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Predictive Analysis of Controllers' Cognitive Errors Using the TRACEr Technique: A Case Study in an Airport Control Tower

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Abstract

Background: In complex socio-technical systems like aviation systems, human error is said to be the main cause of air transport incidents, accounting for about 75 percent of these incidents and events. air traffic management (ATM) is considered a highly reliable industry; however, there is a persistent need to identify safety vulnerabilities and reduce them or their effects, as ATM is very human-centered and will remain so, at least in the mid-term (e.g., until 2025).

Objectives: The current study aimed to conduct a predictive analysis of controllers' cognitive errors using the TRACEr technique in an airport control tower.

Materials and Methods: This paper was done as a qualitative case study to identify controllers' errors in an airport control tower. First, the controllers' tasks were described by means of interviews and observation, and then the most critical tasks, which were more likely to have more errors, were chosen to be examined. In the next step, the tasks were broken down into sub-tasks using the hierarchical analysis method and presented as HTA charts. Finally, for all the sub-tasks, different error modes and mechanisms of their occurrence were identified and the results were recorded on TRACEr worksheets.

Results: The analysis of TRACEr worksheets showed that of a total 315 detected errors, perception and memory errors are the most important errors in tower control controllers' tasks, and perceptual and spatial confusion is the most important psychological factor related to their occurrence.

Conclusions: The results of this study led to the identification of many of the errors and conditions that affect the performance of controllers, providing the ability to define safety and ergonomic interventions to reduce the risk of human error. Therefore, the results of this study can be a basis for planning ATM to prioritize prevention programs and safety enhancement

Keywords: Airport Control Tower, Human Error, Controller, TRACEr

1. Background

Air transport is considered one of the infrastructures and most important factors related to the production and consumption cycle of national systems in the service section. According to the official statistics in Iran, direct transport activities account for more than 9% of the gross national product (GNP), 15% of gross capital, and almost 1.3 million workers in the country to itself. Air transport is the best, most secure, fastest, and safest means of transport and involves minimum time and cost, brought the air transport into consideration. The aviation industry has strategic aspects in every region and country and represents the economic and industrial development of that country; therefore, this industry should be considered an important factor in the cultural, social, and economic development of every society. An important part of the aviation industry, air traffic management (ATM), includes the interactions between human operators, procedures, and technical systems (hardware and software), and this complex interaction between them determines air traffic safety, which all of them (human operators, procedures, and technical systems), are used to ensure the safe guidance of aircraft on land and air (1). ATM is considered a highly reliable industry. However, recent events related to ATM have called into question this notion of high reliability, and there is a persistent need to identify security vulnerabilities and reduce them or their effects (2). Because ATM is very human-centered, the potential risks of human error in the process are high (3). Studies on aviation incidents also suggest that human error is the main cause of incidents in aviation transport, accounting for about 75% of these incidents and events

(4). Human error in the aviation industry is defined as the incorrect execution of a specific task by a human operator, which causes a series of subsequent reactions to other tasks, and in the end leads to an adverse event or airplane accident (5). Research to identify areas of undesirable events can be a good source of data to reduce or eliminate errors (6). The main focus of research in the field of human error is primarily on error classification schemes and then preventing errors through the design of error tolerant systems (3). Therefore, the use of techniques for human error identification (HEI), which is widely used for the analysis of human operational errors, is useful. Although these techniques have been available for decades and there are many methods for assessing human errors, they are not universal for each domain. There are development processes for various industries, and every technique must be matched with different industrial characteristics. Because ATM performance is very different from nuclear power operation, rail transport, petrochemical, or medical domain performance, there is a need to consider what approaches have been tested for such industries (2). The TRACEr technique was developed in 1999 by England's national air traffic service as a tool for classifying human errors and their causes in air traffic control (7). In many studies related to air traffic control and the aviation industry, the TRACEr technique was used as means of error identification for retrospective and predictive analysis of cognitive errors (8-11). This technique has been recently used in other studies to identify rail transport errors (12). The following are some of the reasons for using the TRACEr technique:

1. It provides a useful and high-level description of possible errors and their classification.
2. It presents specific information about perceptional functions that have flaws and their mechanisms.
3. It expresses the psychological reasons for any error's occurrence.
4. It expresses situations that affect the errors' occurrence.
5. It allows various errors to be retrieved and identified using the key questions.

