhibited outer loadings < 0.70 threshold, they were retained in the model because the overall AVE of the respective construct remained well > 0.50, Composite Reliability (CR > 0.70) which satisfies the established methodological allowances for indicator retention (Hazirah et al., 2021; Saiz-alvarez et al., 2023). Substantively, both indicators capture non-negotiable core components of safety compliance in air traffic operations: Y1 measures strict adherence to Standard Operating Procedures (SOPs) and separation minima (Iwata et al., 2025), while Y2 evaluates precision in mandatory readback/hearback and phraseology protocols (Yang et al., 2023). Removing Y1 and Y2 would severely compromise the content validity of Safety Performance by stripping away its baseline compliance foundation and leaving the construct over-indexed on voluntary safety contributions. Given that the overall AVE for Safety

Performance comfortably exceeded 0.50 (AVE = 0.547) and Composite Reliability remained high (CR= 0.878), retaining Y1 and Y2 is methodologically sound and theoretically necessary.

Furthermore, discriminant validity was evaluated using two robust approaches. First, the Fornell-Larcker criterion presented inTable 4 demonstrates that the square root of the AVE for each construct (displayed diagonally) is consistently greater than its correlation coefficients with any other latent variables, thereby confirming adequate discriminant validity at the construct level. Second,Table 5 indicates that the Heterotrait-Monotrait (HTMT) ratio values across all pairs of constructs are strictly below the conservative threshold of 0.90. This empirical evidence firmly confirms the statistical distinctiveness of all theoretical constructs deployed in this study.

Table 3. Results of measurement model: Reliability and convergent validity

Construct	Indicator	Outer Loading	Cronbach's α	CR	AVE
Mental Workload (MW)	X1	0.881	0.901	0.931	0.771
	X2	0.891			
	X3	0.873			
	X4	0.868			
Psychological Safety (PCS)	Z1.1	0.849	0.861	0.905	0.706
	Z1.2	0.786			
	Z.1.3	0.887			
	Z1.4	0.855			
Situational Awareness (SA)	Z2.1	0.913	0.905	0.940	0.840
	Z2.2	0.912			
	Z.2.3	0.925			
Safety Performance (SP)	Y1	0.686	0.833	0.878	0.547
	Y2	0.637			
	Y3	0.774			
	Y4	0.799			
	Y5	0.775			
	Y6	0.755			

Note: CR= Composite Reliability; AVE= Average Variance Extracted

Table 4. Discriminant validity assessment: Fornell-Larcker criterion

Construct	1	2	3	4
Mental Workload (MW)	*0.878*			
Safety Performance (SP)	-0.610	*0.740*		
Psychological Safety (PCS)	-0.752	0.706	*0.840*	
Situational Awareness (SA)	-0.586	0.667	0.615	*0.916*

Note : Values on the diagonal (in italic) are the square root of the Average Variance Extracted (AVE).

Table 5. Discriminant validity assessment: Heterotrait-monotrait (HTMT) ratios

Construct	HTMT Value	2.5%	97.5%	Conclusion
MW – PCS	0.851	0.780	0.902	Valid
MW – SA	0.642	0.537	0.725	Valid
MW – SP	0.700	0.596	0.784	Valid

PCS – SA	0.691	0.546	0.792	Valid
PCS – SP	0.822	0.720	0.898	Valid
SA - SP	0.756	0.645	0.839	Valid

Note: All values must be below the recommended threshold of 0.90

Based on Table 5, The point estimate of HTMT between Mental Workload and Psychological Safety was 0.851. To rigorously confirm discriminant validity, a bootstrapping procedure (5,000 resamples) was executed to determine the 95% bias-corrected confidence interval. Because the upper bound of the confidence interval is strictly below 1.000 (Henseler et al., 2015), discriminant validity between mental workload and psychological safety is empirically established.

Table 6. Sensitivity Analysis

Path/ Relationship	**Model A (with Y1 & Y2)** (β)	**Model B (Without Y1 & Y2)** (β)	**Stability/ Impact**
H_1 (MW – PCS)	-0.752	-0.751	Stable
H_2 (MW – SA)	-0.586	-0.586	Stable
H_3 (PCS – SP)	0.421	0.372	Stable
H_4 (SA – SP)	0.357	0.359	Stable
H_5 (MW – SP)	-0.085	-0.052	Stable
H_6 (MW – PCS – SP)	-0.316	-0.280	Stable
H_7 (MW – SA – SP)	-0.209	-0.233	Stable

To empirically validate this decision, a sensitivity analysis was conducted comparing the structural model with and without these two indicators. As shown in Table 6, removing Y1 and Y2 resulted in negligible changes to the principal path coefficients ($\Delta\beta < 0.2$) and did not alter any hypothesis testing decisions. Therefore, Y1 and Y2 were retained in the final model to preserve content validity without compromising structural stability.

