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The Dynamics of Dirty Dozen Human Errors in ATC Training Simulations Under Unusual Conditions

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Abstract

This study investigates the dynamics of Dirty Dozen human error factors within Air Traffic Control (ATC) training simulations conducted under unusual conditions such as emergencies, urgency events, and communication failures. Using a Grounded Theory approach, data were collected from 13 cadets of the Aerodrome Control Tower program at the Surabaya Aviation Polytechnic through participatory observation, in-depth interviews, and supporting documentation. The analysis employed open coding, axial coding, and selective coding, leading to the construction of a conceptual model that explains the emergence and interaction of Dirty Dozen factors. Findings reveal that these factors often arise simultaneously and reinforce one another, primarily triggered by operational pressure, limited resources, and insufficient preparedness in non-technical skills. Contextual elements within the learning environment—such as informal norms and technical limitations of the simulator—also intensified the occurrence of errors. Despite these challenges, cadets demonstrated adaptive strategies including communication adjustments, teamwork improvisation, and stress management techniques. The study highlights the systemic and dynamic nature of Dirty Dozen factors and underscores the need to integrate non-technical skill development into ATC training programs to strengthen human error mitigation from the early stages of professional education.

Keywords: *Dirty Dozen, human error, Air Traffic Control, training simulation, Grounded Theory, unusual conditions, human factors*

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INTRODUCTION

Safety has always been the cornerstone of aviation operations, with air traffic controllers (ATCs) playing a critical role in maintaining order and ensuring the separation of aircraft[1]. In recent years, the emphasis on human factors has gained significant importance, as human error remains one of the leading contributors to aviation incidents[2,3]. Data from the Indonesian National Transportation Safety Committee (KNKT) between 2015 and 2024 reported 121 aviation accident investigations, of which 43% were attributed to human factors and human errors[4]. This highlights the urgency of addressing human limitations as a systemic safety issue rather than an individual shortcoming[5,6].

Among the various frameworks developed to understand human error, the concept of the Dirty Dozen a set of twelve common human factors such as lack of communication, fatigue, stress, and lack of teamwork has been widely applied in both operational and training contexts[7].

Within the scope of ATC education, simulation-based training is designed to reflect the complexity and unpredictability of real-world scenarios, including unusual conditions such as emergencies, urgency situations, and communication failures[8]. These conditions demand quick, accurate, and well-coordinated responses, making them an ideal setting to explore the presence and dynamics of Dirty Dozen factors. While existing research on ATC training has largely focused on technical competencies, studies examining the role

[1] Kieran Langford and others, '"In Automation We Trust" - Australian Air Traffic Controller Perspectives of Increasing Automation in Air Traffic Management', *Transport Policy*, 125 (2022), 352–62 <https://doi.org/10.1016/j.tranpol.2022.07.001>.

[2] Husam Kharoufah and others, 'A Review of Human Factors Causations in Commercial Air Transport Accidents and Incidents: From to 2000–2016', *Progress in Aerospace Sciences*, 99 (2018), 1–13 <https://doi.org/10.1016/j.paerosci.2018.03.002>.

[3] Damien Kelly and Marina Efthymiou, 'An Analysis of Human Factors in Fifty Controlled Flight into Terrain Aviation Accidents from 2007 to 2017', *Journal of Safety Research*, 69 (2019), 155–65 <https://doi.org/10.1016/j.jsr.2019.03.009>.

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[5] Pascale Carayon and others, 'Challenges And Opportunities For Improving Patient Safety Through Human Factors And Systems Engineering', *Health Affairs*, 37.11 (2018), 1862–69 <https://doi.org/10.1377/hlthaff.2018.0723>.

[6] Nick Chater and George Loewenstein, 'The I-Frame and the s-Frame: How Focusing on Individual-Level Solutions Has Led Behavioral Public Policy Astray', *Behavioral and Brain Sciences*, 46 (2023), e147 <https://doi.org/10.1017/S0140525X22002023>.