2. Objectives

Due to the importance of identifying possible errors in the aviation industry and particularly air traffic control, this study was done with the aim of conducting a predictive analysis of controllers' cognitive errors using the TRACEr technique. For this purpose, the root causes of controllers' errors were identified in the airport control tower.

3. Materials and Methods

This study is a qualitative case study. The environment for identifying errors is the control tower of an airport in Iran with a population of about 15 controllers in five shifts of three persons. In each shift, there is one person who serves as the main controller and two auxiliary controllers. The main controllers have rating licenses and are responsible for their shift.

3.1. A Description of the Study Environment

To identify and better understand the errors, it is useful to gain familiarity with the environment and equipment in this study. The flight control tower (tower) is responsible for providing air traffic control service in a usually cylindrical area around the airport and up to a certain height; this area often varies according to the number of flights and facilities of each airport. Those who are responsible for controlling the terminal traffic are called controllers. Controllers, according to the work area classification, are divided into three units: the tower, the radar approach control unit (approach), and the flight path control unit (control center). In some airports, controllers work in the tower and the approach simultaneously, while in other areas, the approach and tower are quite separate from each other and work independently. In the environment of this study, controllers should perform both the approach and control tower duties. In the environment of this study, the controllers' equipment and facilities for flight guidance include meteorological status equipment, current status declaration equipment for the airport area as the ATIS, radio conversation equipment with the pilot and control center, the light screen of the ramps and the airport region in the form of a touch screen with a flashing visual alarm system, and a radar screen to see the flights on the defined airlines. There is also an alarm system and a light gun for emergency situations to guide planes to the airport landing region in the case of losing radio contact, microphones and headsets for conversations with the pilot, and flight strips with certain colors for writing the information of each flight with respect to the flight direction (e.g., blue paper strips for departure flights, red paper strips for arrival flights).

3.2. Method

In this study, the TRACEr technique proposed by Shorrock and Kirwan was used to analyze predictive cognitive errors (8). First, thorough information was gathered on general descriptions of controllers' air traffic control tasks and the devices (types of devices used by controllers for guidance flights) of this section through interviews and observations, reviewing controllers' duties, devices, and prior research that has been done in the control tower. Then the most critical tasks that are more likely to cause errors were selected to examine and identify errors. The controllers' tasks were analyzed hierarchically using hierarchical task analysis (HTA), tasks and sub-tasks were determined. Eleven main tasks were identified. In the next stage, with field surveys and interviews with controllers, the types of errors and different causes of their occurrence based on the structure of the TRACEr method on all sub-tasks derived from the previous step were identified by the researcher in the worksheet, according to the following steps:

1. Determining the external error mode (EEM): The EEM is actually the external and visible mode of actual or potential errors according to the reasonable consequences of one's wrong actions. Thus, the possible errors are described in three categories: qualitative and selection errors, sequence and time errors, and communication errors (Box 1). This classification of the EEM in the TRACEr technique has been adapted from Swain and Guttmann's classification (13). As an example, the controller transfers incorrect data (communication error) or does not do monitoring (omission error of the qualitative and selection error type), 2. Performance-shaping factors (PSFs): This step classifies the factors that influence or can influence controllers' performance and enhance error occurrence or help to improve errors in accordance with the factors classification in Box 2. Identifying the internal error mode (IEM): In this step, the IEM is expressed and specific information is presented about what cognitive functions and what method failed or could fail. Error examination at this point is done in, 4.areas: perception, memory, decision-making and planning, and action in accordance with the error classification in Table 1. The TRACEr technique this step is based on a human information processing model (Figure 1) in which human error is considered an error in human information processing and is compatible with Wickens's model from 1992 (8, 14). 5. Psychological error mechanisms (PEMs): PEMs involve psychological reasons for any internal error (Table 1). For example, the controller forgets to do flight monitoring and the psychological reason for this is that the controller was distracted by other tasks, 6. Error detection and recovery: At this stage, it becomes clear which errors can be identified and which can possibly be recovered. Finally, with the help of EXCEL software, data were analyzed and the percentage and frequency was determined for all errors. The implementation process used in this study based on the TRACEr technique is presented in Figure 2.

