Human Factors Evaluation of ATC Operational Procedures in Relation to Use of 3D Display

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Abstract. In this paper, Holding Stack Management (HSM), Continuous Climb Operations (CCO), Continuous Descent Operations (CDO), and Trajectory Based Operations (TBO) procedures are assessed in relation to the use of an additional 3D display. Two display seetings are compared, namely 2D+3D and 2D only. Twelve Air Traffic Control Officers (ATCOs) took part in the experiment. Traditional questionnaires such as NASA TLX, TRUST, etc. were given at the end of each 30-minute trial for each display setting. Electroencephalogram (EEG) was recorded during the experiments to continuously monitor the changes of the brain states of the ATCOs. The results of the data analyses show that by using 2D+3D display setting, more positive emotions, but higher stress and workload levels were experienced by ATCOs in TBO, CCO and CDO procedures than in 2D setting. In HSM, reduced stress and significantly lower cognitive workload were experienced by ATCOs when they were using 2D+3D setting.

Keywords: Human Factors · Air Traffic Control · 3D Visualization · Brain States Monitoring · EEG

1 Introduction

With the growing number of flights, Air Traffic Control Officers (ATCOs) receive, perceive, and process an increasing amount of information, which brings a higher risk of the introduction of human errors [1].Cognitive abilities of the ATCOs play an important role in keeping track of aircraft. Currently, there are several automation tools and constraints to assist the controllers in separating aircraft in a high-density airspace. For example, limiting the maximum number of aircraft entering the airspace sector can help to ensure that the ATCOs' workload is not exceeded [2]. However, using the today's techniques remains inherently limited by controllers' cognitive workload and would not be able to support the traffic growth in time to come [3]. The dynamic environment is a challenge to ATCOs where they continuously receive a lot of information from several sources and have to break it down in a logical manner.

Current air traffic control (ATC) radar screens take a form of a 2D plan view with three degrees-of-freedom: magnification, altitude and longitude panning with respect to the screens' axes - with aircraft altitude data presented as numbers next to the aircraft's blip. As the altitude of aircraft is not graphically represented, ATCOs must construct a mental image of the vertical separation of the aircraft in the given airspace. Cases when ATCOs are losing the mental image of the airspace can occur in situations where ATCOs experience high traffic "compounded by unscheduled interruptions" [4]. As such, the rebuilding of the mental image is necessary, requiring considerable time and mental effort. This building of a mental image of airspace is also necessary whenever an ATCO relieves a colleague at a control position. Hence, it has been proposed that 3D visualisation of airspace could help ATCOs manage the increasingly large amounts of data that comes with the heavier air traffic better [1]. Furthermore, 3D visualisation could reduce the time and efforts needed for an ATCO to build mental images of the airspace under his/her control.

A study had shown that 3-dimensional (3D) displays support mental model of traffic and terrain and are effective in decision making for maneuvering the aircraft on the vertical plane [5]. Thus, the research for 3D display implementation and efficiency needs to be further carried out. It also demonstrated in [5] that the use of 3D visualisation of airspace could assist ATCOs in properly managing airspaces with heavy traffic or holding stack management operation. Both 2D and 3D representations have their strengths, with 2D's core advantage is precise lateral positioning, while 3D views allow viewers quickly gain an understanding of the overall three-dimensional situation of space. By using both displays, the relative positions and motions of objects in the display can be quickly determined, especially in holding stack management operation. In the case of holding stack, where multiple aircraft hold around the same waypoint (but at different altitudes) simultaneously, the multiple flight labels and blips would overlap and clutter in 2D visualization, which is undesirable as display clutter influences performance [6]. This can be addressed by using an interactive 3D display that can be oriented to show the "side view" of airspace (and by extension, holding stack) to display the vertical separation of aircraft accurately.