[7] Obianuju Nzelu, 'Human Factors: The Dirty Dozen in CTG Misinterpretation', *Global Journal of Reproductive Medicine*, 6.2 (2018) <https://doi.org/10.19080/GJORM.2018.06.555683>.

[8] Dimas Arya Soeadyfa Fridyatama, Suparji Suparji, and Meini Sondang Sumbawati, 'Developing Air Traffic Control Simulator for Laboratory', *TEM Journal*, 2023, 1462–74 <https://doi.org/10.18421/TEM123-26>.

of human factors in educational simulations remain limited[9].

The Dirty Dozen factors may emerge not only from individual limitations but also from contextual influences such as resource constraints, instructional environments, or informal peer norms. Recognizing and addressing these elements early in professional education can enhance students' resilience and reduce the risk of error once they transition into operational roles.

This study employs a Grounded Theory approach to explore how Dirty Dozen factors emerge, interact, and are managed by ATC students during Aerodrome Control Tower (TWR) simulations under unusual conditions. By analyzing experiences through in-depth interviews, participatory observations, and documentation, this research aims to contribute both theoretically by expanding the understanding of human factors in ATC education—and practically by offering recommendations for integrating non-technical skill development into training curricula.

RESEARCH METHODS

1. Research Design

This study employed a qualitative approach with Grounded Theory methodology to explore the dynamics of Dirty Dozen human error factors in Air Traffic Control (ATC) training simulations under unusual conditions[10]. Grounded Theory was chosen because it allows for the systematic development of theory from empirical data, particularly suitable for underexplored phenomena such as the manifestation and interaction of Dirty Dozen factors in ATC education.

2. Participants

The research involved 13 cadets enrolled in the Aerodrome Control Tower (TWR) program at the Surabaya Aviation Polytechnic Indonesia. Participants were selected using purposive sampling based on their active involvement in simulation-based training sessions and their willingness to provide data through observation and interviews. All participants were in the same academic cohort, ensuring a comparable training background while allowing variation in individual experiences.

3. Data Collection

Data were collected through three complementary techniques:

[9] Lotte Abildgren and others, 'The Effectiveness of Improving Healthcare Teams' Human Factor Skills Using Simulation-Based Training: A Systematic Review', *Advances in Simulation*, 7.1 (2022), 12 <https://doi.org/10.1186/s41077-022-00207-2>.

[10] Khaldoun M. Aldiabat and Carole Lynne Le Navenec, 'Data Saturation: The Mysterious Step in Grounded Theory Methodology', *Qualitative Report*, 23.1 (2018), 245–61 <https://doi.org/10.46743/2160-3715/2018.2994>.

1. Participatory Observation – Researchers directly observed cadets during simulation sessions involving unusual conditions, such as emergencies, urgency events, and communication failures, to capture real-time behaviors and interactions.
2. In-depth Interviews – Semi-structured interviews were conducted with all cadets to explore personal experiences, perceptions, and coping strategies related to the Dirty Dozen factors.
3. Supporting Documentation – Training logs, instructor notes, and simulator records were analyzed to triangulate and validate observational and interview findings.

4. Data Analysis

The data were analyzed following the Grounded Theory procedures proposed by Strauss and Corbin (1990), consisting of:

1. Open Coding: breaking down data into discrete units of meaning and labeling them with initial codes.
2. Axial Coding: grouping codes into categories and identifying relationships among them.
3. Selective Coding: integrating categories into a core conceptual model that explains the emergence and interaction of Dirty Dozen factors[11].

The analysis was iterative, using the constant comparative method to refine categories across different data sources. Memo writing was applied throughout the process to capture analytical insights and theoretical reflections.

RESULT AND DISCUSSION

1. Emergence of Dirty Dozen Factor

The data analysis revealed that all twelve factors of the Dirty Dozen emerged during Air Traffic Control (ATC) training simulations under unusual conditions. While the intensity and frequency of each factor varied across sessions, certain patterns were consistent. Among them, communication failures, operational pressure, stress, and lack of teamwork were observed most frequently and played a central role in shaping the dynamics of human error.

