THE JOURNAL OF NAVIGATION (2020), **73**, 678–696. © The Royal Institute of Navigation 2019
doi:10.1017/S0373463319000882

EEG-Based Analysis of Air Traffic Conflict: Investigating Controllers' Situation Awareness, Stress Level and Brain Activity during Conflict Resolution

Fitri Trapsilawati, Muhammad Kusumawan Herliansyah,
Agustyandini Sekar Asih Nur Sari Nugraheni, Mifta Priani Fatikasari,
and Gharsina Tissamodie

(*Department of Mechanical and Industrial Engineering, Faculty of Engineering,
Universitas Gadjah Mada, Jalan Grafika no. 2, Yogyakarta 55281, Indonesia*)
(E-mail: fitri.trapsilawati@ugm.ac.id)

The effects of air traffic conflict geometry have been well investigated in prior studies, particularly in the context of the pilot, though little in the context of the air traffic control officer (ATCO). No study to date has investigated the effects of conflict geometry on human factors variables of ATCOs through objective and physiological approaches. This study examines the effects of conflict geometries on ATCO situation awareness, stress level and brain activity during conflict resolution. Fifteen participants were instructed to resolve six different conflict geometries: crossing level, crossing non-level, converging level, converging non-level, overtaking level, and overtaking non-level. The results indicate that converging and crossing conflicts led to lower situation awareness (SA), higher stress level, and higher theta activation at the temporal and parietal lobes. Level conflict led to lower SA. The findings offer two implications, providing insights for the formal guidelines in ATC conflict resolution training and provision of inputs for the conflict resolution aid development.

KEYWORDS

1. Conflict geometry. 2. Air traffic control. 3. Situation awareness. 4. EEG, brain activity.

Submitted: 22 March 2019. Accepted: 2 October 2019. First published online: 20 November 2019.

1. INTRODUCTION. The rapid rise in air traffic density has induced a higher possibility of air traffic conflict, proven by the increased number of pilots who reported near mid-air collisions, from 85 cases in 2012 to 350 cases in 2016 (USDOT, 2016). This increase has introduced a challenge to air traffic management systems, given that the current systems have already been approaching maximum capability (CANSO, 2012).

Air traffic conflict occurs when two aircraft fail to keep the minimum separation required for safe passage. Each aircraft in the sky currently should fly with minimum separation of five nautical miles laterally and 1,000 feet vertically (Nolan, 1999). When this minimum separation is violated, the conflicting aircraft pair typically have different positions involving lateral angle of the trajectory intersections, such as crossing, converging, and overtaking both at level and non-level altitude, which is defined as ‘conflict geometry’ (Erzberger, 2006; Thomas and Wickens, 2005).

Understanding conflict geometry of conflicting aircraft is essential; it affects the detection and resolution of the conflict. Prior studies have examined conflict geometry from both the pilot and ATCO points of view. The effects of conflict geometry were mainly examined with respect to pilots’ manoeuvring preferences. Pilots generally prefer to turn away from intruder aircraft and tend to choose vertical manoeuvres for conflict resolution (Thomas and Rantanen, 2006). Rantanen and Nunes (2005) investigated conflict geometry effects on conflict detection performance and found a hierarchical strategy of resolution, with pilots first checking altitude information and then other dimensions. Eyferth et al. (2003) investigated three different conflict classifications (crossing, descending and same level) on performance and found that vertical conflicts were detected faster, with a higher ATCO confidence level.

Conflict resolution was examined in other investigations as well. Rantanen and Wickens (2012) performed a study analysing 256 conflict resolution manoeuvring cases obtained from five air traffic control (ATC) centres in the US. Their results revealed conflict geometry effects on ATCO manoeuvring preferences. They also found regular patterns of conflict resolution manoeuvres, where vertical manoeuvres were preferred over lateral ones due to gravity exploitation, easy visualisation, rapid execution and preservation of airspace structure.

Numerous studies of conflict geometry have focused on performance and resolution manoeuvring preferences. However, to our knowledge based on an exhaustive literature review, several research gaps remain to be addressed by the present study: (1) no study has examined the effects of various conflict geometries on ATCO cognitive aspects, particularly situation awareness; (2) prior studies have never investigated the conflict geometry effects on ATCO stress level; and (3) no study has been conducted to explore what is actually happening in the brains of ATCOs during conflict resolution.

ATCOs must direct a correction manoeuvre to avoid air traffic conflict in an effective and expedient manner. In their investigational study of conflict resolution data, Rantanen and Wickens (2012) identified a pattern in conflict resolution manoeuvring wherein ATCOs tended to apply vertical manoeuvre more than lateral and speed manoeuvres. This might be due to the difficulty level of the resolution manoeuvre and conflict geometry involved, with vertical manoeuvre being the most expeditious manoeuvre to apply, followed by a lateral manoeuvre including heading, and lastly a speed manoeuvre.

ATCOs must manage numerous aircraft at a time, and when a conflict occurs the time interval between conflict alert and collision is exceedingly short, triggering immediate ATCO stress. This issue is also related to the situation awareness of the ATCOs. If an ATCO encounters high stress, then their spontaneity, situation awareness, prediction and decision-making skills, as well as focus and concentration, would be degraded, thus compromising the airspace safety within their controlled sector. Therefore, the investigation of conflict geometry effects on these human factor issues, including situation awareness (SA) and stress level, are inevitably essential to enhancing air traffic safety.

Further, there are several measures of stress level, including subjective, performance-based and physiological stress (Hou et al., 2017). Subjective stress measurement is typically performed using questionnaires, but the results tend to also be subjective and are hard to continuously evaluate across the entire experiment or observation. Performance-based measures are derived from task performance during the experiment or observation. This measure can reflect the performance accurately, but cannot directly detect the stress level encountered by participants. To address these issues, physiological measurement of brain activity allows for providing continuous evaluation and direct analysis of stress level in real time.

Throughout these studies, there is little information concerning formal standards taught for conflict resolution during ATCO training. Although the definitions and guidelines for each type of separation standard is provided partially by ICAO (2013), no clear guidance is available on how to resolve various conflicts effectively and efficiently. The instructors transfer such know-how information to the novice controllers during their on-the-job training in the ATC facilities (Rantanen and Wickens, 2012). Examining the effects of general conflict geometry on ATCO SA, stress level and brain activity during conflict resolution will greatly benefit the formulation of formal standard of conflict resolution manoeuvres based on ATCO mental state. To this end, we conducted an experimental study where participants with ATC training were responsible for controlling aircraft and resolving conflicts with various geometries. The study further highlighted extant research gaps, and hypotheses were derived accordingly based on the literature review, as elaborated in Section 2.

2. LITERATURE REVIEW.

2.1. *Conflict geometry and air traffic complexity.*

Several prior studies tied air traffic complexity with geometric relationships between aircraft (Histon et al., 2002; Murphy et al., 2012). Boag et al. (2006) proposed levels of air traffic conflict difficulty in terms of relational complexity. If an aircraft does not violate any separation minima, then the relational complexity is 0. If an aircraft is in a one-dimensional conflict, then the complexity or difficulty level is 1. When a conflict involves more than one dimension, the difficulty level increases accordingly. They validated this metric using the rating of the ATCOs.