4.2. Structural Model Evaluation

To ensure that the structural framework satisfies the established evaluation thresholds, a two-step assessment of model fit and collinearity was conducted. First, the PLS algorithm yielded a Standardized Root Mean Square Residual (SRMR) value of 0.086. Adhering to the recommended fit criteria where values less than 0.08 to 0.10 indicate an acceptable fit (Ammad et al., 2025), this outcome demonstrates that the proposed model achieves an adequate level of structural fit. Second, an evaluation of the Outer Variance Inflation Factor (VIF) revealed that all indicator and construct values remained strict < 5. This statistical evidence confirms the absence of critical multicollinearity issues, further validating the robustness and overall fit of the measurement and structural models in this study. To minimize potential common-method variance inherent in cross-sectional self-reported survey designs, both procedural and statistical controls were applied. To assess the presence of Common Method Bias (CMB) (see Table 7), full anonymity was guaranteed to all air traffic controllers to reduce social desirability bias and a full collinearity test was performed following the approach proposed by (Kock, 2015). The resulting inner VIF values for (MW), (PCS), (SA), and (SP) were all below the conservative threshold of 3.3, suggesting that common method bias is not a pervasive issue / not a major concern in this study, although it cannot be completely ruled out given the cross-sectional, single-source nature of the data.

Table 7. Indicator-level Collinearity Diagnostics (Outer VIF)

Construct	Full Collinearity VIF	Threshold	Result
MW	2.473	< 3.3	CMB is not a concern
PCS	2.843	< 3.3	CMB is not a concern
SA	1.957	< 3.3	CMB is not a concern
SP	2.164	< 3.3	CMB is not a concern

The structural framework in PLS-SEM is primarily evaluated through the determination coefficient R^2 and predictive relevance Q^2predict as outlined by Hair et al. (2017). According to established methodological benchmarks, R^2 values are categorized into three distinct explanatory power thresholds: weak (0.25), moderate (0.50) and substantial (0.75) (Hair et al., 2019). As displayed in Table 8 the empirical results demonstrate robust structural capacity across all endogenous constructs

Table 8. R^2 and Q^2predict

Construct	R^2	Q^2predict
Safety Performance (SP)	0.586	0.365
Psychological Safety (PCS)	0.565	0.505
Situational Awareness (SA)	0.344	0.634

First, the primary target construct, SP, achieved an R^2 value of 0.586. This indicates that 58.6% of the variance in air traffic controllers' safety performance is explained by the combined effects within the structural framework. Following the established PLS-SEM benchmarks (Hair et al., 2019), this coefficient reflects a moderate-to-substantial explanatory capacity. Furthermore, the intermediate endogenous construct, PCS, yielded an R^2 of 0.565, showing that 56.5% of its variance is accounted for by its antecedents (moderate strength). Meanwhile, **SA** exhibited an R^2 value of 0.344, representing a moderate level of variance explanation 34.4%.

Second, to assess the out-of-sample predictive capability, the Q^2predict metrics were obtained via the PLSpredict procedure. All endogenous variables demonstrated Q^2predict values substantially greater than the threshold of zero. Specifically, **SA** achieved the highest predictive relevance score Q^2predict = 0.634, followed by **PCS** Q^2predict = 0.505 and **SP** Q^2predict = 0.365). These positive values confirm the solely on positive Q^2 and structural stability of the proposed conceptual model.