Box 1. EEM Taxonomy

Selection and Quality
Omission
Action too much
Action too Little
Action in Wrong mirection
Wrong Action on right object
Right Action on Wrong object
Wrong Action on Wrong object
Extraneous act
Timing and Sequence
Action too long
Action too short
Action too early
Action too late
Action repeated
Miss-ordering
Communication
Unclear information transmitted
Unclear information recorded
Information not sought/obtained
Information not transmitted
Information not recorded
Incomplete information transmitted
Incomplete information recorded
Incorrect information transmitted
Incorrect information recorded

Box 2. PSF Taxonomies

PSF Taxonomies
Traffic and airspace. e.g. traffic complexity
Pilot/controller communications. e.g. rt workload
Procedures. e.g. accuracy
Training and experience. e.g. task familiarity
Workplace design, hmi and equipment factors. e.g. radar display
Ambient environment. e.g. noise
Personal factors. e.g. alertness/fatigue
Social and team factors. e.g. handover/takeover
Organisational factors. e.g. conditions of work

Table 1. IEMs and PEMs

Cognitive Domains	
IEM	**PEM**
Perception	
No detection (visual)	Expectation bias
Late detection (visual)	Spatial confusion
Misread	Perceptual confusion
Visual misperception	Perceptual discrimination failure
Misidentification	Perceptual tunneling
No identification	Stimulus overload
Late identification (visual)	Vigilance failure
No detection (auditory)	Distraction/preoccupation
Hearback error	
Mishear	
Late auditory recognition	
Memory	
Forget to monitor	Similarity interference
Prospective memory failure	Memory capacity overload
Forget previous actions	Negative transfer
Forget temporary information	Mislearning
Misrecall temporary information	Insufficient learning
Forget stored information	Infrequency bias
Misrecall stored information	Memory block
	Distraction/preoccupation
	Incorrect knowledge
Judgment, Planning, and Decision Making	
Misprojection	Lack of knowledge
Poor decision	Failure to consider side or long-term effects
Late decision	Integration failure
No decision	Misunderstanding
Poor plan	Cognitive fixation
No plan	False assumption
Under-plan	Prioritization failure
	Risk recognition failure
	Decision freeze
Action Execution	
Selection error	Manual variability
Positioning error	Spatial confusion
Timing error	Habit intrusion
Unclear information transmitted	Perceptual confusion
Unclear information recorded	Functional confusion
Incorrect information transmitted	Dysfluency
Incorrect information recorded	Misarticulation
Information not transmitted	Inappropriate intonation
Information not recorded	Thoughts leading to actions
	Environmental intrusion
	Other slip
	Distraction/preoccupation

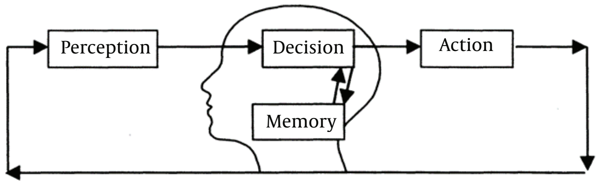

Figure 1. Human Information Processing Model

4. Results

HTA tables have been designed and TRACEr worksheets were also completed for controllers' 11 major tasks. The HTA image of departure flight guidance tasks along with a part of its completed worksheets has been provided in Appendices of this article. The results of the TRACEr technique application for these tasks showed that in 84 sub-tasks derived by HTA, there were 315 errors in the controllers' tasks. Regarding the percentage of error rates