The complexity is related with the closure angle and time of flight as indicated by aircraft speed (Hilburn, 2004), as well as by location and time to form a ‘flight shape profile’ of future trajectory (Wee et al., 2018). Another study by Wee et al. (2019) attempted to measure the complexity of a dynamic airspace using the eye-tracking method and develop a framework for it by syncing the raw eye data and the raw radar data involving aircraft position and label data. Connecting this with the relational complexity of the situation, the difficulty level of air traffic conflict varies depending on its geometry as well as time of flight. Erzberger (2006) suggested that converging conflict involving three geometrical dimensions as well as sequencing constraints is the most difficult to resolve. Crossing is the second most difficult, since it does not involve flight time for sequencing constraint. Lastly, overtaking is perceived as least difficult because it only deals with one geometrical dimension and speed.

Although studies about conflict geometry have been well documented in conflict detection, there is a general lack of studies in conflict resolution. Research concerning conflict geometry has merely focused on task performance and manoeuvring options. Despite the contribution of conflict geometry to different levels of conflict difficulty, there has been no study available to investigate the effects of conflict geometry on SA and stress level as essential human factor variables underlying ATCO stress states.

2.2. *Situation awareness in air traffic control.* *Situation awareness* is a cognitive state related to the assessment of dynamic situation through environmental cues (Isaac and Ruitenberg, 2017) and is an essential requirement for safe operation in complex air traffic control systems (Sarter and Woods, 1991). Extensive research concerning SA is available in the ATC domain, and is mainly focused on the investigation of traffic load as well as display on SA. Nunes (2003) manipulated air traffic into two levels (i.e. low and high airspace load) and found that the SA was worse during high airspace load. Concerning display, Suijkerbuijk et al. (2005) found that vertical situation displays (VSDs) promoted higher SA than did only horizontal situation displays. Correspondingly, Endsley et al. (1999) found that predictive display better enhanced ATCO SA than did baseline display. In addition, Li et al. (2017) found that more parameters accounted in an alarm system can also potentially promote situation awareness in vessel traffic operations. A more recent study in vessel traffic also proposed a smart alarm system that involved various multimodal cues, including sound, geometric and haptic cues to enhance SA of operators (Li et al., 2019a). These collective findings might be explained by the fact that participants who demonstrate high cue utilisation have higher SA (Falkland and Wiggins, 2019).

Conflict geometry is a vital aspect in conflict resolution handling. Moreover, regardless of the importance of SA in air traffic as a vital requirement in air traffic control operations, there have been no studies to investigate conflict geometry and its relation to SA. This reveals the first gap. Referring to the different conflict geometry in Section 2.1, we hypothesised that higher SA would be observed during the resolution of conflict involving fewer dimensions (H1), since ATCOs could have higher cue utilisation on fewer dimensions.

2.3. *Air traffic controllers' stress.* Stress is an essential variable to be investigated in ATC domain, since the majority of ATCOs (more than 88 per cent) encounter stress during their work (Grandjean et al., 1971). An empirical study analysing ATC stress using questionnaire and saliva tests indicated excessive stress for ATCOs (Zeier, 1994). Air traffic control is a stringent work domain, with strict operational procedures and constraints. The job characteristics and the significant responsibility induce enormous stress (Jou et al. 2013). Jou et al. (2013) found that the highest trigger of ATCO stress was the air traffic load, including the stricter attentions required during traffic conflict resolution. However, prior studies have only concentrated on shift (Freitas et al., 2017), eye movement (Renata et al., 2018) and traffic load (Prevot et al., 2012; Westin et al., 2013; Yang and Dattel, 2017) as the main causes of stress, fatigue and workload.

Though numerous studies have shown that stress is an important construct in ATC and is affected by shift and traffic load, due to stricter attentions required, no previous study dissected the effect of aircraft structure on ATCO stress level during conflict resolution. This highlights the second gap. Given different difficulty levels of conflict geometry as mentioned in Section 2.1, we hypothesised that ATC stress levels would vary depending on conflict geometries, where stress level would be highly induced during the resolution of more-complex conflicts (H2).

2.4. *EEG studies in air traffic control.* EEG has been widely used in human-related studies. According to Tan and Nijholt (2010), brain activity is the only physiological function that remains active when humans lose control of their physical movement, such as arm, eye, head, or speech control. The brain is the most complicated body part, processing both sensory and motor functions (e.g. planning, pattern recognition, reasoning). Indeed, there

Figure 1. Electroencephalogram (EEG) device (Emotiv, 2019).

are many other physiological measures available to investigate cognitive functions, such as heart rate, eye movement and saliva. Although the eye movement can be associated with an individual's mental fatigue state (Renata et al., 2018), and there is a correlation between the increase in eye movements and the response time in different mental fatigue (Li et al., 2019b), numerous other cognitive processes remain that are difficult to measure by external manifestation. Brain sensing, therefore, is a promising measure for directly quantifying and studying the cognitive aspects of a human being (Tan and Nijholt, 2010).

This applies in the ATC context and several studies supported the idea. Wilson (2002) analysed physiological responses, including heart rate, brain activity and blink rates, during different flight rules (i.e. visual flight rules (VFR), instrument flight rules (IFR), and high-speed instrument flight rules) and registered significant changes on the brain activity due to varying flight rules. Other studies (Astolfi et al., 2012; Di Stasi et al., 2015; Kiroi et al., 2016) also empirically analysed the brain activity during different phases of flight using EEG and found that EEG was an informative means for assessing each flight phase. The highest brain activity was observed during landing and takeoff, and lower brain activity occurred during cruising. There was also a coherent correlation in the frontal and parietal lobes between pilot and copilot during collaborative tasks. Hou et al. (2017) also validated use of the EEG to measure real-time workload in the ATC domain.

The brain is the control centre of the human body, and consists of four lobes: frontal, parietal, temporal, and occipital. The frontal lobe is associated with problem-solving (Dharmawan, 2007), visual attention and planning (Abbass et al., 2014). The parietal lobe controls sensory and motor system, awareness and perception (CNS, 2017; Smelser and Baltes, 2001). The temporal lobe deals with information filtering (Gamon, 2016), object recognition (Abbass et al., 2014) and sensory processing, as well as memory operations involved in ATC tasks (Giraudet et al., 2015). The occipital lobe is responsible for visual perception (e.g. colour perception) (Frackowiak, 1998).

The brain lobes consist of so many neurons. The activity of these neurons is reflected through electric pulses, so-called brainwave. Human brain has different wave frequencies depending upon their cognitive processes. Delta frequency waves occur when humans fall asleep (Bernardi et al., 2019). Alpha waves are commonly observed during relaxation (Lagopoulos et al., 2009). Theta waves are associated with short-term memory (Klimesch, 1994). Theta wave activity is also a reliable measure of mental workload

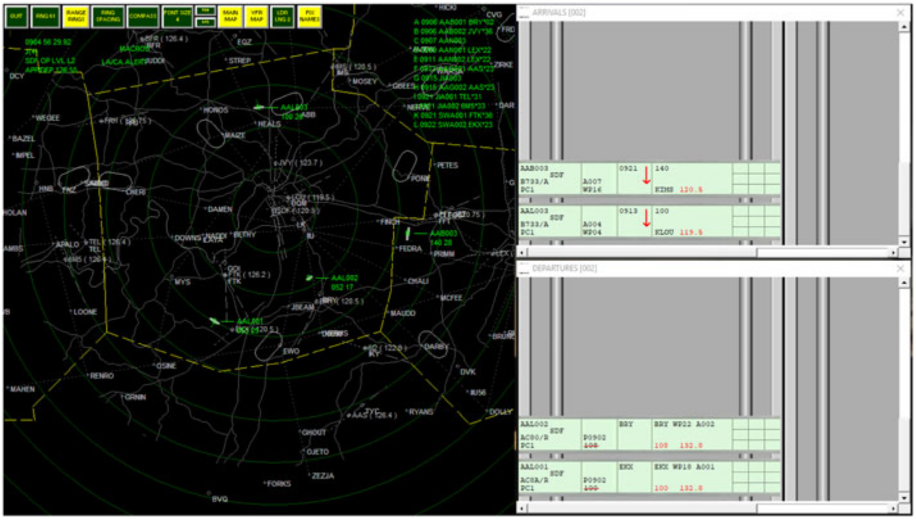

Figure 2. ATC Simulator®2.