Table 9. PLSpredict Report

Target Indicator	Q2 Predict	PLS-SEM	Linear Model (LM)	Differences (PLS-LM)	Result Comparison
SP1	0.158	1.044	1.06	-0.016	PLS-SEM < LM
SP2	0.105	0.916	0.935	-0.019	PLS-SEM < LM
SP3	0.329	0.839	0.838	0.001	PLS-SEM > LM
SP4	0.154	0.945	0.956	-0.011	PLS-SEM < LM
SP5	0.229	0.863	0.874	-0.011	PLS-SEM < LM
SP6	0.23	0.835	0.848	-0.013	PLS-SEM < LM

To assess the out-of-sample predictive power of the model, the PLSpredict procedure was executed in SmartPLS 3 with 10 folds and 10 repetitions. The results showed Table 9 that the majority of Safety Performance indicators (5 out of 6) yielded lower RMSE values in the PLS-SEM estimation compared to the LM benchmark. Consequently, the model demonstrates medium out-of-sample predictive power.

4.3. Control of Variable Analysis, Measurement Invariance Assessment (MICOM), Multi-Group Analysis (PLS-MGA) Analysis

To account for potential clustering and contextual effects resulting from operational variations across Tower, APP, and ACC facilities, two dummy variables (TWR and APP, with ACC serving as the reference group) were included as controls in the structural model. As shown in Table 10 the primary mediation pathways remained statistically significant ($p < 0.001$), whereas neither dummy variable exhibited a significant effect on safety performance ($p > 0.05$). *A post-hoc power analysis was conducted using* GPower 3.1 to evaluate the statistical power for detecting group differences given our subgroup sample sizes (TWR = 87, APP = 62, ACC = 55). For the smallest pair-wise comparison (APP vs. ACC, total N = 117) with α = 0.05 (two-tailed), the achieved statistical power (1 - β) was 0.74 for medium effect sizes (d = 0.50) and 0.97 for large effect sizes (d = 0.80). This indicates that the subgroup sample sizes provide sufficient statistical power to detect medium-to-large structural path differences across operational settings, although detecting very small differences (d < 0.30) remains limited due to sample size constraints.

Table 10. Control of Variable Analysis Results

Structural Path / Relationship	Path Coeff (β)	Sample Mean	Std. Deviation	*t*-Statistic	*p*-Value	Decision
Main Path: PCS – SP	0.431	0.486	0.057	5.736	0.000	Supported
Control: TWR – SP	0.073	0.074	0.051	1.440	0.150	Not Significant
Control: APP – SP	0.021	0.021	0.045	0.473	0.636	Not Significant

Prior to evaluating the structural differences between groups, a measurement invariance analysis was conducted to ensure that the constructs were conceptualized and understood equivalently across the different operational units (TWR, APP, and ACC). Establishing this measurement invariance provided the necessary foundation for valid multi-group comparisons

Table 11. Measurement Invariance Assessment (MICOM) Results

Construct	Group	Step 1 (Configural)	Step 2: Compositional Invariance (c=1)	Step 2: p-value	Step 3a: p-value	Step 3b: p-value	Result
Mental Workload	TWR vs APP	Yes	0.999	0.12	0.588	0.644	Full Invariance
	TWR vs ACC	Yes	1	0.916	0.433	0.863	Full Invariance
	APP vs ACC	Yes	0.999	0.284	0.849	0.457	Full Invariance
Psycological Safety	TWR vs APP	Yes	1	0.835	0.693	0.469	Full Invariance

	TWR vs ACC	Yes	1	0.771	0.868	0.14	Full Invariance
	APP vs ACC	Yes	1	0.916	0.836	0.496	Full Invariance
SItuational Awareness	TWR vs APP	Yes	0.999	0.071	0.038	0.601	Partial Invariance
	TWR vs ACC	Yes	1	0.811	0.09	0.428	Full Invariance
	APP vs ACC	Yes	0.999	0.129	0.713	0.831	Full Invariance
Safety Performance	TWR vs APP	Yes	0.997	0.443	0.054	0.887	Full Invariance
	TWR vs ACC	Yes	0.998	0.729	0.104	0.608	Full Invariance
	APP vs ACC	Yes	0.998	0.625	0.783	0.771	Full Invariance

