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Review Article

Overview of Studies on the Cognitive Workload of the Air Traffic Controller

Ebru Yazgan[1]* Erdi Sert[2] Deniz Şimşek[3]

[1] *Eskisehir Technical University, Faculty of Aeronautics and Astronautics, Eskisehir, Turkey*
eyazgan@eskisehir.edu.tr - 0000-0002-6545-8536

[2] *Eskisehir Technical University, Faculty of Aeronautics and Astronautics, Eskisehir, Turkey*
erdisert1907@outlook.com - 0000-0001-5553-4235

[3] *Eskisehir Technical University, Faculty of Sports Sciences, Eskisehir, Turkey*
ds@eskisehir.edu.tr - 0000-0001-5452-6006

Abstract

Air Traffic Control Officer (ATCO) will be the branch that will have the most impact on the air transport system. The duty of ATCOs is to prevent the collision of airplanes in the air provided by the controllers on the ground and overcome the possible confusion. Being exposed to a very high cognitive workload of ATCOs, one of the high-risk occupational groups, is important in terms of flight safety. However, it has been observed that studies on the differences in cognitive workload that may occur between experienced and inexperienced ATCO under different task difficulties are quite insufficient in the literature. This study presents research studies on cognitive workload measurement methods and ATCO's cognitive workload. In this study, the importance of determining the cognitive workload and its measurement methods is explained. In addition, literature studies related to the cognitive workload of ATCOs, particularly by using eye tracker, are presented.

Keywords

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1. Human Factors

Ergonomics (or human factors) is an applied discipline that draws on basic research in (behavioural) science and engineering and fieldwork and experience in industrial practice and many other domains. The goal of Ergonomics is to match how people work, their environment, their tools and equipment, and the products they use to human qualities and limits (Moray, 2005).

Bailey (1982) describes a similar tendency to equate poor system performance with poor human performance. However, detailed analyses of accidents and near-accidents reveal that human error is rarely the sole cause of poor system performance. Bailey cites three examples, including Three Mile Island nuclear incident and aircraft accidents, to illustrate this point. In order to understand why accidents, errors, or any unexpected system behaviours occur, one must look beyond human behaviour to the rest of the system. Important factors which need to be investigated are:

1. Design of system components, particularly human-machine interfaces.
2. State of the system leading up to the incident (e.g., stable/unstable, quiet/busy, on a course/off course, etc.)
3. Operator's cognitive and physical workload
4. Work organisation (e.g., shift system and during shift, supervision, design of workgroups)
5. External factors (e.g., weather)

It is now universally acknowledged that human error is cited as the primary cause of about 70% of aircraft accidents (Edwards, 1995). The term "human factors" has grown increasingly popular as the commercial aviation industry has realised that human error, rather than mechanical failure, underlies most aviation accidents and incidents. Human factors involve gathering

*: Corresponding Author Ebru Yazgan, eyazgan@eskisehir.edu.tr
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information about human abilities, limitations, and other characteristics and applying it to tools, machines, systems, tasks, jobs, and environments to produce safe, comfortable, and effective human use. Human factors are dedicated to better understanding how humans can safely and efficiently integrate with the technology in aviation. Despite rapid gains in technology, humans are ultimately responsible for ensuring the success and safety of the aviation industry. Therefore, they must continue to be knowledgeable, flexible, dedicated, and efficient while exercising good judgment. Because technology continues to evolve faster than the ability to predict how humans will interact with it, the industry can no longer depend on experience and intuition to guide decisions related to human performance. Instead, a sound scientific basis is necessary for assessing human performance implications in design, training, and procedures, just as developing a new wing requires sound aerodynamic engineering. In addition, human factors specialists participate in analysing operational safety and developing methods and tools to help operators better manage human error (Graeber, 2021).

Aviation as a system is safe. Safety is made by people doing the work every day. Safety is made at the intersection of man (a human being), machine (an aircraft, a helicopter or an airplane) and procedures. Nevertheless, safety is also made at the confluence of boundaries:

- The boundary of economic failure
- The boundary of functionally acceptable performance
- The boundary of unacceptable workload.