Importantly, these factors rarely appeared in isolation; instead, they often interacted and reinforced one another. For instance, stress frequently co-occurred with lack of communication, while fatigue was linked with reduced awareness. Such interconnections intensified error likelihood and highlighted the systemic nature of human factors in ATC education.

To provide a clearer overview of how each Dirty Dozen factor manifested in the training environment, the findings are summarized in Table 1. The table outlines the specific forms of manifestation for each factor and provides concrete examples observed during simulation sessions.

[11] Juliet M. Corbin and Anselm Strauss, 'Grounded Theory Research: Procedures, Canons, and Evaluative Criteria', *Qualitative Sociology*, 13.1 (1990), 3–21 <https://doi.org/10.1007/BF00988593>.

Table 1: Emergence of Dirty Dozen Factors

Dirty Dosen Factor	Manifestation in ATC Training Simulations (Students)	Example from Simulation Session
Lack of Communication	Students failed to clarify/repeat critical messages, leading to misunderstandings.	Mis-sequencing aircraft due to incomplete altitude readback.
Complacency	Over-reliance on routine procedures, delayed recognition of unusual conditions.	Ignoring unexpected aircraft maneuvers assuming "system will stabilize."
Lack of Knowledge	Limited understanding of emergency protocols, hesitation in applying phraseology.	Uncertain responses to urgency calls from pseudo-pilot.
Distraction	Divided attention due to simultaneous tasks caused missed readbacks.	Missing clearance confirmation while handling emergency arrival.
Lack of Teamwork	Poor task-sharing; peers reluctant to intervene when one student overloaded.	Delayed response when overloaded student not supported.
Fatigue	Extended simulation hours increased mental exhaustion, slowing responses.	Forgetting call signs toward the end of session.
Lack of Resources	Simulator limitations and insufficient reference material constrained responses.	Delayed radar updates heightened uncertainty in traffic management.
Pressure	High operational demands led to rushed communication and overlooked instructions.	Handling multiple conflicting aircraft in limited time.
Lack of Assertiveness	Students reluctant to correct peers' errors due to hierarchy/norms.	Not challenging incorrect clearance given by peer.
Stress	Stress observed through physical (trembling voice) and behavioral (hesitant decisions) indicators.	Pausing excessively before issuing emergency instructions.
Lack of Awareness	Over-focus on one emergency reduced situational awareness of other traffic.	Issuing unsafe clearance to secondary aircraft.
Norms	Informal peer norms encouraged shortcuts in communication phraseology.	Using non-standard ICAO phraseology following peers' habits.