Figure 3. Xavier software (Emotiv).

during time-related tasks, such as that for ATC (Shou and Ding, 2013). Beta waves control emotion (Li et al., 2018).

Despite the promising insight that EEGs can offer about the higher-order human cognitive processing that takes place in the brain (Weiland et al., 2013), there has been no study to examine the effect of different conflict geometry on brain activity. The EEG studies have been limited to flight phases, rules and information display (Borghini et al., 2015). This is the third gap. Since conflict geometry is highly associated with air traffic safety, its dynamic effect on brain activity should be studied and, hence, is addressed in this research.

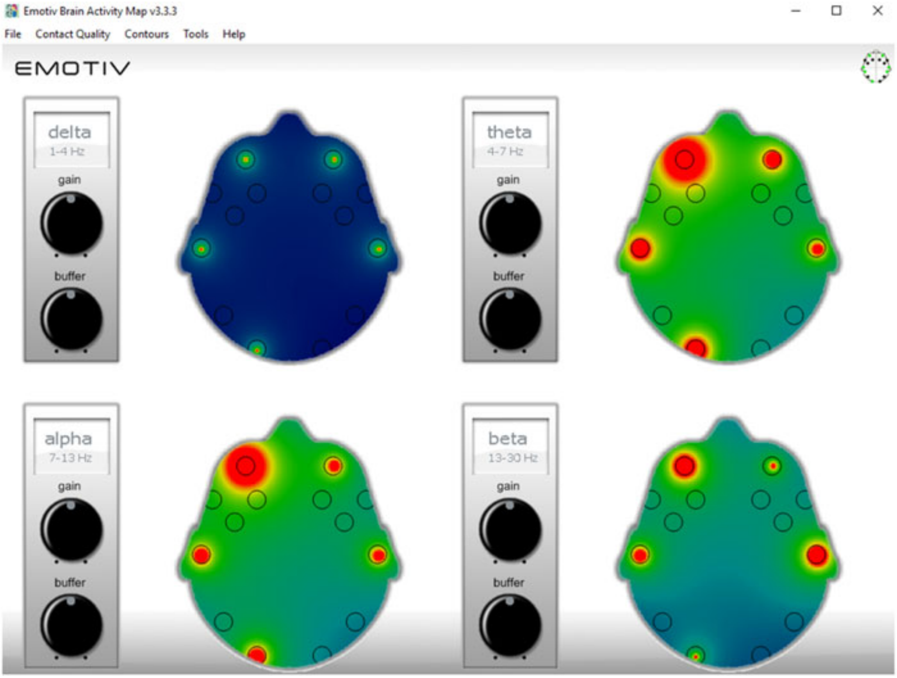

Figure 4. Brain Activity Map software.

Table 1. Experimental design.

Condition	Crossing	Converging	Overtaking
Level	X	X	X
Non-Level	X	X	X

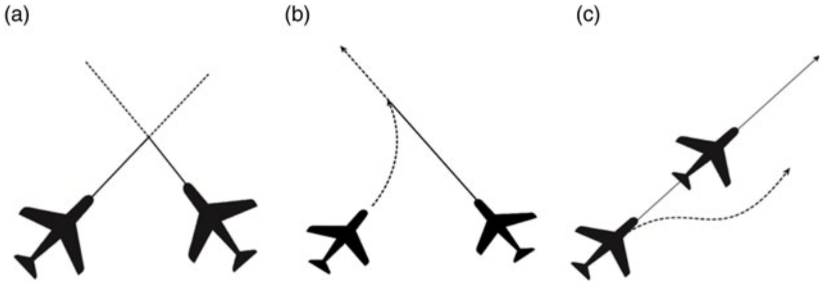

Figure 5. Lateral conflict geometries: (a) crossing, (b) converging, (c) overtaking conflicts.

Because human brains have different lobes and waves associated with different functions, we hypothesised that various conflict geometries would affect ATCO brain activity during conflict resolution. Particularly, the lobes related to the visual attention and information processing as well as waves associated with memory would be more activated during the resolution of conflict involving more geometrical dimensions (H3).

3. METHODS.

3.1. *Participants.* Fifteen male undergraduate students aged 20 to 23 years old participated in the research. The students received ATC training and had at least a 70 per cent score in the ATC task. During the training, there were six conflict scenarios, and only those participants who successfully resolved at least five conflict scenarios could join the formal data collection. According to Pierce et al. (2013), an ATCO is declared as qualified when obtaining a 70 per cent score for the AT-SAT test.

3.2. *Apparatus.* Three work stations were provided for the ATCO, the pseudo-pilot and the experimenter. At the first work station, two monitors were provided for the ATCO, displaying the ATC simulator and situation awareness queries. The ATCO was requested to wear a five-channel electroencephalogram (EEG) device (Figure 1) on their head during the experiment. At the second station, the ATC simulator display and control (i.e. keyboard and mouse) were provided for the pseudo-pilot to respond to the ATCO's commands. The ATCO–pilot communication was conducted through verbal command, mimicking real ATC operations. An ATCSimulator®2, a PC-based ATC simulator displaying a 60-NM range radar display, arrivals and departures flight progress strips (Figure 2), was used. ATCSimulator®2 is also equipped with an ATC-Sector Design Kit (ATC-SDK) to create air traffic and conflict scenarios by manipulating fleet times, entry and exit points, and speeds of aircraft. The ATC simulator would activate an alert indicated by a beeping sound when a conflict occurred (i.e. when five-nautical-mile lateral and 1,000-feet vertical separations were violated).

At the third station, a monitor was provided for the experimenter to monitor the ATCO stress level and brain activity using Xavier (Figure 3) and Brain Activity Map (Figure 4) software, respectively.

3.3. *Design.* A within-subjects design with two factors (i.e. lateral and vertical) was adopted (Table 1). The lateral factor consisted of three levels: crossing, converging, and overtaking, as shown in Figure 5. The vertical factor had two levels: level and non-level. *Crossing conflict* occurs when two aircraft having different directions intersect at one point in their respective paths. *Converging conflict* occurs when two aircraft fly into one merging point on their paths. *Overtaking conflict* occurs when two aircraft are on the same airway and direction, with the following aircraft flying faster than the preceding one. The conflict was at level position when the two conflicting aircraft were at the same altitude. Non-level conflict occurred when both conflicting aircraft were at different altitudes but remained within less than 1,000 feet separation. The conflict scenarios were presented with double cross-over design, where half of the participants first encountered level conflict and the remaining half first encountered non-level conflict. Each one-third of participants encountered crossing, converging, and overtaking first, respectively.