In [7], it concludes that 3D interface might be useful to display and solve potential conflicts as a 3D perspective might ease the conflict resolution in TBO. It also suggests that a 3D interface may speed up and improve the controller's ability to judge whether a certain CCO is authorized at a particular time. The HSM requires the ATCO to make judgments on vertical arrangements, rather than preserving horizontal separations. Thus by exploiting 3D graphics, it may be possible to visualize the stack in a more intuitive way, including the location of each aircraft within the racetrack patterns. In this way, controllers could be able to process the stack more effectively or even issue exit clearances to selected aircraft other than the one at the bottom of the stack (e.g. the ones closer to the exit point) [7]. In this paper, Holding Stack Management (HSM), Continuous Climb Operations (CCO), Continuous Descent Operations (CDO), and Trajectory Based Operations (TBO) procedures are chosen to study possible advantages of an additional 3D display in a 2D+3D setting. An experiment is designed and carried out, which uses NARSIM as the air traffic simulator and compares the traditional 2D display setting with the proposed 2D+3D display setting.

Twelve ATCOs participated in the experiment. Traditional human factors study questionnaires such as NASA-TLX, TRUST, etc., and Electroencephalogram (EEG) based emotion, stress and cognitive workload recognition to measure cognitive performance of ATCOs are used. EEG-based algorithms have high temporal resolution and allow recognizing emotion, stress and cognitive workload when the subject is performing the tasks. It has been successfully applied in human factors evaluation of conflict resolution aid and tactile user interface in air traffic control system [8]. Thus, the goal of this study is to examine the effectiveness of use of the 2D+3D display setting in comparison with the traditional 2D setting in supporting HSM, CCO, CDO and TBO procedures by evaluating the possible changes in cognitive workload, stress and emotion levels, and performance parameters of ATCOs.

2 Related Work

2.1 HSM, CCO, CDO and TBO procedures

The following operational procedures are investigated in the experiment to study human factors in relation to the use of the additional 3D display by ATCOs.

Holding Stack Management. HSM is defined as managing aircraft using the holding procedure. The holding procedure is a preassigned route, which contains aircraft inside a specified airspace sector while the ATCO gives them further instructions for clearance [9]. An aircraft is required to go into a holding procedure when an ATCO experiences high volume of traffic in the approach sector beyond what he/she could handle for a determined or non-determined time period. The ATCO then directs the aircraft to hold at a holding fix before permitting them inside the approach sequence. Pilots must obey to the holding procedure standards under the Instrument Flight Rules (IFR). This includes the speed of aircraft, entry procedures, rate of turn, and separation from other flights.

Continuous Climb Operation. The concept of CCO is being developed as the usable means of Departure Area Management. The framework of a CCO is defined as a continuous climb from take off to its cruising altitude. It is a flight operation where aircraft climbs to cruising altitudes without the need for level flight at intermediate altitudes. This operation offers a wide range of benefits such as the reduction in fuel burn, noise emissions, and radio telephony time while increasing the predictability of flight paths for both controllers and pilots [10].

Continuous Descent Operations. Similar to the CCO above, CDO could be applied when the aircraft was initialized to descend at a delayed time as compared to the conventional descent. CDO does not necessary mean the removal of step level-offs at the intermediate altitude but the reduction of the number of changes that the aircraft experiences in its approach [11]. It should be taken into consideration that certain limitations such as requirements for efficient scheduling and sequencing may still be present and thus, it makes CDO less usable. However, in CDO, a descending aircraft has reduction of fuel burn by having the smooth approach with minimum losses.

Trajectory Based Operation. Trajectory Based Operation provides highly flexible lateral and vertical flight profiles, which are modified based on the required accuracy, climbing and descending operations and traffic conditions. To optimize Trajectory Based Operation, the most suitable route from the origin to the destination should be identified based on airspace constrains as well as meteorological situations [12]. The development of computational algorithms to optimize TBO indicates evolution from the conventional Air Traffic Control methodologies currently in use. Thus, TBO can lead to lesser restrictions and improve airspace efficiency and capacity.