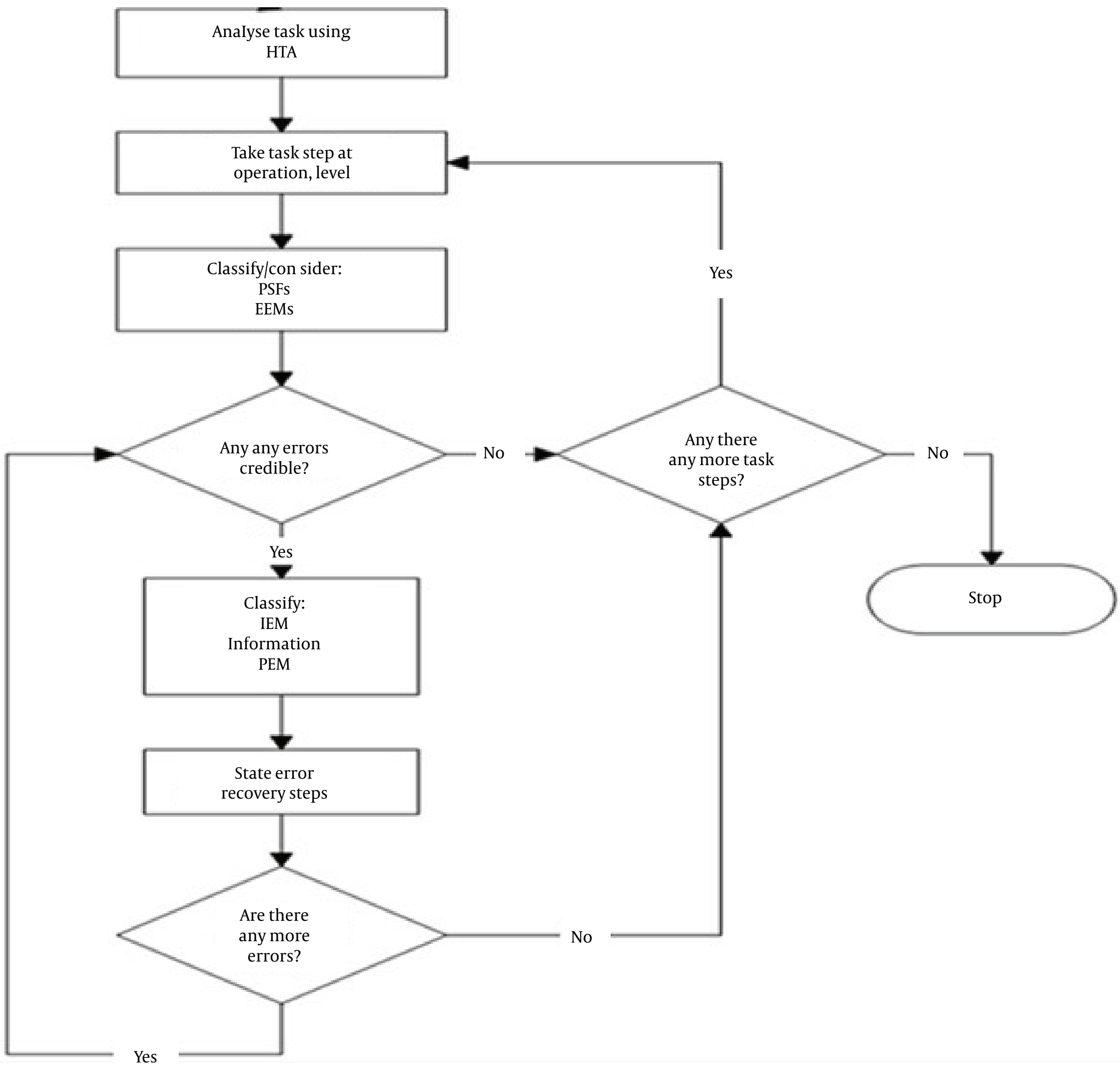

Figure 2. The Steps of the TRACEr Technique

among external errors shown in Table 2, qualitative and selection errors accounting for 57% and a frequency of 73 form the largest number of external errors, followed by sequence and time errors with 23.40% and communication errors with 19.50% were respectively the most frequent external errors. Among the qualitative and selection errors, omission and then wrong actions on the right objects were the most frequent errors. Regarding the sequence and time errors, most errors were due to controllers' late action. In the third category of errors, communication errors typically involved inaccurate and unclear transfers of information or unclear records of information. In classifying the internal errors, which include errors of perception, memory, decision-making and action, as shown in Table 3, memory errors (31.5%) were the most common, followed by perception errors (26.7%), action (26.2%), and decision-making (15.5%). Most memory errors are related to forgetting the action, prospective memory failures, and forgetting the previous actions. Perception errors tended to involve inaccurate visual perception, hearback errors, and the misreading of information; in the case of action errors, data transfer errors and then time errors were the most common types of errors. In the case of decision-making and planning errors, poor decision-making and inaccurate prediction were the most frequent. The results of the PEM and PSFs are shown in Tables 4 and 5. Among the PEMs, which account for the most probable reason for error occurrence, preoccupation and distraction were the most common causes, with 29.41%, followed by perceptional confusion, spatial confusion, and memory capacity overload. In the case of PSFs, the