Human Factors has come to be concerned with diverse elements in the aviation system. These include human behaviour and performance; decision-making and other cognitive processes; the design of controls and displays; flight deck and cabin layout; communication and software aspects of computers; maps, charts and documentation; and the refinement of staff selection and training. Each of these aspects demands skilled and effective human performance (CAA-CAP 720, 2002).

Aviation management is becoming more and more critical with the increasing passenger capacity and the number of flights. With the automated world, aviation management also reduces the human factor. With systems such as ADS-B (Automatic Dependent Surveillance-Broadcast) and Mode-S that provide faster and more reliable data transfer to the ATCO, human-caused errors in aviation management are tried to be prevented.

In the second section of this study step, the cognitive workload is briefly explained to better understand the importance of determining the cognitive workload as the main subject of this study is cognitive workload and ATCO. In the third section, cognitive workload measurement methods are presented. Then literature studies related to the cognitive workload of ATCOs. The final section provides a conclusion based on the research explained in other sections, and future research are explored.

2. Cognitive Workload

In the world countries which developing as industrially since the middle of the 20th century has increasing tendency work which has consisted of cognitive work rather than physical work.

Many of us are familiar with this kind of work, such as driving a car and using a computer. In addition, many of the work named high risk are characterised by more cognitive demands than physical demands. The work of pilots, train drives, medical personnel and process control operators can be given examples of such jobs (Megaw, 2005).

There is no universally accepted definition of cognitive (or mental) workload, and it is often considered by analogy to the physical workload. However, it can be said that cognitive workload refers to all cognitive activities such as estimation, decision making, communication, identification and search, and is defined as the relationship between the cognitive resources required to perform a task and the ability of individuals to use these resources. The cognitive workload is a subjective concept that cannot be measured directly or considered an absolute value. However, given that the human mind can process the information at a limited rate, then the cognitive workload is the percentage of the capacity used at any time point (Galy et al., 2018).

Gopher and Donchin (1986) stated that cognitive workload was a feature of direct response, rules, control systems that mediate between stimuli and information processing. The researchers emphasised that cognitive workload was characteristic of the human-workload cycle. The effects of workload on human performance were studied only concerning the model of the human processing process.

The workload is often defined in terms of getting the job done or job requirements factors. However, since these factors are related to complex situations, it would be pointless to think of the workload in only one direction. Therefore, these factors are briefly as follows.

Task Demands: Task demands can be defined as the workload resulting from the analysis of the jobs requested from the operator. However, individual differences must be considered. For example, a novice and an experienced person will experience different workload levels while performing the same job.

Effort: It is the value of effort on the job. (e.g. cognitive processing resources distribute consciously) When exposed to high job demands, one should not choose to increase the level of effort within this situation.

Performance: Most studies on workload deal with the levels of performance that is achieved. However, performance measures cannot be alone considered as a sufficient measure of workload. (Farmer et al., 2003)

It is simply the amount of cognitive effort that one puts into a task, and requires actions such as concentration, reminder, decision making, and attention, and is essentially related to the individual's cognitive abilities and how the information is received and processed, and at the end leads to decision making and action, In other words, Cognitive Workload is a level of cognitive need or an analytical effort required by an individual to fulfil the physical, spatial, and environmental demands of a specific task (Safari et al., 2013).

Cognitive fatigue is characterised by subjective feelings of "tiredness" and "lack of energy". This psychobiological state has been extensively researched on professions where cognitive demand is very high, such as drivers and air pilots and its contribution to the development of work-related musculoskeletal disorders (Goode, 2003).

Determining the workload in cognitive work has increasing importance. The reason for this situation can be listed as follows:

1. When the operator has to work around the limits of his/her capacity, the probability of errors occurring is very high.
2. Load reactions occur when the operator has to work for a long time under high workload conditions.
3. When the factors that constitute a high workload can be identified, job structuring and working environment can be developed.
4. When the expected workload is known, new jobs or job assignments can be made more quickly.
5. Workload determination is also essential in wage policy, personnel selection and personnel training (Fığlalı, 1998).