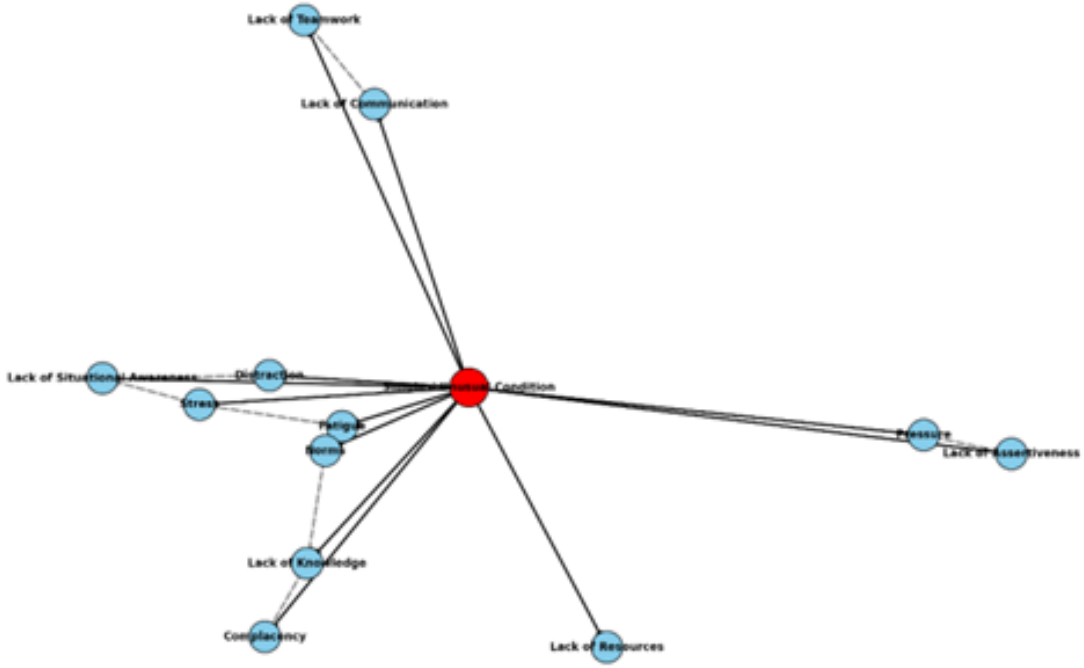


Figure 1. Interactions among Dirty Dozen Factors in ATC Training Simulations

The network diagram provides a visual representation of how the Dirty Dozen factors interacted during ATC training simulations under unusual conditions. The model shows that Stress functioned as a central node, strongly connected to Pressure, Lack of Communication, and Fatigue. This suggests that stress was not an isolated phenomenon, but rather a consequence of multiple converging pressures within the simulation environment[12].

Another important cluster was the link between Lack of Communication and Lack of Teamwork, which often reinforced one another. When communication was unclear, task-sharing became ineffective, leading to increased workload for individual students. Conversely, weak teamwork created further communication breakdowns[13].

The diagram also highlights the role of Norms in shaping student behavior. Informal group norms were directly connected to Lack of Assertiveness and Communication, illustrating how peer culture sometimes discouraged students from challenging mistakes or using standard phraseology.

[12] Haidong Wang and others, 'Literature Review on Pressure–Velocity Decoupling Algorithms Applied to Built-Environment CFD Simulation', *Building and Environment*, 143 (2018), 671–78 <https://doi.org/10.1016/j.buildenv.2018.07.046>.

[13] Lauren Blackwell Landon, Kelley J. Slack, and Jamie D. Barrett, 'Teamwork and Collaboration in Long-Duration Space Missions: Going to Extremes.', *American Psychologist*, 73.4 (2018), 563–75 <https://doi.org/10.1037/amp0000260>.

Furthermore, Distraction and Lack of Awareness formed a distinct pairing, reflecting how cognitive overload during emergencies reduced students' situational awareness. Lack of Resources, while less interconnected, still contributed to operational pressure by limiting students' ability to respond effectively.

Overall, the network diagram underscores the systemic and interconnected nature of Dirty Dozen factors. Rather than acting independently, these factors emerged as part of a dynamic web of interactions, amplifying human error risks in training contexts.

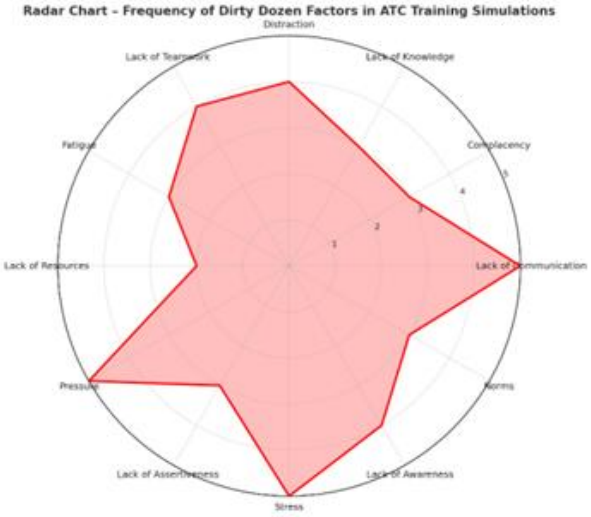


Figure 2. Frequency of Dirty Dozen Factors in ATC Training Simulations

The radar chart illustrates the relative frequency of Dirty Dozen factors observed during ATC training simulations under unusual conditions. Three factors emerged as the most dominant: Lack of Communication, Pressure, and Stress. These factors consistently appeared across multiple simulation sessions and often acted as primary triggers for subsequent errors. For instance, communication breakdowns frequently escalated under time pressure, creating stressful scenarios that challenged students' decision-making capabilities.