workload due to the traffic volume and the conversation load (induce of conversation between controller and pilot, controller and controller in other airport, controller and land safety) with (36.21%), personal factors such as fatigue and alertness (31.35%), and training and experience (9.71%) were the most common factors affecting controllers' performance.

Table 2. Summary of EEM Results

Error Types	EEM	Frequent	Total	Percent
Selection and quality			73	57
	Omission	27		
	Action too little	10		
	Action in wrong direction	16		
	Wrong action on right object	20		
Timing and sequence			30	23.40
	Action too long	1		
	Action too short	2		
	Action too early	5		
	Action too late	21		
	Miss-ordering	1		
Communication			25	19.50
	Unclear information transmitted	1		
	Incomplete information transmitted	4		
	Incorrect information transmitted	10		
	Information not transmitted	1		
	Unclear information recorded	3		
	Incorrect information recorded	3		
	Information not recorded	1		
	Incomplete information recorded	2		

Table 3. Summary of IEM Results

Cognitive Domains	IEM	Frequency	Total	Percent
Perception			50	26.73
	Visual misperception	8		
	Misread	6		
	Misidentification	5		
	Late detection (visual)	5		
	No detection (visual)	5		
	Late auditory recognition	3		
	No detection (auditory)	3		
	Late identification (visual)	3		
	Hearback error	7		
	Mishear	5		
Memory			59	31.55
	Forget to monitor	25		
	Prospective memory failure	12		
	Forget previous actions	10		
	Forget temporary information	3		
	Misrecall temporary information	2		
	Forget stored information	2		
Judgment, planning, and decision making			29	15.50
	Misprojection	8		
	Poor decision	10		
	Late decision	2		
	Poor plan	7		
	No plan	3		
Action execution			49	26.20
	Selection error	2		
	Timing error	18		
	Transmission error	16		
	Record error	13		