2.2 Human Factors Study in ATC

Cognitive workload in the context of Air Traffic Control is the mental effort required from ATCOs to process information with the aim of resolving, controlling and managing the given air traffic situation. As air traffic continuously rises in the past and coming decades, it is expected that ATCOs will face an increasing workload when they manage such dense airspace. In the recent years, a consensus has been achieved among research and operational communities on the importance of understanding human factors [13]. For example, to be able to reduce workload at working place, one has first to be able identifying the various aspects that contribute to cognitive workload in humans through some discrete measurement. It is widely accepted that there are three main classifications for the workload measurement: physiological, subjective, and performance-based measures [14]. The subjective scores are the most commonly used method and they are the basic criteria to compare other measures. However, recently, physiological measures started to be more in use as they are effective in the continuous measuring of the cognitive workload [14], making it useful to evaluate human factors in varying traffic levels scenarios in ATC [8]. The NASA-TLX form [15] is a multidimensional subjective measurement method which quantitatively represents the subject's perception of the workload experienced during the experiment in the form of 6 factors, namely mental demand, physical demand, temporal demand, performance, effort, and frustration level. Compared to unidimensional subjective scores, the multidimensional nature of the NASA-TLX form provides more in-depth analysis of the many aspects of workload [14].

Besides the traditional questionnaires, biosignals such as EEG, heart rate, etc. are used in human factor studies in ATC. The advantage of the biosignals is the continuous monitoring of the subjects psychophysiological states during the task performance. EEG-based technology has an advantage over other technologies as it has higher accuracy and high temporal resolution. There are already existing algorithms proposed to recognize emotion, workload, and stress, which are applied for data analyses in this paper. For emotion recognition, we use the subject-dependent algorithm proposed in [16] that recognizes negative, neutral, and positive emotional states with the predicted accuracy for 3 emotions as 72.22%. For mental workload recognition, we use the subject-dependent algorithm proposed in [17] that recognizes four levels of workload with the predicted accuracy as 80.09%. For stress recognition, we use the subject-dependent algorithm proposed in [18] that recognizes emotion-related 8 stress levels. Those algorithms use advanced machine learning techniques. The signal is filtered with bandpass, the features such as fractal dimension, statistical features are then extracted, and SVM classifier is used for classification.

3 Experiment

An experiment is proposed and carried out with 12 ATCOs to assess the use of the additional 3D display in HSM, CCO, CDO, and TBO procedures. EEG signals are recorded during the experiment to monitor the changes of the brain states such as emotion, stress, and cognitive workload of the subjects while they are working with 2D display and 2D+3D display settings. During the experiment, we have a series of questionnaires for the subjects to fill in, including intake questionnaire, and NASA-TLX, TRUST [19] questionnaires, and survey after each trial. The intake questionnaire includes demographical questions, ATCOs background, and consent form to participate in the experiment. The TRUST questionnaire contains two parts: deception and trust between the subjects and the system.

3.1 Subjects

The study involves 12 ATCOs, who have an experience in regulating air traffic in the Approach and Tower Control, as well as 3 students from the Nanyang Technological University to play the role as pseudo-pilots. These students have good knowledge in ATC and are familiar with the radiotelephony and the user interface of the air traffic simulator NARSIM. Six out of the 12 ATCOs are males. Three of 12 are approach controller trainees with 1-year experience; four are tower controllers with 6 to 7 years of experience; the rest are approach controllers with 1.5 to 8 years of experience.

3.2 2D+3D Display and ATC Simulation

The NLR Air Traffic Control Research Simulator (NARSIM) is used to represent the Terminal Control Area (TMA) of Singapore Changi Airport with the updated Standard Instrument Departure (SIDs) and Standard Arrival Routes (STARs) used by Civil Aviation Authority of Singapore (CAAS). The implemented 2D+3D system comprises the existing 2D visualisation display from NARSIM and an additional 3D display. The 3D display allows ATCOs to manipulate the plan view of the airspace into a perspective view, enabling them to view the vertical profiles of aircraft. Thus, it allows ATCOs to have better perspective of such profiles, and reduces potential workload that could arise in many situations, from heavy air traffic to unforeseen circumstances. In addition, the 3D display has features that are not available in a 2D only display such as “focus conflict” and “interactive trajectory prediction” functions. Fig. 1 shows the set-up of apparatus used in this study as follows.