According to Sanders and McCormick (1993), a useful measure of cognitive workload should meet the following criteria:

1. *Sensitivity*: The measurement must distinguish intuitively arising business situations that require different levels of workload.
2. *Selectivity*: The measurement should not be affected by factors that are not usually considered part of the cognitive workload, such as physical load or emotional stress.
3. *Interference*: The measurement should not interfere with the performance of the primary task whose workload has been previously assessed.
4. *Reliability*: The measurement must be reliable; the results must be reproducible over time.
5. *Acceptability*: The measurement technique must be accepted by the person being measured.

2.1. Reasons for Measuring Cognitive Workload

The most important reason for measuring cognitive workload is measured cost of jobs to estimated performance of system and operator. Although this is an intermediate measure and is also used to compare system designs, procedures, or person assignment requests where increasing business demands lead to unacceptable performance, workload metrics assess the system's attractiveness if performance measures fail to distinguish between options. This approach is implicitly believed that as the work gets harder, performance often decreases, the response of time and errors increase, control variability increases, per unit time, is completed too little work, job performance strategies change. There is the less residual capacity to deal with other issues.

Although it is generally accepted that there is a difference between workload and performance, it is not well understood. Within a situation, part of the system designer's goal is to optimise system performance and workload (Cain, 2007).

3. Cognitive Workload Measurement Methods

There is no direct method for measuring cognitive workload. Instead, some measurements have been developed. Common types of indirect cognitive Workload measurement techniques include the following components:

- Physiological Measurements (EEG, Eye Tracker)
- Performance Measurements (Primary Task Measurement, Secondary Task Measurement
- Subjective Measurements (SWAT, NASA-TLX)

Neither of these techniques is a mere measure of cognitive workload. The influence of other factors distorts each one. Combining two or more techniques is recommended as the most effective approach (O'Donnell and Eggemeier., 1986; Yazgan and Erol, 2013).

3.1. Physiological Measurements

One approach to evaluating cognitive workload is used to the physiological signals received from the operator. Changes in cognitive activities (including cognitive workload) are associated with changes in the body function in some measures. This measurement's rationale is that the information processing process involving the central nervous system, or its indicators, is measurable (Sander and McCormick, 1993). The most commonly used measurements are; heart rate, blink rate, breathing rate, and brainwave activity (Wilson and Eggmeier, 2006; Yazgan and Erol, 2013).

3.1.1. Eye Tracker

Visual information is essential in one operation of many systems. Operator blinking speed is reduced in high workload situations with a significant visual component. Blinking is usually measured electrophysiologically or using small cameras. Blinks are determined, and their speed, length of closure and amplitude are measured. There are many situations where blinking speed does not decrease in some of the visual demands of a job. Blinking is sensitive and diagnostic (Wilson and Eggmeier, 2006; Yazgan and Erol, 2013; Palma Fraga et al., 2018; Palma Fraga et al., 2020).

With the eye tracker, the pupil radius of the participants, the number of blinking, the mean blink time, the number of eye fixation, the eye fixation time, the average number of fixations, the frequency and number of eye saccades, and finally, the average eye saccade time can be measured. Blink duration and saccadic distance are expected to decrease inversely with the air traffic density in the eye-tracking device. The pupil diameter is expected to change in direct proportion. However, in the planned experiment, the areas of interest (AOI, Area of Interest) will be created. It is planned to reveal the browsing time and eye heat map on the AOI of the participants and reveal whether there is a difference between experienced and inexperienced. In this study, air traffic controllers, one of the critical elements in Air traffic Control and Management, are divided into two groups as experienced and inexperienced. It aims to measure cognitive workloads with Eye-Tracking Device. However, it is planned to conduct a statistical analysis of whether the possible cognitive fatigue levels of the air traffic controller, which plays at least as many roles as the pilot for flight safety, correlate with work experience under different task difficulties.