There were three dependent measures in this study: situation awareness (SA), stress level and brain activity. Situation awareness was assessed during the entire experiment using the Situation Present Assessment Method (SPAM) (Durso et al., 1999). The accuracy and time required to answer the SPAM queries after the participants were ready reflect the measure of SA (Durso et al., 2004). Consequently, probe response latency and accuracy were recorded as SA measures. Probe response latency indicated the time interval between the onset of a question and a participant's response, while the percentage of the correct response toward the SA questions reflected the accuracy.

For *the stress level*, Xavier software from Emotiv was used to record the stress level of the participants. The Xavier software provides the stress level along the experiment time.

Only the stress level data during conflict resolution of each conflict scenario were captured and analysed.

The brain activity was recorded using Brain Activity Map software that showed signal power of alpha, beta, delta and theta frequencies for each brain channel. There were five channels observed in this study, including right and left frontal, right and left temporal, and parietal lobes. Each channel was perceived as activated when the power of each frequency registered as high, as indicated by the red region over the channel.

3.4. *Tasks and procedure.* Participants were requested to perform ATC tasks, particularly to maintain separation between aircraft and resolve potential conflicts. The pilot–ATCOs communication was accomplished through voice transmission. The participants handled all arriving and departing aircraft in their controlled sector. Participants were requested to provide altitude clearance for landing, instruct an instrument landing system (ILS) clearance for approach and hand over the aircraft to the tower controller. Participants were also responsible for achieving climb of the aircraft to an appropriate exit altitude and handing over the aircraft to adjacent facilities.

The pseudo-pilot inserted keystroke commands to the ATC simulator in accordance with the ATCO's voice directions. The keystroke commands were translated into a synthetic pilot voice according to formal ATCO–pilot communication phraseology.

An average three-hour training session was provided for participants before the experiment. During the training session, participants were briefed and introduced to the ATC simulator. In the training session, six conflict geometries were provided for participants to resolve. Participants who successfully resolved at least five conflict geometries were eligible to proceed to the experiment session. By the end of the training session, all departing and arriving aircraft could be successfully cleared by the participants.

Prior to the experiment session, participants filled out a consent form. After that, an EEG device was set and calibrated to each participant. During the experiment session, six conflict geometries were placed in the scenario. There were four-minute intervals between each conflict geometry scenario. On top of the conflicting pairs, there were dummy aircraft set as traffic aircraft in the scenario, to preserve the ecological validity of the experiment. Participants were instructed to resolve the conflicts and perform other appropriate ATC activities (e.g. climb and land the aircraft) to deal with the simulated air traffic conditions.

Situation awareness-ready probes and questions were also provided during the experiment. If participants had additional cognitive resources, they were encouraged to respond to the SA probes and questions. Each probe appeared every four minutes and there were six probes throughout the experiment, corresponding to the conflicts. If participants did not respond within one minute to the presence of the probes, the probes would disappear.

3.5. *Statistical analysis.* A 3(lateral) × 2(vertical) repeated-measure ANOVA was performed to analyse probe response latency and stress level. In addition to the omnibus analysis, post-hoc tests using Least Significant Difference (LSD) were performed for appropriate variables. If the data violated the assumption of normal distribution, then non-parametric tests including Friedman and Wilcoxon signed-rank tests were performed for the lateral and vertical factors, respectively.

The probe response and the brain activity data were binary. Since the observations were also dependent, analyses were performed using Generalised Estimating Equations (GEE) to fit both conditions. The GEE method was chosen because it did not require linear relation between independent and dependent variables nor normality and homogeneity assumptions of the data.

Table 2. The brain activity results.

Brain section	Wave frequency	Factor	X^2	P-value	Significance
Right frontal lobe	Theta	Lateral	1·99	0·369	Not sig
		Vertical	2·14	0·144	Not sig
	Alpha	Lateral	3·05	0·218	Not sig
		Vertical	4·85	0·028	Significant
	Betha	Lateral	3·92	0·141	Not sig
		Vertical	0·54	0·461	Not Sig
Right Temporal Lobe	Theta	Lateral	19·05	0·000	Significant
		Vertical	0·61	0·434	Not Sig
	Alpha	Lateral	4·16	0·125	Not Sig
		Vertical	0·79	0·373	Not Sig
	Betha	Lateral	1·50	0·472	Not Sig
		Vertical	0·17	0·682	Not Sig
Parietal Lobe	Theta	Lateral	7·43	0·024	Significant
		Vertical	0·07	0·797	Not Sig
	Alpha	Lateral	0·06	0·986	Not Sig
		Vertical	2·90	0·088	Not Sig
	Betha	Lateral	1·15	0·469	Not Sig
		Vertical	0·43	0·513	Not Sig

Table 3. Parameter estimates of right temporal alpha.

Reference category: Yes				
Status		B	df	Sig
No	Overtaking*Converging	0·628	1	0·219
	Crossing* Converging	−0·239	1	0·763
	Overtaking* Crossing	0·867	1	0·181
	Non-level* Level	−1·323	1	0·028

*indicates the comparison value between the pairs.

Table 4. Parameter estimates of right temporal theta.

Reference category: Yes				
Status		B	df	Sig
No	Overtaking* Converging	2·513	1	0·001
	Crossing* Converging	0·785	1	0·326
	Overtaking* Crossing	1·728	1	0·000
	Non-level * Level	−0·516	1	0·434

Table 5. Parameter estimates of parietal theta.

Reference category: Yes				
Status		B	df	Sig
No	Overtaking* Converging	1·107	1	0·013
	Crossing* Converging	3·58	1	1·000
	Overtaking* Crossing	1·107	1	0·047
	Non-level * Level	0·11	1	0·797

4. RESULTS.

4.1. *Situation awareness measures.*

4.1.1. *Probe response latency.* Due to the violation of normality, a non-parametric Friedman test was conducted and rendered a significant chi-square value of 8·08 ($p = 0{\cdot}018$), supporting H1. Post-hoc tests using a Wilcoxon signed-rank test were performed and revealed that the probe response latency for converging conflict ($Mdn = 12$) was significantly higher than in the overtaking conflict ($Mdn = 12$), $Z = 2{\cdot}38$, $p = 0{\cdot}017$, indicating lower SA during converging conflict as compared to during overtaking conflict. There was no significant difference between crossing ($Mdn = 13$) and converging ($Mdn = 12$), $Z = 0{\cdot}14$, $p = 0{\cdot}89$, nor between crossing ($Mdn = 13$) and overtaking ($Mdn =$ 12),

$Z = 1{\cdot}72$, $p = 0{\cdot}085$. The H1 was therefore partially confirmed. For the vertical factor, a Wilcoxon test was also performed and showed significant effect, $Z = 2{\cdot}93$, $p < 0{\cdot}01$, indicating that SA was lower when two aircraft were at a level position ($Mdn = 13$) than when at a non-level position ($Mdn = 12$).

4.1.2. *Question probe response.* No significant effect of lateral factor was found on question probe response ($\chi^2(2) = 1{\cdot}74$, $p = 0{\cdot}419$). The vertical factor was also not significant in affecting question probe response ($\chi^2(1) = 1{\cdot}65$, $p = 0{\cdot}199$).