Other factors with moderate frequency, such as Distraction, Lack of Teamwork, and Lack of Awareness, were also significant in shaping simulation outcomes. These factors typically co-occurred with high-pressure scenarios, indicating that when students struggled to manage stress, they also experienced decreased situational awareness and ineffective collaboration.

Meanwhile, factors such as Complacency, Lack of Knowledge, Fatigue, Lack of Assertiveness, and Norms appeared with moderate-to-low frequency, yet their presence was still relevant. For example, informal norms encouraged non-standard phraseology, while fatigue contributed to delayed responses toward the end of simulation sessions.

The least frequent factor observed was Lack of Resources, primarily linked to technical limitations of the simulator rather than students' internal performance. This suggests that while systemic constraints influenced certain errors, the majority of Dirty Dozen factors were rooted in human dynamics under pressure.

Overall, the radar chart reinforces the systemic and interactive nature of human error in ATC training. It highlights the need for stronger emphasis on communication skills, stress management, and pressure handling in educational settings to prepare students for complex operational environments.

2. Simultaneous and Interrelated Dynamics

The findings revealed that Dirty Dozen factors rarely appeared in isolation; instead, they tended to emerge simultaneously and were often interdependent. This simultaneity created complex chains of human error that amplified the difficulty of managing unusual conditions within the ATC training simulations.

One of the most evident patterns was the strong association between Stress, Pressure, and Lack of Communication. High operational pressure often triggered stress, which in turn reduced students' ability to articulate clear instructions. Once communication began to break down, teamwork also deteriorated, creating a cycle that magnified the risk of error.

Another significant interrelation involved Distraction, Fatigue, and Lack of Situational Awareness. When students were cognitively overloaded by multiple tasks or prolonged sessions, distraction and fatigue emerged almost simultaneously. These conditions often led to lapses in situational awareness, such as overlooking secondary traffic or misinterpreting readbacks.

The role of Norms added a socio-cultural layer to this dynamic. Informal peer norms often interacted with Lack of Assertiveness and Lack of Communication, discouraging students from questioning incorrect instructions or insisting on ICAO-standard phraseology. As a result, errors were reinforced by group behavior, not just individual limitations.

Overall, the dynamics showed that human error in ATC training was not the result of isolated factors, but rather the outcome of interconnected processes. This interdependence highlights the importance of addressing multiple factors simultaneously in training programs, rather than focusing on single aspects of performance[14].

[14] Stefanie S Sebok-Syer and others, 'Considering the Interdependence of Clinical Performance: Implications for Assessment and Entrustment', *Medical Education*, 52.9 (2018), 970–80 <https://doi.org/10.1111/medu.13588>.