Apparatus 1 is the main 2D radar display, a conventional 19.75 by 19.75 inch Plan Position Indicator (PPI) positioned in front of the subject. The 2D display provides an overview of the air traffic simulation and displays the information about the aircraft such as the position, airspeed, current flight level and the assigned flight level. The subject performs his/her tasks by clicking on the labels using only the mouse interface.

Apparatus 2 is the flight data display. It gives the subject the information of all the aircraft in the simulation. The flights in blue strips are the departing aircraft with information of the type of aircraft, take-off runway and the flight level for clearance. The flights in yellow strips are the arriving aircraft displaying information such as the type of aircraft, runway for landing, current flight level and assigned flight level.

Apparatus 3 is the 3D display (18.75 x 18.75 inch monitor screen), positioned on the left side of the subject's sight. Interface is by mouse only (right click to pan; scroll to zoom; left click to rotate), however, assume and transfer could not be done on the 3D display. Several functions are available at the top left and right corner of the display as follows:

1. Reset Camera: to reset the 3D view to the default.
2. Waypoints: to show the waypoints names along SIDs and STARs.
3. Safe Distance: to display cylindrical shaped (semi-transparent) around aircraft to help determine if aircraft are within safe zone.
4. Weather: not applicable in this study.
5. Prohibited/Restricted/Danger Areas: to display area that are not suitable for flights
6. Flight Labels: to collapse or expand the flight labels.
7. Focus Conflict: to zoom into the conflicting aircraft if there are any.
8. Clear TP: to remove Trajectory Prediction lines
9. Trajectory Prediction: to predict the position of aircraft in time to come. The time for prediction can be controlled interactively using the slider bar at the top right corner of the display.

Apparatus 4 is the Emotiv headset [20] which measures the psychophysiological changes. Emotiv EPOC has 14 channels located at AF3, F7, F3, FC5, T7, P7,O1, O2, P8, T8, FC6, F4, F8, and AF4. Every subject is required to wear the headset throughout the entire duration of the experiment. The subjects' EEG signals are recorded using Apparatus 5, a laptop with the Emotiv program connected via wireless Bluetooth.

The three students underwent 6 months of basic ATC training procedures to take part in this study as pseudo-pilots. They communicate with the subjects during the experiment. A pseudo-pilot uses a computer screen with the blipper displaying flight strips of aircraft under his/her control as well as the same overview 2D radar display that the subject is viewing. The blipper allows pseudo-pilots to control the maneuvers of aircraft after receiving commands from the ATCOs such as changing flight levels, heading, hold at specific waypoints, and transferring flights to radar or tower.

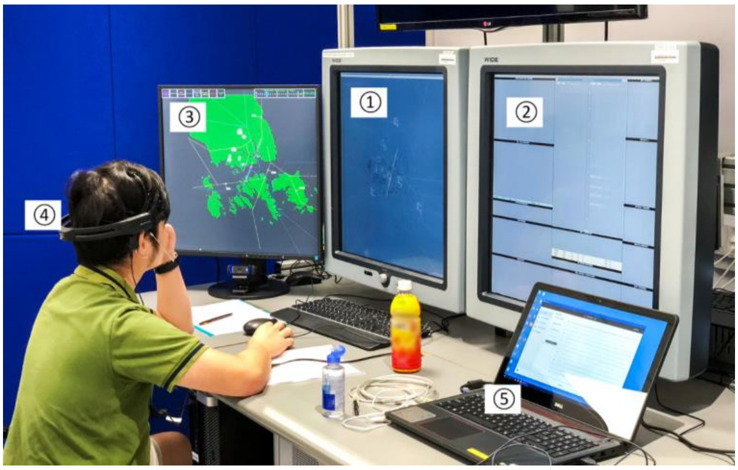

Fig. 1. Setup of the experiment.