As shown in Table 11 configural invariance was established qualitatively across all pairwise comparisons (TWR vs. APP, TWR vs. ACC, and APP vs. ACC). Identical indicators, measurement models, structural specifications, and data treatment algorithms were consistently applied to all operational groups, Compositional invariance was assessed by examining the original correlation values (c) against the permutation results. The correlation values for all constructs across all group pairs approached unity ($c \geq 0.997$). Crucially, the permutation p-values for Step 2 were all well above the threshold of 0.05 (ranging from 0.071 to 0.916). This confirms that compositional invariance was fully achieved, establishing that the composite scores represent the exact same constructs across TWR, APP, and ACC environments. Equality of composite means (Step 3a) and variances (Step 3b) was evaluated to determine whether full or partial invariance was established: MW, PCS, and SP demonstrated no statistically significant differences in composite means ($p > 0.05$) or variances ($p > 0.05$) across all pairwise comparisons, establishing full measurement invariance for these constructs. SA achieved full measurement invariance for the TWR vs. ACC ($p_{\text{mean}} = 0.090, p_{\text{var}} = 0.428$) and APP vs. ACC ($p_{\text{mean}} = 0.713, p_{\text{var}} = 0.831$) comparisons. However, for the TWR vs. APP comparison, a statistically significant difference was observed in composite means ($p_{\text{mean}} = 0.038$), resulting in partial measurement invariance. Because compositional invariance (Step 2) was successfully established across all constructs, and all constructs achieved either full or partial invariance in Step 3, the dataset satisfies the necessary econometric criteria for multigroup analysis (PLS-MGA). Consequently, differences in structural path coefficients

across TWR, APP, and ACC operational personnel can be compared and interpreted with confidence**.**

Table 12. Multi-Group Analysis (PLS-MGA) Result

Path	**(β)TWR**	**(β)APP**	**(β)ACC**	**TWR vs. APP Δ(β)**	**TWR vs. APP p-value**	**TWR vs. ACC Δ(β)**	**TWR vs. ACC p-value**	**APP vs. ACC Δ(β)**	**APP vs. ACC p-value**	**Results**
MW - PCS	-0.725	-0.816	-0.748	0.091	0.167	0.023	0.765	-0.068	0.387	No significant difference across groups
MW - SA	-0.488	-0.716	-0.638	0.228	**0.014**	0.15	0.171	-0.078	0.416	Significant difference (TWR vs. APP)
MW-SP	-0.155	-0.171	0.094	0.016	0.945	-0.249	0.166	-0.265	0.234	No significant difference across groups
PCS - SP	0.308	0.477	0.697	- 0.169	0.334	-0.389	**0.031**	-0.22	0.264	Significant difference (TWR vs. ACC)
SA - SP	0.384	0.275	0.23	0.109	0.54	0.154	0.255	0.045	0.773	No significant difference

across groups

A partial least squares multigroup analysis (PLS-MGA) was conducted to evaluate structural path differences across TWR (n = 87), APP (n = 62), and ACC (n = 55) personnel. The results indicated that the structural model is not entirely homogeneous. While several pathways demonstrate structural invariance across the units, specific relationships within the safety mechanisms exhibit significant heterogeneity depending on the operational environment. MGA results revealed two statistically significant path differences across the operational settings. First, regarding the impact of MW on SA, a significant group difference was identified between TWR and APP controllers ($\Delta\beta = 0.228, p = 0.014$), APP controllers manage high-density, converging traffic operating at varying speeds and altitudes within a confined terminal airspace, relying entirely on 2D radar displays. In this instrument-heavy environment, cognitive overload can rapidly narrow a controller's attention, significantly degrading their overall situational awareness. Conversely, TWR controllers benefit from direct visual observation of the airfield. These direct visual cues provide a more intuitive and immediate spatial awareness, which appears to make their SA slightly more resilient to sudden spikes in mental workload. Although MW negatively affects SA across all groups, the adverse impact is substantially more pronounced in the APP ($\beta = -0.716$) than in the TWR ($\beta = -0.488$). Second, for the path from PCS to SP, a significant difference emerged between TWR and ACC personnel ($\Delta\beta = -0.389, p = 0.031$). PCS exerts a significantly stronger positive effect on SP among ACC controllers ($\beta = 0.697$) compared to TWR controllers ($\beta = 0.308$), ACC operations involve managing vast en-route sectors, high-altitude cruising traffic, and complex sector-to-sector handovers. In such a strategic and highly procedural environment, safety performance relies heavily on systemic adherence to protocols, long-term planning, and a strong shared safety culture. In contrast, while PCS remains essential in the TWR , their operations are highly tactical and immediate. TWR safety performance is often heavily influenced by rapid, individual reactions to real-time visual events, making the statistical link between systemic safety culture and daily safety performance slightly less pronounced than in the ACC environment. These heterogeneous paths underscore the necessity of tailoring workload management and safety interventions to the unique characteristics of each ATC unit. Conversely, the PLS-MGA results demonstrate structural invariance across the remaining three paths. Specifically, the relationships between MW and PCS, MW and SP, as well as SA and SP, yielded no significant differences across any of the group comparisons (TWR vs. APP, TWR vs. ACC, and APP vs. ACC). The p-values for these multigroup comparisons consistently exceeded the threshold for statistical significance.