4.2. *Stress level.*

The effect of lateral geometry on stress level was significant, $F(2, 28) = 3{\cdot}51$, $p = 0{\cdot}044$, indicating that H2 was supported. The post-hoc tests (LSD) showed that stress level was higher during converging conflict ($M = 56{\cdot}23$, $SD = 19{\cdot}96$) than during overtaking conflict ($M = 50{\cdot}27$, $SD = 14{\cdot}00$) ($p = 0{\cdot}022$). No significant differences were found between converging and crossing ($M = 50{\cdot}07$, $SD = 10{\cdot}96$) ($p = 0{\cdot}062$), nor between crossing and overtaking ($p = 0{\cdot}938$). The vertical geometry was not significant, $F(1, 14) = 2{\cdot}36$, $p = 0{\cdot}147$. The Mauchly's statistical test indicated that assumption of sphericity for interaction data had been violated ($\chi^2(2) = 15{\cdot}59$, $p < 0{\cdot}01$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0{\cdot}59$). The interaction effect between lateral and vertical geometries on the stress level was also not significant, $F(1{\cdot}18, 16{\cdot}48) = 0{\cdot}79, p = 0{\cdot}405$.

4.3. *Brain activity.*

GEE analyses to examine the effects of lateral and vertical factors were performed for each brainwave frequency at each channel. The overall results are shown in Table 2. The vertical factor was significant in influencing the alpha frequency in the right frontal lobe ($\chi^2(1) = 4{\cdot}85$, $p = 0{\cdot}028$). The lateral factor was significant in influencing the theta frequency in the right temporal ($\chi^2(2) = 19{\cdot}05$, $p < 0{\cdot}01$) and parietal ($\chi^2(2) = 19{\cdot}05$, $p < 0{\cdot}01$) lobes, respectively. These significant results showing that H3 was upheld were further elaborated in the following.

4.3.1. *Right frontal lobe – alpha frequency.* The parameter estimates shown in Table 3 indicated that the alpha frequency at the right frontal lobe was more activated when the conflict was non-level than when the conflict was level ($B = -1{\cdot}32, p = 0{\cdot}028$). Alpha waves are associated with relaxation; the activation of alpha wave during non-level conflict indicated that non-level conflict was less complex than was level conflict. This was particularly true given harder visualisation of aircraft flying at similar altitude. There was no difference in the right temporal lobe activity due to the lateral geometry.

4.3.2. *Right temporal lobe – theta frequency.* For the right temporal lobe, as shown in Table 4, the theta frequency was more activated during converging conflict than during overtaking conflict ($B = 2{\cdot}51$, $p = < 0{\cdot}01$). It was also more activated during crossing conflict than during overtaking conflict ($B = 1{\cdot}73, p =< 0{\cdot}01$). Theta frequency is usually observed during high mental workload and is associated with memory. Converging and crossing conflicts led to higher workload and required greater memory functions to be resolved since both conflicts involved greater spatial dimensions as well as time of flight to consider than did overtaking conflict.

4.3.3. *Parietal lobe – theta frequency.* The results shown in Table 5 revealed that converging conflict was associated with higher activation of theta frequency at the parietal lobe than was overtaking conflict ($B = 1{\cdot}11$, $p = 0{\cdot}013$). Similarly, crossing conflict was also associated with higher activation of the frequency than was overtaking conflict ($B = 1{\cdot}11$, $p = 0{\cdot}047$). Theta activation in the parietal lobe is also associated with memory to promote position awareness. Converging and crossing conflicts required complex analyses of distance, route and speed of aircraft.

5. DISCUSSION.

The current experiment addressed the gap of the conflict geometry investigations of prior studies that focused only on the manoeuvring preferences of the pilot and included little examinations from the perspective of ATCOs. We found significant effects of lateral and vertical conflict geometries on various human factors elements examined through objective and physiological approaches to disclose what happens with ATCO cognitive resources during conflict encounters. We believe that this is the first study to examine these issues.

The SA was lower in converging conflict than in overtaking conflict. ATCOs only considered speeds of conflicting aircraft, so it was easier for ATCOs to detect and resolve the conflict earlier (Krozel and Peters, 1997). In addition, SA was low when ATCOs focused on the conflicting aircraft (Chatterji and Sridhar, 2001). For the vertical factor, SA was lower when two aircraft were at a level position than when they were at a non-level position. This is particularly true since level conflict demanded that ATCOs be stricter for information selection and analysis; therefore, their focus was on the level information and neglected other non-conflict information (Sperandio, 1978). In addition, the visualisation of conflict involving vertical attribute was harder than conflict involving lateral conflict, since the information regarding z-axes was only provided on the data-tag and needed to be processed further in the working memory (Trapsilawati et al., 2017).

The result on stress level was in the expected direction, along with the SA finding that converging conflict led to higher stress than did overtaking conflict. This was due to the additional resources needed to predict the closest point of approach in terms of angle in the converging conflict, which was not the case in the overtaking conflict, since both aircraft were already on the same route. Scallen et al. (1996) supported this observation that converging conflict is difficult and challenging to resolve, a fact proven by the high number of unresolved converging conflicts in their research. Erzberger (2006) also agreed that two aircraft flying convergent into a same point was the most difficult conflict to resolve, therefore triggering higher stress levels.

Importantly, we did research on participants' brain activity while resolving conflict and found several interesting results, confirming H3. First, we found that alpha wave frequency in the right frontal lobe was more activated during non-level conflicts than during level conflicts. The right frontal lobe is highly associated with complex decision-making ability that requires prediction and judgement (Gomez-Beldarrain et al., 2004). During conflict resolution, ATCOs must predict and simulate outcomes to achieve an effective resolution. Alpha waves are associated with the semantic memory storage in the long-term memory

(Klimesch, 1999). The semantic memory is related to knowledge and learning results, such as fact, concept and numerical process (Rihs et al., 2007). During the experiment phase, alpha wave frequency decreased during visual attention (Rihs et al., 2007); this indicates that higher visual attention was required when the two aircraft were at the same altitude (i.e. level conflict). This finding is supported by a prior study (Siddiqee, 1973), which stated that level conflict was more complex and often occurred during cruising.

Our second important finding was higher activation of theta frequency in the right temporal lobe during converging and crossing conflicts than during overtaking conflict. The function of the temporal lobe is to form memory and filter new information (Gamon, 2016). The main function of the right temporal lobe is forming nonverbal memory and aiding visual identification (Kimura, 1963). *Nonverbal memory* relevant to the ATCOs is memory about the airspace picture, route and radar map. ATCOs must possess high visual identification, since the radar monitoring process is extremely complex. ATCOs must identify the intersecting trajectory between the conflicting aircraft pair during crossing and converging conflicts, requiring high visual identification (Christien et al., 2002). In addition, theta waves deal with the episodic or short-term memory (Klimesch et al., 1994). Episodic memory plays a role in remembering new information. As this memory must store an increasing amount of information, the theta wave frequency will increase accordingly. Theta frequency is correlated with difficult mental activity, such as gathering, collecting, processing, learning and remembering information (Jimenez-Molina et al., 2018). The increase in theta frequency during converging and crossing conflicts showed that both conflicts required more episodic memory than did overtaking conflict. ATCOs tended to use short-term memory while resolving conflicts and directing the aircraft to the original position after the conflict point (Groome and Eysenck, 2016).