3.3 Procedure

The experiment comprises two parts: using the NARSIM 2D radar display only and using the 2D+3D to perform HSM, CCO, CDO, and TBO. During the experiment, each subject follows the procedure:

1. Briefing of the experiment.
2. Filling up the intake questionnaire.
3. Training on the 2D NARSIM and 2D+3D. Each subject has 120 minutes training session to get familiar with 2D+3D display setting.
4. Setting-up of EEG headset and calibration of the EEG-based emotion and workload recognition algorithms [16, 17].
5. Conducting experiment part 1 (2D only or 2D+3D) which lasts for 30 minutes.
6. Filling up the questionnaires (NASA-TLX, TRUST) for part 1.
7. Conduct experiment part 2 (2D+3D or 2D only) which lasts for 30 minutes.
8. Filling up questionnaires (NASA-TLX, TRUST) for part 2 and the survey.

The steps from 5 to 8 are repeated for HSM, CCO, CDO, and TBO operational procedures. The balanced square Latin design is employed for the experiment. In each session of the experiment, subjects are required to communicate with the pseudo-pilots to issue appropriate altitudes, to maintain separation between aircraft, to accept all aircraft that entered their sector, to hand-off aircraft that left their sector, and to issue the correct radio frequency change. At the end of the experiment, a survey questionnaire is given to get feedback from ATCOs towards the 2D+3D display setting.

4 Data Analyses Results

The data including EEG, subjective ratings, and performance-based measures from NARSIM are collected during the simulation conducted in 2D and 2D+3D display configurations. The average of cognitive workload, emotion, and stress recognized from EEG is calculated across the 12 subjects for 2D and 2D+3D settings respectively. A paired two-tailed t-test is applied to check the significance of the difference between 2D and 2D+3D settings for each mental state. The significance level is set up at 5%, and the null hypothesis is defined as follows: the use of the 2D+3D display does not produce any significant differences as compared to the traditional 2D display. We analyze the results of HSM, CCO, CDO, and TBO procedures respectively.

For HSM, the average EEG workload across all 12 subjects is computed and plotted with 1-minute interval in Fig 2. The average workload recognized from EEG over the entire 30 minutes trial is 1.48 and 1.34 for 2D and 2D+3D display respectively. In other words, the average EEG workload experienced in 2D+3D display is lower as compared to the 2D display only. Paired t-test is carried out, and the result is presented in Table 1. It shows that the difference of cognitive workload experienced by ATCOs when they are working with the 2D+3D display and 2D display is significant ($p < 0.05$). The mean EEG stress experienced in 2D+3D display is also lower as compared to 2D display but not significantly ($p > 0.05$). However, the ATCOs feel significantly more negative when they are using 2D+3D. The average EEG emotion and stress across all the 12 subjects are computed and plotted with 1- minute interval in Fig 3 and 4 respectively. Two parameters are obtained from NARSIM system, namely fuel burn and radio telephony. Significantly higher fuel burn is observed in 2D+3D display ($p<0.05$) than in 2D only display. However, no significant difference of radio telephony parameter ($p>0.05$).

Besides analyzing the bio-signals and performance parameters from NARSIM for HSM, the correlation between the ratings received using traditional NASA-TLX meth-od and the workload recognized from EEG data is studied. Positive correlation has been found between NASA-TLX and EEG workload results for both display modes, which means the subjective rating is consistent with the workload results from EEG. From the results of the TRUST questionnaire, 55% of the ATCOs trust more in the traditional 2D display. This could be due to the better familiarity and day-to-day work with 2D display.

Another interesting observation is that the EEG cognitive workload of the ATCOs is negatively correlates with their corresponding years of experience. Though the correlation is not significant ($p>0.05$), it may indicate that the more experience the subject has, the lower the EEG workload he/she experiences when he/she is performing operational procedures regardless of the display modes. Similarly, the correlations between years of experience and EEG stress/emotion levels may also indicate that ATCOs with more years of experience are more positive and less stressed when they are using the 2D+3D display comparing to the less experienced subjects.

From the survey questionnaire, the following feedback was given by ATCOs: 1) they feel positive about being able to see the aircraft in 3D at holding stack; 2) they have better situational awareness when aircraft in holding is visualized in 3D. On the other hand, they criticized that 1) the current implementation of the interface is not very user friendly as they were not able to input headings and level easily; 2) there is a difference between how the mouse works for 2D and 3D Display, and it causes difficulty to change quickly from one to the other. Despite on the drawbacks of the current implementation, the results of the data analyses con-firm the advantage of using the additional 3D display during HSM operation.