4.4. Hypothesis Testing

Table 13 displays the bootstrapping results derived from 5,000 resamples in SEM-PLS. The analysis demonstrates that mental workload (MW) exerts a negative and statistically significant effect on both psychological safety (PCS) and situational awareness (SA), validating $\mathbf{H_1}$ and $\mathbf{H_2}$. Concurrently, both PCS and SA exhibit significant positive influences on SP, thereby supporting $\mathbf{H_3}$ and $\mathbf{H_4}$. In contrast, the direct path from MW to SP is statistically non-significant, supporting the rejection of $\mathbf{H_5}$ as a direct linear path. Second, the evaluation of Cohen's f^2 effect sizes indicates that PCS ($f^2 = 0.175$) and SA ($f^2 = 0.157$) contribute to medium-to-substantial unique

predictive power toward SP, whereas the direct effect of MW is negligible (f^2= 0.007). Furthermore, the structural assessment confirms the presence of highly significant indirect effects. Both PCS ($t = 5.491, p < 0.001$) and SA ($t = 5.084, p < 0.001$) emerge as potent mediators bridging the relationship between MW and SP, thus confirming the indirect-only mediation hypothesized in **H6** and **H7**. A comprehensive visualization of the final structural model, along with the corresponding R^2 values, is illustrated in

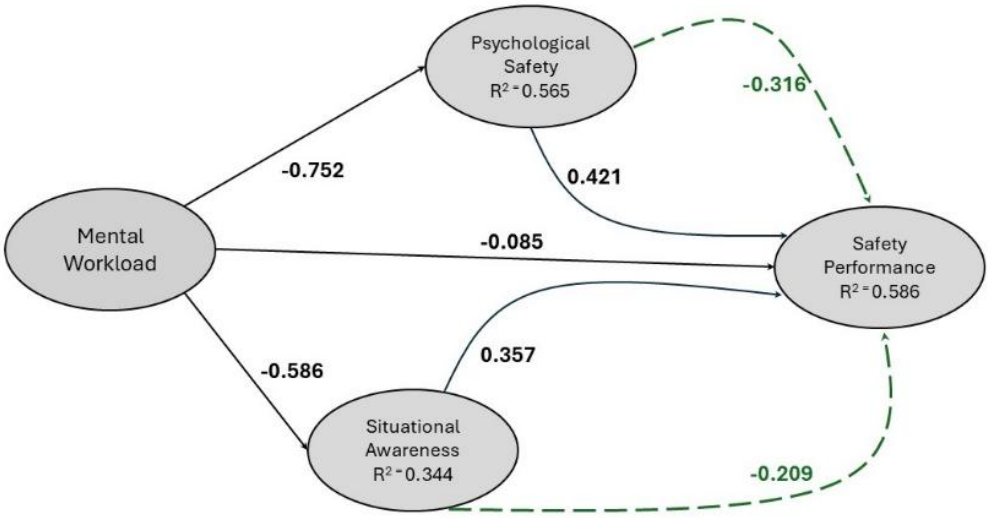
Figure 2.

Table 13. Summary of hypothesis testing results (bootstrapping)

Hypho/ Variable	Path Coef (β)	Sample Mean (M)	(STDEV)	T Stat	P Values	F^2	95% Confidence Interval		Remarks
							2.50 %	97.50 %	
H1 (MW – PCS)	-0.752	-0.752	0.033	22.799	0.000	1.298	-0.807	-0.679	Supported
H2 (MW – SA)	-0.586	-0.588	0.044	13.18	0.000	0.524	-0.666	-0.491	Supported
H3 (PCS – SP)	0.421	0.43	0.074	5.850	0.000	0.175	0.268	0.561	Supported
H4 (SA – SP)	0.357	0.335	0.067	5.044	0.000	0.157	0.214	0.480	Supported
H5 (MW – SP)	-0.085	-0.088	0.071	1.194	0.233	0.007	-0.223	0.058	Not Supported
H6 (MW – PCS – SP)	-0.316	-0.324	0.059	5.491	0.000	-	-0.433	-0.198	Supported