Every stage of cognitive fatigue such as blink rate, fixation number and fixation time can be monitored gradually with the Eye tracker, which can be considered as newer than other methods. In addition, the Eye-Tracker, which is easier to analyse than other physiological measurements, is a lightweight device.

In addition to eye-tracking technology, other approaches are available based on neuro-ergonomics, the science that investigates the relationship between human behaviour and the brain (Parasuraman and Rizzo, 2007; Parasuraman, 2003) to understand the underlying mechanisms of the brain. These techniques generally consist of quantifying changes in the human brain electromagnetic or hemodynamic activity. They are both sensitive to changes in human mental workload (Parasuraman, 2011) while exposed to complex tasks. On the other hand, hemodynamic activity can be measured through a functional near-infrared (fNIR) spectroscopy device to quantify changes in blood oxygenation during neural activity (Izzetoglu et al., 2004; Izzetoglu et al., 2005; Bunce et al., 2006; Izzetoglu et al., 2019; Palma Fraga, 2020).

Electroencephalography (EEG) has long been a cost-effective method for assessing cognitive workload. Cognitive workload increase is consistently correlated with an increase in the frontal theta (4-8 Hz) and beta (13-30 Hz) band power and parietal alpha (8-12 Hz) band power. However, despite the high temporal resolution, EEG suffers from difficulties with localisation of the sources and an associated low spatial resolution (Aghajani et al., 2006; Parasuman and Wilson, 2008; Ayaz et al., 2012; Palma Fraga et al., 2020).

Furthermore, physiological analyses including electrocardiography (EKG), electromyography (EMG), respiratory measurements, electrodermal activity (EDA) (Caldwell et al., 1994; Wientjes, 1992) and skin temperature measurements are also included in the studies conducted on the determination of mental workloads. In addition, oculometric analysis, including the acoustic properties of human speech, eye gaze and pupil analysis, and facial analysis are also evaluated in studies (Wilson and Eggemeier, 1991; Ćosić et al., 2019a; Ćosić et al., 2019b; Kesedžić et al., 2020). In this context, one of the most researched psychophysiological measures is related to changing cardiac activity (e.g. heart rate variability) during mental workload (Speyer et al., 1988; Aricò et al., 2017).

3.2. Performance Measurements

Performance metrics indicate operator workload from some method of the operator's capabilities to perform a system function or a job (Wilson ve Eggemeier, 2006; Yazgan and Erol,2013).

Performance measures can be classified into two main types:

- Primary task measurements
- Secondary task measurements

Primary task measures are capable of discriminating the resource competition between individual differences. For example, speed instability, distance headway instability, a lateral position from road centreline, lane excursion, time spent out of lane can be widely used to represent the primary driver performances.

Secondary task measures are more diagnostic than primary task measures and subjective measures. The correct response, time response of additional secondary task is a well-known example of secondary task performance measures in driving research. For example, the sensitivity of secondary reaction time in general aviation training has been investigated regarding the differences in the difficulties within and between the two flight scenarios. Flight scenarios are designed to show different workload levels and are based on data from previous studies (Eggmeier and Wilson, 1991).

3.3. Subjective Measurements

Subjective measures are becoming an increasingly important tool in system evaluations and have been used extensively to assess operator workload. The reasons for the frequent use of subjective procedures include their practical advantages (ease of implementation, non-intrusiveness) and current data, which support their capability to provide sensitive measures of operator load. In addition, as human-machine systems have become more complex and automated, evaluations based on the operator's performance have become prohibitively tricky, and the need to assess subjective cognitive workload has become critical (Rubio et al., 2004).