Table 1. T-test for average EEG workload over total time for HSM operational procedure

	workload		Emotion		stress	
	2D	*2D+3D*	*2D*	*2D+3D*	*2D*	*2D+3D*
Mean	1.482	1.335	1.029	1.091	1.465	1.446
Variance	0.029	0.029	0.010	0.006	0.011	0.035
P(T<=t) two-tail	1.067E-05*		0.044*		0.553	

*Significant at $p < 0.05$;

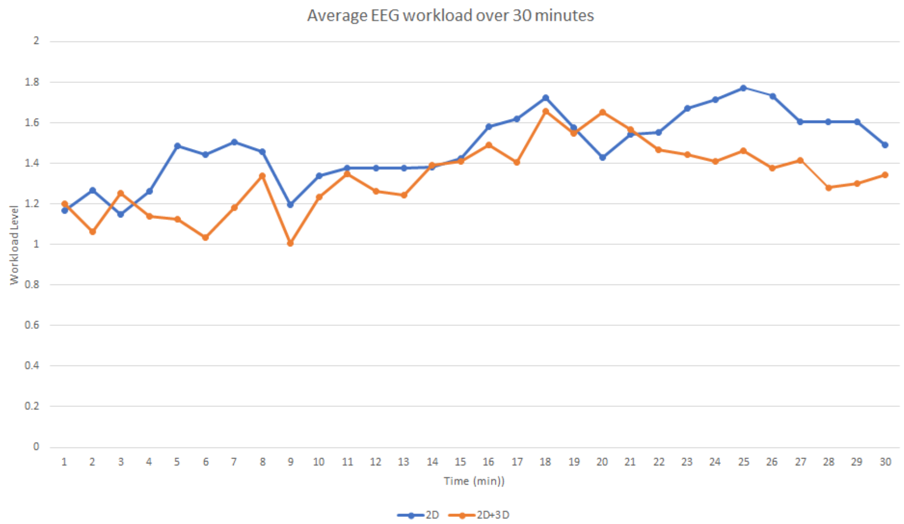

Fig. 2. Average EEG workload over total time for HSM operational procedure.

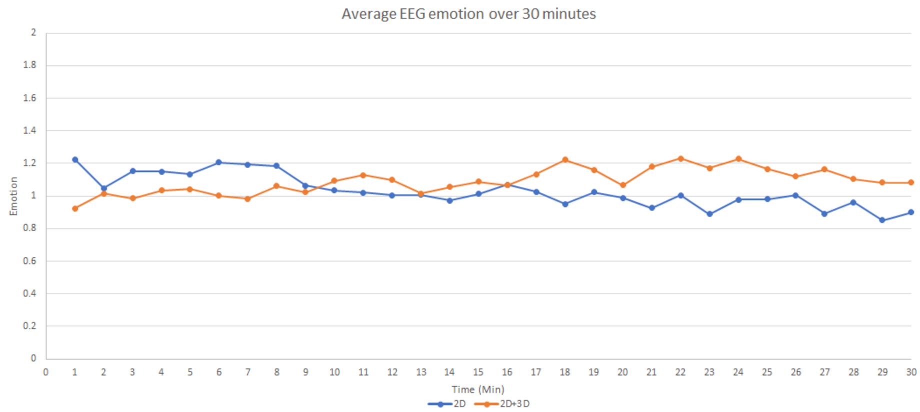

Fig. 3. Average EEG emotion over total time for HSM operational procedure.