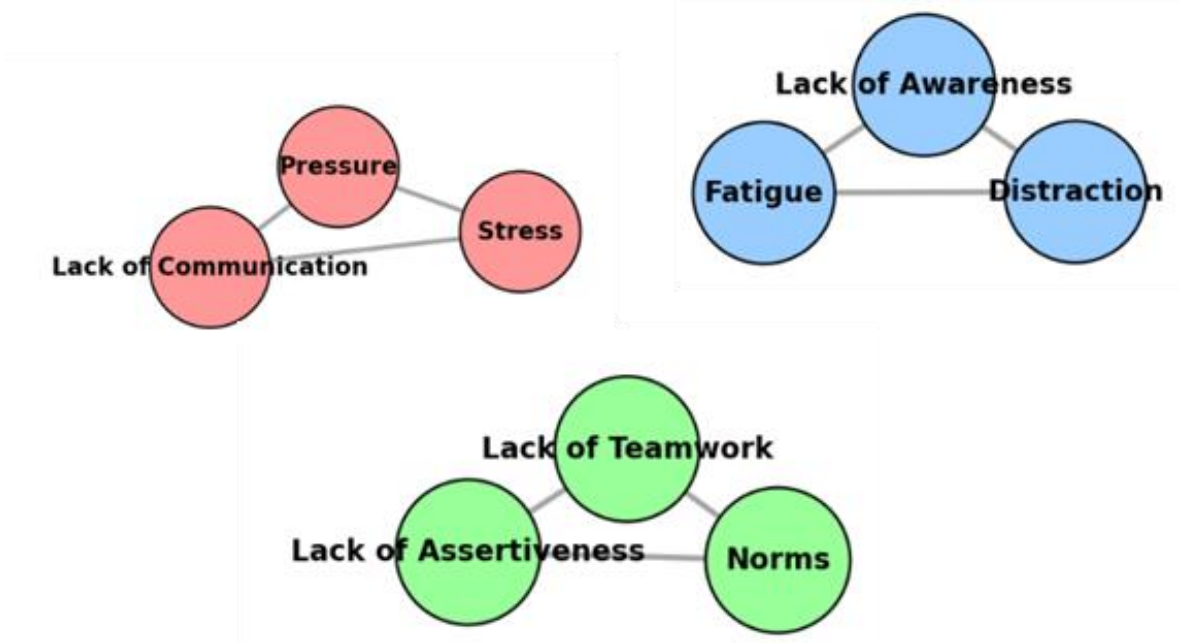


Figure 3 Simultaneous Dynamics of Dirty Dozen Factors

The cluster analysis of Dirty Dozen factors revealed three dominant groupings that frequently appeared together during ATC training simulations under unusual conditions (see figure 3).

Cluster 1 – Operational Core (Pressure, Stress, Lack of Communication)

This cluster reflects the core mechanism of error generation. High operational pressure created psychological stress, which in turn impaired students' ability to maintain clear and effective communication. Once communication was disrupted, coordination across the simulation quickly deteriorated. This cluster shows that pressure-induced stress was the central driver of communication breakdowns, which became the foundation for subsequent errors.

Cluster 2 – Cognitive-Physiological Strains (Fatigue, Distraction, Lack of Awareness)

The second cluster represents the mental and physical strains resulting from extended or cognitively demanding sessions. Fatigue and distraction typically appeared simultaneously, and both contributed to reduced situational awareness. When awareness declined, students overlooked secondary traffic, misread instructions, or lost track of priorities. This highlights the vulnerability of cognitive resources under prolonged stress and workload.

Cluster 3 – Socio-Cultural Reinforcers (Norms, Lack of Assertiveness, Lack of Teamwork)

The third cluster illustrates the social and cultural dimension of error dynamics. Informal norms among peers discouraged assertiveness, making students reluctant to correct mistakes or challenge the use of non-standard phraseology. This lack of assertiveness undermined teamwork, as collaboration became less effective when students avoided conflict. As a result, group culture reinforced the occurrence of errors instead of preventing them.

Taken together, the three clusters demonstrate that Dirty Dozen factors are not isolated but tend to form interactional patterns. These patterns cut across operational, cognitive, and socio-cultural domains, reinforcing the systemic and multi-dimensional nature of human error in ATC training.



Figure 4 Causal Loop Diagram: Interactions Leading to Human Error in ATC Simulations

The causal loop diagram illustrates how multiple Dirty Dozen factors interacted in a chain of cause-and-effect relationships during ATC training simulations under unusual conditions (see figure 4). At the center of this dynamic was Operational Pressure, which consistently acted as the primary trigger. Once pressure increased, students experienced heightened Stress, which then cascaded into several secondary effects.

Stress had a direct negative impact on communication, leading to incomplete or unclear instructions. This breakdown in communication further reduced Teamwork, as students failed to coordinate effectively. In parallel, stress also contributed to Distraction and Fatigue, both of which undermined Situational Awareness. When awareness declined, students were more likely to overlook secondary traffic or misinterpret critical information.