Table 4. Summary of PEM Results

PEM	Frequency	Percent
Distraction/preoccupation	50	29.41
Memory capacity overload	13	7.64
Vigilance failure	7	4.11
Spatial confusion	16	9.41
Perceptual confusion	19	11.17
Lack of knowledge	7	4.11
False assumption	7	4.11
Inappropriate intonation	6	3.52
Memory block	6	3.52
Expectation bias	5	2.94
Prioritization failure	6	3.52
Perceptual tunneling	5	2.94
Failure to consider side or long term effects	1	0.58
Stimulus overload	1	0.58
Risk recognition failure	2	1.17
Environmental intrusion	3	1.76
Similarity interference	3	1.76
Incorrect knowledge	2	1.17
Infrequency bias	2	1.17
Risk negation or tolerance	2	1.17
Manual variability	4	2.35
Misarticulation	1	0.58
Insufficient learning	1	0.58

Table 5. Summary of PSF Results

PSF	Frequency	Percent
Traffic and airspace (traffic complexity, rt workload)	67	36.21
Procedures (complexity, accuracy, number)	6	3.24
Training and experience	18	9.72
Workplace design, hmi and equipment factors	15	8.10
Personal factors (alertness/fatigue)	58	31.35
Social and team factors	5	2.70
Ambient environment (light, noise)	5	2.70
Organizational factors	11	5.94
Total	185	100