H_7 (MW – SA – SP)	-0.209	-0.196	0.039	5.084	0.000	-	-0.289	-0.132	Supported

Figure 2. Final Structural model results



This study investigates the structural mechanisms underpinning safety performance among Air Traffic Control (ATC) personnel in Indonesia, positioning MW as a primary antecedent. Rather than demonstrating a direct, linear influence on safety outcomes, empirical testing confirms that MW operates through an indirect-only mediation structure governed by two parallel pathways: PCS ($\beta = -0.316, p < 0.001$), and SA ($\beta = -0.209, p < 0.001$). Table 13 details the empirical path estimates, confirming that all indirect and specific direct paths (H_1–H_4, H_6, H_7) are statistically significant, whereas the direct relationship between MW and SP (H_5) is non-significant.

4.5. Direct Antecedents of Psychological Safety and Situational Awareness

The direct effect of mental workload on psychological safety (H_1) is negative and highly significant ($\beta = -0.752, p < 0.001$), demonstrating that acute cognitive overload severely degrades an individual controller's perceived psychological safety. In high-density ATC

operations, when task complexity exceeds optimal human processing capacity, controllers experience heightened stress, cognitive fatigue, and decision-making anxiety. This compromised psychological state prompts controllers to hesitate during time-critical operations, elevating the probability of operational near-misses. This finding extends recent work by (Gu & Wang, 2026), reinforcing that workload-induced fatigue heightens defensiveness and lowers individual perceptions of support among high-risk operators. Similarly, mental workload exerts a strong negative direct effect on situational awareness (H_2) $\beta = -0.586, p < 0.001$, Under peak traffic volume, adverse weather events, or complex sector configurations, cumulative cognitive demands saturate working memory capacity. Consequently, the individual attentional focus required to continuously process, comprehend, and project spatio-temporal traffic dynamics becomes severely constricted (Morgenthal & Metz, 2025). This empirical evidence confirms that unmitigated workload spikes directly disrupt basic cognitive filtering at the individual controller level behind the radar screen.

4.6. Catalysts of Safety Performance: Psychological Safety and Situational Awareness

Conversely, psychological safety demonstrates a potent positive impact on safety performance (H_3) $\beta = 0.421, p < 0.001$. Within air traffic control environments, safety performance relies not only on passive compliance with standard operating procedures (SOPs) but also on active safety participation. Psychological safety acts as a crucial socio-technical catalyst, encouraging controllers to communicate early hazard warnings, report near-misses, and engage in collaborative error recovery without fear of punitive repercussions (Mogård & Rørstad, 2023). Furthermore, a psychologically safe environment serves as a protective buffer during time-critical crises, stabilizing cognitive functions and reducing performance volatility under high stress (Abousoliman et al., 2026) ; Za et al., 2021).

In parallel, situational awareness exhibits a significant positive direct effect on safety performance (H_4) $\beta = 0.357, p < 0.001$. In ATC operations, situational awareness represents the core cognitive continuum underlying all radar-monitoring decisions. This continuum operates across Endsley's three chronological tiers. First Perception (Level 1) Continuous acquisition of real-time flight telemetry (altitude, air speed, heading), second Comprehension (Level 2) Real-time synthesis of traffic patterns to execute aircraft sequencing and maintain separation minima, third Projection (Level 3) Forward-looking trajectory extrapolation to forecast and resolve potential conflict points 5 to 10 minutes in advance. The empirical confirmation of H_4 verifies that maintaining this tripartite cognitive continuum optimizes real-time separation precision and minimizes loss-of-separation risks (Hauss & Eyferth, 2003; Naderpour et al., 2016).

4.7. The pattern of indirect-only mediation: Linear Non-Significant (H_5)

Intriguingly, the direct relationship between mental workload and safety performance (H_5) is statistically non-significant ($\beta = -0.085, p = 0.232, T = 1.194$). The empirical findings demonstrate that the direct effect of mental workload on safety performance is statistically non-significant, as this relationship is fully mediated through psychological safety and situational (Derdowski & Mathisen, 2023; Z. Wang et al., 2021). This full mediation pattern highlights that mental workload does not directly impair or enhance safety outcomes; rather, its operational influence contributes significantly to controllers' cognitive processing and interpersonal safety climate.