3.2.1. NASA-TLX

Hart and Staveland developed the NASA-TLX Scale in 1988 to quantify the physical and cognitive cost or workload associated with performing a given task. Since its initial creation, the scale has seen widespread use in public and private industries to evaluate the benefits and possible interference caused by a set variable, such as a new form of technology. The NASA-TLX Scale has demonstrated very low interrater variability due to its category weighting system, which accounts for an individual's self-reported strengths and weaknesses (Hart et al., 2006)

The NASA-TLX provides the entire subjective workload value based on a weighted average evaluation over six subscales or dimensions. The six scales evaluated are:

1. Cognitive demands.
2. Physical demands.
3. Temporal, time demands.
4. Own performance.
5. Effort.
6. Frustration.

Each of the six scales is used to show the basis for the characteristics of the subjective workload. In the final part of the job, people make evaluations on each of the six scales. These evaluations are then weighted to the total workload related to the performance of the job based on personally generated data, including each dimension's contribution. The weighted evaluations are then combined to form the entire index of subjective workload (Eggemeier et al., 1991). NASA TLX is applicable to the in-flight simulator, real flight jobs, air defence, remotely controlled vehicles and different business environments such as signal sensing (Damos, 1991).

3.2.2. SWAT

The Subjective Workload Assessment Technique (SWAT) (Reid & Nygren, 1988) is a subjective rating technique that uses three levels: (1) low, (2) medium, and (3) high, for each of three dimensions of time load, cognitive effort load, and psychological stress load to assess workload.

Subjective techniques have the advantage of being reasonably easy to manage and explain and do not require extensive training or equipment to be implemented. However, although subjective workload measurements are frequently used in aviation applications, they tend to be situation-specific and fail to consider changes in the operator's emotional state, natural ability, experience, learning ability, and adaptation. Moreover, subjective measurements, when used alone, are insufficient to explain the brain mechanisms related to work performance, and more importantly, from a system design point of view, they cannot be used for continuous real-time monitoring of the workload (Öztürk, 2006).

4. Literature Studies Related to Cognitive Workload of ATCO's

Strang et al. (2014) searched that heart rate examined correlates of cognitive workload in a Large-Scale Air-Combat Simulation Training Exercise; measurements based on physiological data are expected in calculating cognitive workload in aviation.

Collet et al. (2003) studied that subjective aspects of cognitive workload in air traffic control cognitive fatigue was calculated with subjective methods. Contrary to this study, it was planned to use Eye Tracker because physiological data were considered more reliable methods.

When the literature was examined, it was seen that Eye Tracker in Aviation is less. Therefore, unlike other studies, it will be analysed the cognitive fatigue of ATCO by using the Eye Tracker device in our future work. In this study, literature studies about the measurement methods of cognitive workload, particularly by using eye tracker in the aviation sector, is examined.

Ahlstrom and Friedman-Berg (2006) calculated the cognitive workload that occurs when the meteorology radar is added to the working environment. 6 experienced air traffic controllers participated in this study. Eye tracker and subjective measurement methods were used in the calculation of cognitive workload. It was concluded that by increasing the number of aircraft, blink time and the distance of saccades decreased, and the pupil diameter increased. These results conclude that there is a positive relationship between subjective measurements and eye movements. In this study, the relationship between eye movements and cognitive fatigue was investigated, but no difference was revealed between experienced and inexperienced air traffic controllers.

Another study was carried out by Marchitto, Benedetto, Baccino, and Canas (2015). Inexperienced 26 students who do not wear glasses were included in the study voluntarily. Subjective, physiological (with eye tracker) and performance measurements were made in the study investigating the proportionality of the subjective methods of cognitive workload during the management of the airspace of the air traffic controller with the eye movements. Since the participants were inexperienced, the summary of the study and the distinction to be used in the study (1000 feet separation, 5 miles side separation) were explained, and the training was given beforehand. As a result of the study, a positive proportion was measured between total fixation number and fixation time and cognitive workload. In addition, there was a positive correlation between performance measures and subjective measurements. However, when the differences between this study and the planned study were examined, no distinction was made between experienced and inexperienced air traffic controllers. The difference in cognitive workload that could occur in any task change was not measured.