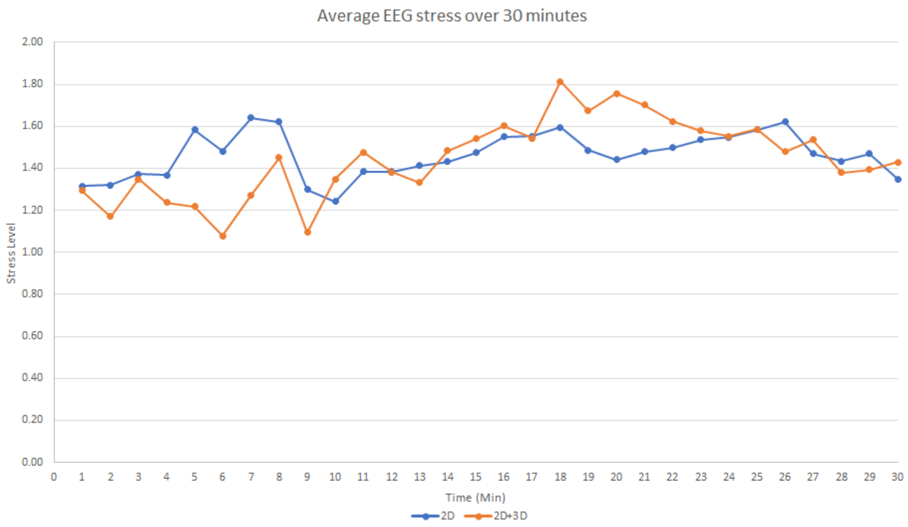

Fig. 4. Average EEG stress over total time for HSM operational procedure.

However, the data analyses results show that ATCOs may not benefit much from the use of the 2D+3D setting when they are performing CCO, CDO and TBO. The t-test on the average workload by 1-min interval shows that the ATCOs' EEG-based cognitive workload and stress levels are significantly higher ($p<0.05$). However, the ATCOs experience more positive emotions with 2D+3D display comparing to 2D only display (significantly more positive for CCO and CDO while not significantly for TBO). For CCO, it can be seen from NASA-TLX, the ATCOs have higher workload when they are using 2D+3D setting but not significantly ($p>0.05$). Equal number of ATCOs have trust in 2D and 2D+3D settings by results from the TRUST questionnaire. The fuel burn is lower but not significantly ($p>0.05$) and the radio telephony time increases but not significantly when 2D+3D is used ($p>0.05$). For CDO, from NASA-TLX, 2D+3D has higher workload ratings than 2D but not significantly ($p>0.05$). 58.3% of ATCOs have more trust in 2D radar as it is seen from the TRUST questionnaire. The fuel burn is higher but not significantly ($p>0.05$) and the radio telephony time increases but not significantly ($p>0.05$) when 2D+3D display setting is used comparing to 2D one. For TBO, the ATCOs rate in NASA-TLX that they have lower workload when using 2D+3D than 2D only display but not significantly ($p>0.05$). Equal number of ATCOs have trust in 2D and 2D+3D settings by results from the TRUST questionnaire. The fuel burn output by NARSIM is higher, and the radio telephony time increases when 2D+3D is used but not significantly ($p>0.05$).

5 Conclusion

In this paper, we proposed and implemented the experiment to study Holding Stack Management, Continuous Climb Operations, Continuous Descent Operations, and Trajectory Based Operations procedures in relation to the use of the additional 3D display in 2D+3D setting. Twelve Air Traffic Control officers (ATCOs) were invited to take part in the experiment which used the EEG-based emotion and stress recognition algorithms to evaluate whether the additional 3D display setup can be beneficial to ATCOs when HSM, CCO, CDO, and TBO operational procedure were performed. A 30-minute scenario was implemented and performed in 2D display only and 2D+3D settings. EEG data were recorded and traditional human factors questionnaires were given to the participants. State-of-the-art algorithms of cognitive workload, emotion and stress recognition from EEG were implemented to process and analyse the data. The results of the data analyses showed that by using 2D+3D display setting, more positive emotions were experienced by ATCOs in TBO, CCO and CDO procedures than in 2D setting; however, they had higher stress and workload levels than in 2D setting in those procedures. In HSM, reduced stress and significantly lower workload were experienced by ATCOs when they were using 2D+3D setting. Thus, ATCOs benefited from use of 3D visualization in HSM operational procedure. The experiment results showed that further improvement of the 3D display implementation and analyses of operational procedures in relation to 3D visualization could reduce cognitive workload and stress of ATCOs in increasing traffic density demand.

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