This result diverges from traditional linear models in safety literature (e.g., Guti & Jim, 2025), which assume that mental workload directly degrades human performance. Within ATC domain dynamics, an increase in task volume does not automatically precipitate operational failure. When workload escalates, experienced controllers frequently adapt by activating

compensatory strategy mechanisms—increasing vigilance, narrowing search strategies, and strictly prioritizing core separation tasks (Izadi Laybidi et al., 2022; Meier & Wüstenbecker, 2026; Xiong et al., 2023).

Furthermore, historical safety telemetry indicates that operational incidents frequently occur during low-density traffic conditions (underload). Under low-demand scenarios, reduced mental workload promotes monotony, vigilance decrements, and attentional mind-wandering, allowing latent conflicts to unfold undetected (Pattyn et al., 2008).

4.8. Dual-Pathway Mediation Mechanisms (H_6 & H_7)

The empirical confirmation of H_6 (β = -0.316, t = 5.491, $p < 0.001$) and H_7 β = -0.209, t = 5.084, $p < 0.001$) establishes a indirect-only mediation framework. This finding shows that high mental workload degrades safety performance via two distinct, complementary channels:

First, the Interpersonal-Psychological Pathway (H_6): Grounded in the Job Demands-Resources (JD-R) framework (Scholze & Hecker, 2024). Excessive workload functions as an acute job demand that drains cognitive and emotional reserves. As psychological stamina depletes, controllers perceive their interpersonal environment as threat prone. Consequently, self-protective defensiveness increases, leading to hesitation in reporting errors or seeking operational assistance—behaviors vital for organizational safety resilience (Newman et al., 2017; Yu et al., 2025). Second, the Cognitive Processing Pathway (H_7): Grounded in Cognitive Load Theory (Halpin, 2026; L. Liu et al., 2026), human working memory possesses finite processing capacity. When task complexity spikes, attentional tunneling occurs (Xiong et al., 2023), systematically impairing Level 1–3 situational awareness and triggering latent cognitive lapses behind the radar display.

The parallel mediation analysis reveals that both PCS ($\beta = -0.316, p < 0.05$) and SA ($\beta = -0.209, p < 0.05$) serve as statistically significant indirect pathways between MW and SP. While both mechanisms contribute significantly to explaining this relationship, PCS demonstrated a numerically larger indirect association in this sample. Given the cross-sectional design of this study, these findings represent significant indirect associations rather than definitive temporal causality. In line with contemporary mediation frameworks (Hayes, 2017; Zhao et al., 2010) the non-significant direct relationship suggests that mental workload does not directly predict safety outcomes in this sample; rather, its association with safety performance is indirect associations through controllers' psychological states and cognitive awareness. Specifically, elevated MW is negatively associated with perceived PCS, which in turn correlates with reduced SA and lower SP.

This statistical equivalence highlights the dual-channel nature of cognitive and interpersonal resources in high-risk operational environments. On one hand, situational awareness represents the cognitive mechanism—enabling controllers to maintain accurate environmental tracking, pattern recognition, and conflict projection despite high task demands. On the other hand, perceived psychological safety represents the interpersonal-climate mechanism—fostering an environment where controllers feel safe to communicate operational risks, voice concerns, and coordinate under stress. Mitigating the adverse impacts of mental workload requires a balanced organizational strategy that simultaneously preserves individual situational awareness and reinforces individual perception of psychological safety.

5. Conclusion and Suggestion

This study clarifies the underlying mechanisms governing aviation safety by evaluating the indirect-only mediation framework of safety performance among Air Traffic Control (ATC) personnel in Indonesia. The empirical evidence yields a pivotal theoretical insight, The direct path from Mental Workload to Safety Performance was not statistically significant. This finding indicates that Mental Workload does not exert a direct linear impact on safety performance when accounting for intermediate psychological and cognitive mechanisms. Instead, the effect of Mental Workload is fully mediated through Psychological Safety and Situational Awareness, therefore both mechanisms pathways contribute significantly to the outcome, with psychological safety demonstrating a more prominent indirect association within this specific sample.