Di Stasi et al. (2010) evaluated the cognitive workload of inexperienced air traffic controllers in different task difficulties. In the study, cognitive workload calculation methods, eye tracking device for physiological measurements, MWT (Mental Workload Test) for subjective measurements and secondary task performance measurement methods were used. In the secondary business, method measurements were measured the number of wrong answers and non-responses. As a result, a positive correlation was found between task difficulties and subjective measurement results in this study. Contrary to expectations, although the number of wrong answers was expected to increase with the difficulty level, a decrease was observed. On the contrary, the number of non-responses increased. In this study, no distinction was made between experienced and inexperienced air traffic controllers.

Averty et al. (2004) examined cognitive fatigue in a real work environment. In this study, the subjective work method of 25 experienced and licensed air Traffic Controllers, who were assigned to approach control at the French Saint Exupery airport, was measured. In this study, the term TLI (Traffic Load Index) was found by adding the number of aircraft in the area of responsibility and time load. The study was planned in a way that each controller would perform 1-hour duty in a real environment. In this study, only subjective measurement methods were used as measurement methods and no distinction was made between experienced and inexperienced air traffic controllers.

Bruder et al. (2013) analysed the cognitive workload of experienced and inexperienced air traffic controllers to monitor the system during automated airspace control. Air traffic controllers and pilots participated in this study. Twenty-one of the participants is experienced and active in their duties. Eighteen participants are controllers, and three are pilots. Participants were asked to identify errors. AOI (Area of Interest) heat maps were created by measuring each participant with an eye tracker. As a result of the measurement, there was no significant difference between experienced and inexperienced participants. This situation related to that task of monitoring is mentally relatively simple. In this study, only physiological measurement was used as the measurement method. Airspace control and management did not exercise; only the task of finding errors was performed.

5. Conclusion

The aviation industry is an increasingly critical industry where the consequences of any human error can lead to the loss of many people's lives. For this reason, personnel working in every field in the aviation sector are essential, and the minor mistake that can be made can lead to negative results. The air traffic controller works with the most difficult critical decisions, with the effort and knowledge to make as soon as possible. For this reason, the cognitive workload of the air traffic controller is vital due to the criticality of its work. Within precise results cannot be obtained in measuring cognitive workload, different measurement methods are used.

Many methods can be used to measure cognitive fatigue. While some methods use physiological values, cognitive fatigue is calculated with the questions asked to the user in some methods. In this context, trying to calculate the cognitive fatigue of the ATCO with Eye Tracker, which can be considered new, will constitute the essence of our work. In a future study, we aim to use Eye Tracker, a physiological evaluation for evaluating the cognitive workload of ATCO. First, however, we will work on the simulation, considering flight safety. The number of subjects will be evaluated according to age, gender, and experience. A separate evaluation will be made for each group by planning an experiment using an eye-tracking device. Also, ANOVA statistics will be used in the variance analysis of the obtained data. With the completion of this experiment planned on mental workload, it is envisaged that it will shed light on schools that provide air traffic control training and airports and contribute to the relevant organisations to see the necessary measures to reduce cognitive-induced ATCO errors and to revise their processes. Furthermore, it is thought that this planned experiment will also be of great importance in terms of guiding the aviation literature.

Abbreviations

ADS-B	:	Automatic Dependent Surveillance-Broadcast
ANOVA	:	Analysis of variance
AOI	:	Area of Interest
ATCO	:	Air Traffic Control Officer
EDA	:	electrodermal activity
EEG	:	Electroencephalography
EKG	:	electrocardiography
EMG	:	electromyography
fNIR	:	Functional near-infrared
MWT	:	Mental Workload Test
NASA-TLX	:	National Aeronautics and Space Administration - Task Load Index
SWAT	:	Subjective Workload Assessment Technique
TLI	:	Traffic Load Index

CRediT Author Statement

Ebru Yazgan: Conceptualisation, Writing- Original draft preparation, Visualisation, Investigation, Supervision, Writing - Review & Editing, Project administration **Erdi Sert:** Visualization, Investigation **Deniz Şimşek**: Writing - Review & Editing.

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