Ultimately, these interrelated processes converged into Unsafe Clearances and Errors, which represented the observable outcomes in the simulation environment. Importantly, the diagram also highlights that stress itself fed directly into error outcomes, bypassing intermediate factors in some cases.

Overall, the CLD emphasizes that human error in ATC training was not a linear event but rather the outcome of reinforcing loops where pressure and stress served as central

drivers. This systemic view underlines the necessity of designing training interventions that target multiple factors simultaneously, especially stress management and communication skills.

3. Adaptive Strategies

Despite the frequent emergence of Dirty Dozen factors, students demonstrated several adaptive strategies to cope with challenges during simulations. These strategies reflected their capacity to improvise, regulate stress, and maintain performance under pressure.

a. Communication Adjustments

When communication broke down, students often re-clarified instructions. One student explained: *"Sometimes I just repeated the clearance twice so my partner was sure what I meant"*. Another added: *"If the standard phrase confused them, I simplified the words but kept the meaning the same".*

Students often tried to re-clarify instructions when communication breakdowns occurred. Some shifted to simplified phraseology or repeated critical instructions to reduce ambiguity. While this was not always aligned with ICAO standards, it showed an effort to restore shared understanding in real-time.

b. Teamwork Improvisation

In situations of weak teamwork, some students volunteered to help beyond their assigned roles. As one interviewee stated: *"I reminded my friend about the traffic he missed, even though it wasn't my responsibility, because I didn't want it to cause a conflict"*. In the absence of strong teamwork, some students voluntarily took additional roles to support coordination, such as reminding colleagues of pending tasks or monitoring traffic not under their direct responsibility. This improvisation compensated for reduced collaboration and helped prevent conflicts.

c. Stress and Emotion Regulation

Several students consciously applied stress control. One shared: *"When I was nervous, I tried to breathe slowly before giving instructions"*. Another explained: *"I paused for a moment to calm myself, otherwise my words would get mixed up"*. Several students were observed applying stress management techniques, such as controlled breathing, slowing their speech, or briefly pausing before issuing clearances. These small adjustments were important in preventing stress from escalating into errors.

d. Learning-Oriented Reflection

Informal peer discussions also became a coping tool. A participant noted: *"After the simulation, we talked about mistakes. I realized what I forgot and promised myself not to do it again"*. After simulations, students frequently discussed mistakes informally, sharing perspectives about what went wrong and how to avoid it in the future. Although not structured as formal debriefings, these reflections revealed a culture of peer learning that supported long-term skill development.

Overall, these adaptive strategies highlight that while Dirty Dozen factors intensified under unusual conditions, students were not entirely vulnerable. Instead, they developed practical coping mechanisms that mitigated risks and demonstrated the potential for resilience-building within ATC education.

DISCUSSION

The findings of this study extend the understanding of how Dirty Dozen factors operate within Air Traffic Control (ATC) training under unusual conditions. Previous research has acknowledged the importance of human factors in aviation safety[15,16] yet limited studies have explored their dynamics in educational simulations. This study demonstrates that Dirty Dozen factors not only emerge individually but also interact simultaneously and systemically, reinforcing one another in ways that escalate human error risks.

The strong interrelation between Pressure, Stress, and Communication breakdowns aligns with prior studies in operational ATC contexts, where high workload has been consistently linked to degraded communication and teamwork performance[17]. However, the current research contributes a novel insight by showing that such dynamics already appear in the training phase, indicating the necessity of integrating stress management and communication resilience early in ATC education.

The second cluster Fatigue, Distraction, and Loss of Awareness confirms findings in cognitive psychology that attention and vigilance are highly sensitive to cognitive load[18]. Within the ATC simulation context, this manifested as students overlooking secondary traffic or misinterpreting readbacks. This suggests that simulation design must carefully balance task difficulty and session length to prevent cognitive overload.