A prominent theoretical contribution of this research is the identification of asymmetric mediation effects. This finding extends the Job Demands-Resources (JD-R) model and Cognitive Load Theory within high-reliability organizations, demonstrating that acute task saturation transitions an individual's psychological state from collaborative resilience to defensive self-protection. Consequently, this psychological shift actively suppresses safety-critical behaviors, such as error reporting and hazard communication, well before full cognitive saturation occurs. Practically, these insights demand a paradigm shift in aviation risk management. Air Navigation Services Providers (ANSPs) must move beyond traditional technical fatigue management to actively implement organizational interventions that safeguard psychological safety and protect cognitive bandwidth during high-density operations. In conclusion, mitigating operational incidents in complex airspaces requires a comprehensive approach. Aviation authorities must address both the individual perception of psychological safety and the cognitive readiness of controllers, effectively bridging the gap between human factors theory and proactive safety performance.

6. Limitations and Future Research

Despite providing crucial empirical insights into the socio-technical dynamics of aviation safety, several limitations inherent to this study must be acknowledged to guide future scholarly inquiries, First, this study evaluated the structural relationship between mental workload and safety performance using a linear specification. While the direct path yielded non-significant statistical results, theoretical literature in cognitive ergonomics frequently posits a non-linear or inverted-U relationship, where both excessive mental overload and severe underload (monotony) may degrade operational performance. Because the estimated model did not incorporate quadratic terms, threshold effect specifications, or spline regressions, this study could not empirically verify potential non-linear tipping points. Future studies are strongly encouraged to directly test the 'workload paradox' by specifying quadratic workload metrics to evaluate whether an inverted-U functional form exists within high-risk operational environments.

Second, the empirical architecture of this research relied on a cross-sectional survey design, capturing observational data from controllers at a single point in time. Although the statistical findings established robust indirect pathways connecting mental workload to safety performance via situational awareness and perceived psychological safety, this single-wave measurement design cannot empirically prove strict temporal causality or rule out potential reciprocal dynamics. For instance, controllers who perceive a decline in their operational safety performance or navigate adverse working environments may secondarily report reduced

situational awareness or diminished psychological safety. To overcome these cross-sectional constraints and validate the temporal sequence of the proposed mediating mechanisms, future research should adopt more rigorous methodological designs. Scholars are strongly encouraged to implement longitudinal or time-lagged data collection strategies that track controller perceptions across multiple operational cycles. Furthermore, integrating quasi-experimental workload manipulations or incorporating objective operational metrics—such as real-time sector traffic density, spatial complexity indices, recorded separation conflict counts, and physiological stress markers—would provide a more credible and empirically grounded foundation for confirming the directional causality of workload-induced performance outcomes.

Third, all primary variables, including the dependent variable, Safety Performance, were captured simultaneously through self-reported measurements from the same group of air traffic controllers. Although statistical diagnostics indicated that CMV was within acceptable limits, self-perception bias remains a potential risk; controllers who perceive themselves as highly effective may simultaneously overestimate both their situational awareness and safety performance. To enhance validity, future research should move beyond self-reported metrics and validate the proposed model using objective, independently recorded safety indicators. These may include operational metrics such as separation-loss events, operational deviations, readback/hearback error rates, supervisor/peer evaluations, objective traffic complexity metrics, or official safety-reporting logs.

Lastly, A final limitation concerns the single-level analytical framework adopted in this study. Although air traffic controllers operate within nested organizational structures—such as specific shift teams, control sectors, and operational facilities, the primary constructs, particularly perceived psychological safety, were operationalized and analyzed exclusively at the individual level of perception. This individual-level focus may overlook shared contextual dynamics, supervisory norms, and unit-level safety climates that naturally cluster within specific control facilities. To resolve these analytical boundary conditions, future research should transition from single-level estimations to Multilevel Structural Equation Modeling (MSEM). Scholars are encouraged to aggregate individual controller assessments to the team or facility level, provided that empirical justification for aggregation is rigorously demonstrated. Specifically, future studies should evaluate within-group agreement indices to confirm sufficient inter-rater reliability and conceptual consensus before modeling team-level psychological safety dynamics against organizational safety outcomes.

Declaration of AI and AI-assisted technologies in the writing process.

The authors employed generative artificial intelligence models Gemini 3.1 Pro to assist with linguistic refinement, grammatical precision, and stylistic improvements during the drafting process. The intellectual content, including all analytical findings, data interpretations, and final conclusions, is entirely the work and responsibility of the authors.

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