Our third finding indicated that converging and crossing conflicts also led to higher activation of theta frequency at the parietal lobe than did overtaking conflict. The parietal lobe has the main function of integrating information from sensory receptors to form perception and cognition and to represent it (CNS, 2017). Other functions of this lobe are to promote awareness of position (Frackowiak, 1998; Smelser and Baltes, 2001). This inferred that converging and crossing conflicts required higher awareness than did overtaking conflict. Because the former occurred on two different routes, the ATCOs had to consider the distance between and routes of both aircraft (Trapsilawati et al., 2018). Converging and crossing conflicts also demanded higher short-term memory than did overtaking conflicts since there are more complex aspects to be memorised in conflict resolution, such as the closest point of approach, aircraft routes, altitudes and speeds, whereas overtaking conflicts only required memory for speed and altitude.

The investigation of different conflict geometry and its effects on the objectives and physiological responses of ATCOs provide several implications for the air traffic monitoring (ATM) system. First, the results revealed that crossing and converging conflicts led to reduced SA, higher stress levels, and higher activation of temporal and parietal lobes than did overtaking conflicts. These findings could provide insights for the ATCO training system for conflict resolution that ATCOs should pay more attention in converging and crossing conflicts as well as preserving the aircraft sequence. During crossing conflict, for instance, an aircraft that is far from the airspace boundary or from top of descent should apply step altitude correction for optimum resolution (Erzberger, 2006). Hence, during training, ATCOs should practice more on determining the flight level for stepping up or stepping down relative to the current aircraft flight level. ATCOs should also be trained

Table 6. Summary of research results.

Problems	Hypotheses	Results	Findings
Conflict geometry effects on SA have never been studied	Higher SA would be observed during the resolution of conflict involving fewer dimensions.	SA was lower during converging conflict and when two aircraft were level.	Time pressure and visualisation loads exist in the converging and level conflicts.
Conflict geometry has never been examined on ATCO stress	ATCO stress level would vary depending on conflict geometries where stress level would be highly induced during the resolution of more-complex conflicts.	ATCO stress was higher during converging conflict.	Converging conflict was the most complex conflict for ATCOs due to high spatial and time dimensions.
No study analysing ATCO brain activity given various conflict geometries	Lobes and waves related to the visual attention, information processing, and memory would be more activated during the resolution of conflict involving more geometrical dimensions.	Alpha wave at the right frontal and theta wave at the right temporal as well as parietal lobes were activated.	Dynamic tracking of ATCO brain activity validated that converging and crossing conflicts required higher awareness and memory resources, while level conflict involved more visual attention.

to determine the time when aircraft will first lose separation and be in conflict, as well as the time required to return to its original position after applying step altitude correction. For converging conflict, a path stretch strategy may be applied to preserve the merging sequence (Erzberger, 2006). ATCOs should receive more training in estimating path stretch parameters, such as length of the path, its angle and the ground speed, as well as a speed profile of both aircraft. There is no formal standard used during ATCO training at this time; therefore, a standard should be formulated considering the cognitive load of various conflict geometry. For example, ATCOs should spend more hours in the training to resolve crossing and converging conflicts as mentioned above, and the resolution should also fit the utility in Rantanen and Wickens (2012).

Second, the results could be used as the inputs for the development of conflict resolution aid (CRA), a tool that not only alerts ATCOs about an impending conflict but also provides an advisory to resolve the conflict (Trapsilawati et al., 2016). Converging and crossing conflicts were proven to be most cognitively demanding for human operators; hence, the algorithm for resolution advisory generation of these conflicts should be carefully designed and must consider ATCO cognitive resources. The algorithm for converging and crossing conflicts could adopt resolution manoeuvre and aircraft selection (RAMS) proposed by Erzberger (2006), which can be done in two ways: through spatial domain or time domain. *Spatial domain* transforms a potential conflict encounter into relative position and velocity coordinates of only one aircraft in conflict, whereas the *time domain* method relies on time-shifting due to trajectory change. Integration of the ATCO's cognitive load toward a certain conflict geometry could further improve the selection of spatial- or time-based resolution in the CRA. For instance, a spatial domain that has fewer options should be selected for converging conflicts, thereby allowing ATCOs to better understand the CRA mechanism and get rid of the CRA should there is any reliability issue with it.

However, several limitations exist in this study. First, the medium fidelity of ATC might not fully reflect the real ATC system, given that other environmental factors, such as weather, were not considered during the study. Next, the participants in this study were students. However, our participants received adequate training for the experiment and they were eligible only after passing certain requirements in conflict resolution. Moreover, according to Rantanen and Nunes (2005), ATCOs and students had similar preference in instructing resolution manoeuvring. This study was exploratory in nature: it was our goal to identify what was happening with the objective measures and the brain activity of novice persons during conflict resolution; therefore, employing students as participants tailored the nature of the study (Goritzlehner et al., 2014).

6. CONCLUSION.

Investigation of the influence of conflict geometry on human factor elements has received little attention in prior aviation studies and is even more lacking in the context of ATCOs. The effects of conflict geometry on ATCO SA and stress level have never been examined. In addition, how ATCOs respond to various conflict geometries as reflected through their brain activity has also never been studied. To address these gaps, this study has empirically examined the effects of various conflict geometries on the ATCO SA, stress level and brain activity. The novelty of this study is highlighted and summarised through its findings, as shown in Table 6. The findings were conclusive that converging conflict led to lower SA than did overtaking conflict, due to the different number of aircraft attributes that must be considered. Level conflict also led to lower SA, and this implied that more cognitive resources were required for assessing level conflict because of its visualisation. These findings addressed the first problem, that time pressure and visualisation loads do exist in the converging and level conflicts affecting the ATCO SA. Correspondingly, converging conflict also triggered higher stress than did overtaking conflict. This reveals that converging conflict was the most complex conflict for ATCOs due to high spatial and time dimensions. These objective findings were also empirically supported by our physiological findings. The activation of alpha frequency at the right frontal lobe decreased during level conflict, indicating that higher visual attention was required. Theta frequency at the right temporal lobe was also activated during converging and crossing conflicts, showing that both conflict geometries used more episodic memory than did overtaking conflict. Next, the activation of theta frequency at the parietal lobe inferred that converging and crossing conflicts required high awareness than did overtaking conflict; because both former conflicts occurred on two different routes, ATCOs must consider the distance between and routes of both aircraft. Collectively, addressing the third problem regarding the dynamic tracking of ATCO brain activity, the findings of this study validated that converging and crossing conflicts require higher awareness and memory resources, while level conflict involves more visual attention. In sum, the examination of different conflict geometries on ATCO responses provide empirical supports for designing ATCO training system as well as conflict resolution automation for better ATC operations in the future.

ACKNOWLEDGEMENTS

The research was supported by research grant from the Department of Mechanical and Industrial Engineering, Universitas Gadjah Mada, Indonesia (Grant No. 841/H1.17/TMI/LK/2018).

REFERENCES

Abbass, H. A., Tang, J., Amin, R., Ellejmi, M., and Kirby, S. (2014). Augmented Cognition Using Real-Time EEG-Based Adaptive Strategies for Air Traffic Control. Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 58). Los Angeles, CA: SAGE Publications Sage CA, 230–234.