The influence of Norms, Lack of Assertiveness, and Teamwork failures resonates with organizational culture theories [19], which emphasize how social norms can discourage error reporting or challenge of unsafe practices. The study shows that even in a training environment, informal peer culture may normalize unsafe communication habits, reinforcing the need for instructors to actively monitor and correct social dynamics.

The contextual influences identified namely simulator limitations and peer norms highlight that Dirty Dozen factors are not purely individual but also structurally and culturally embedded. This systemic perspective supports Reason's (1997) model of

[15] Rene Amalberti and Liên Wioland, 'Human Error in Aviation', *Aviation Safety*, 2020, 91–108 <https://doi.org/10.1201/9780429070372-7>.

[16] Kharoufah and others.

[17] P. A. Hancock and Gerald Matthews, 'Workload and Performance: Associations, Insensitivities, and Dissociations', *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 61.3 (2019), 374–92 <https://doi.org/10.1177/0018720818809590>.

[18] Yao Wang and others, 'Identifying Mental Fatigue of Construction Workers Using EEG and Deep Learning', *Automation in Construction*, 151 (2023), 104887 <https://doi.org/10.1016/j.autcon.2023.104887>.

[19] Tawfig Khidir Ibnouf Adham and Amr Sukkar, 'Investigating the Influence of Organizational Culture on Team Management: Exploring Effective Factors and Techniques', *World Journal of Advanced Research and Reviews*, 22.1 (2024), 1684–1702 <https://doi.org/10.30574/wjarr.2024.22.1.1219>.

organizational accidents, where human error arises from latent conditions within the system [20].

Finally, the adaptive strategies demonstrated by students—such as communication adjustments, teamwork improvisation, and stress regulation—illustrate that trainees are capable of developing resilience-in-action. This aligns with resilience engineering perspectives[21], which view safety not only as the absence of error but also as the presence of adaptive capacity.

In summary, this study emphasizes that mitigating human error in ATC training requires a holistic approach:

a. Strengthening non-technical skills (communication, teamwork, stress management).

b. Addressing systemic constraints (simulator design, peer norms).

c. Encouraging adaptive capacity and reflective learning.

Such integration ensures that students are prepared not only for technical competence but also for the complex socio-technical challenges of ATC operations.

CONCLUSION

This study has demonstrated that Dirty Dozen factors in ATC training simulations under unusual conditions are not isolated events but part of a dynamic and systemic interaction. Pressure and stress consistently acted as primary triggers, cascading into communication breakdowns, cognitive strain, and reduced teamwork. These findings confirm that human error is shaped not only by individual limitations but also by contextual elements such as simulator constraints and peer norms.

Importantly, students were not entirely vulnerable to these challenges. They actively engaged in adaptive strategies, including communication adjustments, teamwork improvisation, stress regulation, and reflective learning. These coping mechanisms illustrate the potential for resilience-building even during the training phase.

From a theoretical perspective, this research contributes to human factors literature by integrating the Dirty Dozen framework with a systemic view of socio-technical interactions in ATC education. Practically, the study underscores the importance of embedding non-technical skills training—such as stress management, communication resilience, and assertiveness—into ATC curricula alongside technical competencies. Simulator design improvements and structured debriefings are also recommended to mitigate contextual barriers and foster reflective learning.

Future research may expand this work by including larger and more diverse student populations, testing interventions aimed at reducing Dirty Dozen occurrences, and

[20] Nicki Marquardt, 'Situation Awareness, Human Error, and Organizational Learning in Sociotechnical Systems', *Human Factors and Ergonomics in Manufacturing & Service Industries*, 29.4 (2019), 327–39 <https://doi.org/10.1002/hfm.20790>.

[21] David D. Woods, 'The Theory of Graceful Extensibility: Basic Rules That Govern Adaptive Systems', *Environment Systems and Decisions*, 38.4 (2018), 433–57 <https://doi.org/10.1007/s10669-018-9708-3>.

examining how adaptive strategies evolve over time as students transition into professional ATC environments.

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