5. Discussion

To achieve the research aims, a predictive analysis of controllers' cognitive errors in an airport control tower using the TRACEr technique was conducted. The most commonly applied method for human error identification in ATM is TRACER and this method can be used to ensure that all critical errors and human interactions have been identified (13). Therefore, the use of such a technique that is compatible with the study environment and tested for air traffic increases the accuracy and reliability of the results. The results showed that memory and perception errors are the most frequent in controllers' tasks. Air traffic controllers' tasks demand strong audio-visual perception, and controllers have to process a lot of information in a limited period. In addition, they need to constantly maintain their performance. Therefore, it is not surprising that perception errors occur, including information failing to be identified or detected, or inaccurately detected. The results of the current study are similar to those of Corver (2014). In Cover's study, done in a control center, perception and memory errors were the most common errors. However, in this respect that perception errors prior considered memory errors Is incompatible So that in the Corver's study, perception errors were more frequent than memory errors; this difference may be due to the different nature of the duties of the controller in the control tower versus in a control center (15). The results of another study involving 143 aviation accidents by Jones and Endsley, showed that 72% of the errors caused by controllers are related to perception errors (16). Regarding the types of perception errors, identifying errors are more related to tasks such as radio conversations, marking flight data on the flight progress strips, and monitoring the radar that appear usually as mishearing and hearback error. Regarding visual identification errors that is one item of types perception errors (Table 2), they mostly involved, wrong visual identification, not identifying or misreading that due to the use of handheld and radio devices by controller in directing flights, That, in this study, showed a greater proportion of the perception errors. Other types perception errors are detection errors that involve visual and aural recognition, more frequently involved in radar monitoring duties, in the form of flashing visual and aural warnings recognition, therefore in current study because use of flight strips, procedural method for guidance flights, Since the radar screen in the environment of this study shows flights on airlines on a monitor and has no means of seeing and hearing alerts. the controller does not use it in this field as a working tool, This error is less extensive, visual and hearing recognition errors have small frequency in the controller duties in current study. The types of perception errors (e.g., visual identification, hearback, and misread errors) identified in this study partially correspond with the types of perception errors in Corver's study in 2014 (15) and Shorrock's study in 2007 (9). Regarding the importance of the role of memory in the controllers' tasks, it can also be said that memory lapses cause many events related to ATC (17, 18). This is due to the fact that memory is a significant determining factor of the air traffic controllers' performance and the controller forms a mental picture of the various aspects of a plane and airspace using his/her working memory and long-term memory. Thus, understanding perception and memory errors can prevent many related events. Regarding memory errors, as shown in the results, forgetting tasks and prospective memory failure accounted for most of the memory errors in this study. The failure to remember scheduled tasks, such as writing a new height on the strip, updating, and adjusting the paths on the strip, coordination with the aircrafts, and the early transfer of a plane to the control center, usually occur when traffic is high. Shorrock also reported the highest frequency of this type of memory error in the results obtained by interviews with controllers in the control center and the results obtained by examining aircraft proximity incidents (10). The controllers' tasks in a control tower are operational not operating (the characteristic of an operational task is to carry out an activity through perceptional paths to obtain information and then make a decision by retrieving information from memory and then taking action). Thus, in carrying out an activity at each stage of this process, some slips may occur that, in the result, appear as an error. Slips can occur just in the perception and memory stage and also involve other processing routes at the same time. In addition, the results of a study conducted in 2012 by Hassanzadeh confirm that the human error of cognitive failure that occurs in one or all three steps of processing information arises (19). Therefore, the controller should maintain continuously conscious attention to reduce the amount of possible errors. As also shown in the results, the most common psychological reason for the controllers' errors was preoccupation and distraction. When a controller attends to other tasks, it can decrease his/her attention and lead to an error. As Jones also mentioned, this factor is the most common cause of controllers' failure in monitoring or observing the data (16). Considering the fact that the controller can engage in various types of behaviors under certain circumstances, the identification and evaluation of factors that influence performance is a necessity for preventing and reducing human error to improve safety (20). Therefore, in this study, by identifying these factors, it was found that a high workload due to traffic volume, conversation load, and traffic complexity is the most important factor impacting controllers' performance. Personal factors, such as controller's fatigue, and then experience and training followed as the second and third most effective factors related to controllers' performance. These results, of course, correspond with the findings of De Ambroggi, who examined all the factors that influence controllers' performance in a safety case in a control tower (21). To assess the volume of air traffic and its impact on the incidence of human error in air traffic control, Moon et al. in 2011 showed that various types of human error in ATC are affected by traffic volume and a significant correlation exists between the traffic volume and human errors, which also shows the importance of the traffic volume factor. Therefore, it is necessary to estimate the appropriate traffic volume, air traffic control facilities, and aviation sector conditions to be considered (22). The importance of education and experience was also expressed as an important factor shaping performance in this study. A study done in 2010 by Mazlomi based on the CREAM technique, quality training and work experience is one of the factors associated with reduced quality performance (23). Thus, it is necessary to pay attention to training, and special attention should be given to the systematic planning and scheduling of training, retraining, and refresher educational materials adapted to the requirements of the job and design and implement, to be able hereby, the occurrence of errors in performing controllers' duties can be prevented. e.g., through simulators' design that different working conditions Including emergency situations, types controller performance in high traffic are tested, Strategies teach to deal with such situations. Thus, if we update controllers' functional equipment and replace electronic equipment like electronic flight strips and electronically send direct orders instead of radio conversations as well as use support equipment to detect interferences, such as short-term interference alerts, we can reduce many perception and memory errors by early detection and by providing an opportunity to correct and improve errors as well as reducing controller's mental load that is due to keeping high levels of data and at the same time quick and on time reaction, which requires the controllers' continuous and conscious attention. Indeed. Mental workload will be reduced in various ways. First of all, mental workload has been reduced by either reducing the load on the working memory, or by replacing laborious tasks with tasks involving less actions or require less time with respect to the execution. A study in 2014 was conducted to assess the impact of controllers' support tools on cognitive errors by performing a comparative analysis of the two operational environments using the TRACEr technique as a means of error identification. The findings indicated that errors related to detection, memory, decision-making, and action would be reduced by changing the operational system and applying modern equipment (15). We can conclude that the TRACEr technique, which was developed as a tool for classifying human errors and their causes in air traffic control, easily identifies and separates many errors due to the cognitive nature of air traffic tasks. The findings of this study led to the identification of many errors and the conditions affecting controllers' performance, thus providing the ability to define safety and ergonomic interventions to reduce the risk of human errors. Therefore, the results of this study can be the basis of planning ATM to prioritize prevention programs and safety enhancement.

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Footnotes

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Appendices

Please visit article's online version for appendices.

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