Astolfi, L., Toppi, J., Borghini, G., Vecchiato, G., He, E. J., Roy, A., Cincotti, F., Salinari, S., Mattia, D., He, B., and Babiloni, F (2012). Cortical Activity and Functional Hyperconnectivity by Simultaneous EEG Recordings from Interacting Couples of Professional Pilots. 2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE, 4752–4755.

Bernardi, G., Betta, M., Ricciardi, E., Pietrini, P., Tononi, G., and Siclari, F. (2019). Regional delta waves in human rapid eye movement sleep. *Journal of Neuroscience*, 39(14), 2686–2697.

Boag, C., Neal, A., Loft, S., and Halford, G. S. (2006). An analysis of relational complexity in an air traffic control conflict detection task. *Ergonomics*, 49(14), 1508–1526.

Borghini, G., Aricò, P., Di Flumeri, G., Salinari, S., Colosimo, A., Bonelli, S., Napoletano, L., Ferreira, A., and Babiloni, F. (2015). Avionic Technology Testing by Using a Cognitive Neurometric Index: A Study with Professional Helicopter Pilots. 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE, 6182–6185.

CANSO. (2012). Accelerating Air Traffic Management Efficiency: A Call to Industry. Paper of ATM Global Environment Efficiency Goals for 2050. Civil Air Navigation Service Organization.

Chatterji, G., and Sridhar, B. (2001). Measures for Air Traffic Controller Workload Prediction. Paper Presented at the 1st AIAA Aircraft, Technology Integration, and Operations Forum.

Christien, R., Benkouar, A., Chaboud, T., and Loubieres, P. (2002). Air Traffic Complexity Indicators & ATC Sectors Classification. In Proceedings of the 21st Digital Avionics Systems Conference. IEEE, 2D3-2D3.

CNS. (2017). Parietal Lobes. From www.neuroskills.com/brain-injury/parietal-lobes.php.

Dharmawan, Z. (2007). Analysis of Computer Games Player Stress Level Using EEG Data. *Master of Science Thesis Report, Faculty of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology, Netherlands*.

Di Stasi, L. L., Diaz-Piedra, C., Suárez, J., McCamy, M. B., Martinez-Conde, S., Roca-Dorda, J., and Catena, A. (2015). Task complexity modulates pilot electroencephalographic activity during real flights. *Psychophysiology*, 52(7), 951–956.

Durso, F. T., Hackworth, C. A., Truitt, T. R., Crutchfield, J., and Nikolic, D. (1999). Situation Awareness as a Predictor of Performance in En Route Air Traffic Controllers: DTIC Document.

Durso, F. T., Dattel, A. R., Banbury, S. and Tremblay, S. (2004). SPAM: The real-time assessment of SA. *A Cognitive Approach to Situation Awareness: Theory and Application*, 1, 137–154.

Emotiv. (2019). From www.emotiv.com/epoc/.

Endsley, M., Sollenberger, R., and Stein, E. (1999). The Use of Predictive Displays for Aiding Controller Situation Awareness. Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 43). Los Angeles, CA: SAGE Publications Sage CA, 51–55.

Erzberger, H. (2006). *Automated Conflict Resolution for Air Traffic Control*. Proceedings of the 25th International Congress of Aeronautical Sciences. Hamburg, Germany, 1–27.

Eyferth, K., Niessen, C. and Spaeth, O. (2003). A model of air traffic controllers' conflict detection and conflict resolution. Aerospace Science and Technology, 7(6), 409–416.

Falkland, E. C., and Wiggins, M. W. (2019). Cross-task cue utilisation and situational awareness in simulated air traffic control. *Applied Ergonomics*, 74, 24–30.

Frackowiak, R. S. J. (1998). The functional architecture of the brain. Daedalus (Vol. 127). Cambridge, MA: The MIT Press, 105–130.

Freitas, Â. M., Portuguez, M. W., Russomano, T., de Freitas, M., Silvello, S. L. D. S., and Costa, J. C. D. (2017). Effects of an alternating work shift on air traffic controllers and the relationship with excessive daytime sleepiness and stress. *Arquivos de Neuro-Psiquiatria*, 75(10), 711–717.

Gamon, D. (2016). Your Brain and What It Does. From www.brainwaves.com/.

Giraudet, L., Imbert, J.-P., Bérenger, M., Tremblay, S., and Causse, M. (2015). The neuroergonomic evaluation of human machine interface design in air traffic control using behavioral and EEG/ERP measures. *Behavioural Brain Research*, 294, 246–253.

Gomez-Beldarrain, M., Harries, C., Garcia-Monco, J. C., Ballus, E., and Grafman, J. (2004). Patients with right frontal lesions are unable to assess and use advice to make predictive judgments. *Journal of Cognitive Neuroscience*, 16(1), 74–89.

Goritzlehner, R., Borst, C., Ellerbroek, J., Westin, C., van Paassen, M., and Mulder, M. (2014). Effects of Transparency on the Acceptance of Automated Resolution Advisories. Paper Presented at the Systems, Man and Cybernetics (SMC), 2014 IEEE International Conference on.

Grandjean, E. P., Wotzka, G., Schaad, R., and Gilgen, A. (1971). Fatigue and stress in air traffic controllers. *Ergonomics*, 14(1), 159–165.

Groome, D., and Eysenck, M. (2016). *An Introduction to Applied Cognitive Psychology*. Psychology Press, Oxon, UK.

Hilburn, B. (2004). Cognitive complexity in air traffic control: a literature review. (EEC Note No. 04/04). Brétigny-sur-Orge. Center of Human Performance Research, France.

Histon, J. M., Hansman, R. J., Gottlieb, B., Kleinwaks, H., Yenson, S., Delahaye, D., and Puechmorel, S. (2002). Structural Considerations and Cognitive Complexity in Air Traffic Control. Proceedings. The 21st Digital Avionics Systems Conference (Vol. 1). IEEE, 1C2–1C2.

Hou, X., Trapsilawati, F., Liu, Y., Sourina, O., Chen, C.-H., Mueller-Wittig, W., and Ang, W. T. (2017). EEG-based human factors evaluation of conflict resolution aid and tactile user interface in future air traffic control systems. In: Stanton, NA., Steven Landry, S., Giuseppe Di Bucchianico and Andrea Vallicelli (EDs), *Advances in Human Aspects of Transportation*. Springer International Publishing, Switzerland, 885–897.

ICAO. (2013). *Identify Specific Training for Pilots and Air Traffic Controllers*. Bangkok, Thailand: International Civil Aviation Organization.

Isaac, A. R., and Ruitenberg, B. (2017). *Air Traffic Control: Human Performance Factors*. Routledge, Oxon, UK.

Jimenez-Molina, A., Retamal, C., and Lira, H. (2018). Using psychophysiological sensors to assess mental workload during web browsing. *Sensors*, 18(2), 458.

Jou, R.-C., Kuo, C.-W., and Tang, M.-L. (2013). A study of job stress and turnover tendency among air traffic controllers: the mediating effects of job satisfaction. *Transportation Research Part E: Logistics and Transportation Review*, 57, 95–104.

Kimura, D. (1963). Right temporal-lobe damage: perception of unfamiliar stimuli after damage. *Archives of Neurology*, 8(3), 264–271.

Kiroi, V. N., Aslanyan, E. V., Bakhtin, O. M., Minyaeva, N. R., and Lazurenko, D. M. (2016). EEG correlates of the functional state of pilots during simulated flights. *Neuroscience and Behavioral Physiology*, 46(4), 375–381.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. *Brain Research Reviews*, 29(2–3), 169–195.

Klimesch, W., Schimke, H. and Schwaiger, J. (1994). Episodic and semantic memory: An analysis in the EEG theta and alpha band. *Electroencephalography and Clinical Neurophysiology*, 91(6), 428–441.

Krozel, J., and Peters, M. (1997). Conflict detection and resolution for free flight. *Air Traffic Control Quarterly*, 5(3), 181–212.

Lagopoulos, J., Xu, J., Rasmussen, I., Vik, A., Malhi, G. S., Eliassen, C. F., and Holen, A. (2009). Increased theta and alpha EEG activity during nondirective meditation. *The Journal of Alternative and Complementary Medicine*, 15(11), 1187–1192.

Li, F., Lee, C. H., Xu, G., Chen, C. H., and Khoo, L. P. (2017). A QFD-enabled conceptualization for reducing alarm fatigue in vessel traffic service centre. *Transdisciplinary Engineering: A Paradigm Shift*, 821–828.

Li, J., Zhang, Z., and He, H. (2018). Hierarchical convolutional neural networks for EEG-based emotion recognition. Cognitive Computation, 10(2), 368–380.

Li, F., Chen, C. H., Lee, C. H., and Khoo, L. P. (2019a). A user requirement-driven approach incorporating TRIZ and QFD for designing a smart vessel alarm system to reduce alarm fatigue. *The Journal of Navigation*, 1–21, DOI: https://doi.org/10.1017/S0373463319000547.

Li, F., Chen, C. H., Lee, C. H., and Khoo, L. P. (2019b). Hybrid data-driven vigilance model in traffic control center using eye-tracking data and context data. Advanced Engineering Informatics, 42, 100940.

Murphy, E. D., Albert, H. A., Chen, J. M., and Anderson, G. G. (2012). The Role of Mental Computations in Current and Future En Route Air Traffic Control. Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 56). Los Angeles, CA: Sage Publications Sage CA, 110–114.

Nolan, M. (1999). *Fundamentals of air traffic control*. New York: Cengage Learning.

Nunes, A. (2003). The Impact of Automation Use on the Mental Model: Findings from the Air Traffic Control Domain. Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 47). Los Angeles, CA: SAGE Publications Sage CA, 66–70.

Pierce, L. G., Bleckley, M. K., and Crayton, L. (2013). The Utility of the Air Traffic Selection and Training Test Battery in Hiring Graduates of an Air Traffic-Collegiate Training Initiative Program. Federal Aaviation Administration Oklahoma City Civil Aerospace Medical Inst.

Prevot, T., Homola, J. R., Martin, L. H., Mercer, J. S., and Cabrall, C. D. (2012). Toward automated air traffic control—investigating a fundamental paradigm shift in human/systems interaction. *International Journal of Human-Computer Interaction*, 28(2), 77–98.

Rantanen, E. M., and Nunes, A. (2005). Hierarchical conflict detection in air traffic control. *The International Journal of Aviation Psychology*, 15(4), 339–362.

Rantanen, E. M., and Wickens, C. D. (2012). Conflict resolution maneuvers in air traffic control: investigation of operational data. *The International Journal of Aviation Psychology*, 22(3), 266–281.

Renata, V., Li, F., Lee, C. H., and Chen, C. H. (2018). Investigation on the Correlation between Eye Movement and Reaction Time under Mental Fatigue Influence. 2018 International Conference on Cyberworlds (CW). IEEE, 207–213.

Rihs, T. A., Michel, C. M., and Thut, G. (2007). Mechanisms of selective inhibition in visual spatial attention are indexed by α-band EEG synchronization. *European Journal of Neuroscience*, 25(2), 603–610.

Sarter, N. B., and Woods, D. D. (1991). Situation awareness: a critical but ill-defined phenomenon. *The International Journal of Aviation Psychology,* 1(1), 45–57.

Scallen, S., Smith, K., and Hancock, P. (1996). Pilot Actions During Traffic Situations in a Free-Flight Airspace Structure. Paper Presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting.

Shou, G., and Ding, L. (2013). Frontal Theta EEG Dynamics in a Real-World Air Traffic Control Task. 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE, 5594–5597.

Siddiqee, W. (1973). A mathematical model for predicting the number of potential conflict situations at intersecting air routes. *Transportation Science*, 7(2), 158–167.

Smelser, N. J., and Baltes, P. B. (2001). *International Encyclopedia of the Social & Behavioral Sciences* (Vol. 12). Elsevier Amsterdam, Oxford, UK.

Sperandio, J.-C. (1978). The regulation of working methods as a function of work-load among air traffic controllers. *Ergonomics*, 21(3), 195–202.

Suijkerbuijk, H. C. H., Borst, C., Mulder, M., and Van Paassen, M. M. (2005). Development and Experimental Evaluation of a Performance-Based Vertical Situation Display. AIAA Guidance, Navigation and Control Conference and Exhibit (August), 1–23. https://doi.org/10.2514/6.2005-5961

Tan, D., and Nijholt, A. (2010). Brain-computer interfaces and human-computer interaction. In: *Brain–Computer Interfaces*. Springer, London, 3–19.

Thomas, L. C., and Rantanen, E. M. (2006). Human factors issues in implementation of advanced aviation technologies: A case of false alerts and cockpit displays of traffic information. *Theoretical Issues in Ergonomics Science*, 7(5), 501–523.

Thomas, L. C., and Wickens, C. D. (2005). *Effects of Display Dimensionality, Conflict Geometry, and Time Pressure on Conflict Detection and Resolution Performance Using a Cockpit Display of Traffic Information (A. H. F. Division, Trans.).* Savoy, Illinois: Institute of Aviation, University of Illinois at Urbana-Champaign.

Trapsilawati, F., Chen, C. H., and Khoo, L. P. (2016). An Investigation into Conflict Resolution and Trajectory Prediction Aids for Future Air Traffic Control. ISPE TE, 503–512.

Trapsilawati, F., Wickens, C., Chen, C. H., and Qu, X. (2017). Transparency and Conflict Resolution Automation Reliability in Air Traffic Control. 19th International Symposium on Aviation Psychology, 419.

Trapsilawati, F., Nugraheni, A. S. A. N. S., and Herliansyah, M. K. (2018). Analysis of Air Traffic Conflict Geometry on Brain Activity. 2018 4th International Conference on Science and Technology (ICST) (Vol. 1). IEEE, 1–5.

*USDOT. (2016). Number of Pilot-Reported Near Midair Collisions (NMAC) by Degree of Hazard. From US Department of Transportation. www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_02_15.html.

Wee, H. J., Lye, S. W., and Pinheiro, J. P. (2018). A spatial, temporal complexity metric for tactical air traffic control. *The Journal of Navigation*, 71(5), 1040–1054.

Wee, H. J., Lye, S. W., and Pinheiro, J. P. (2019). An integrated highly synchronous, high-resolution, real-time eye tracking system for dynamic flight movement. *Advanced Engineering Informatics*, 41, 100919.

Weiland, M. Z., Roberts, D. M., Fine, M. S., and Caywood, M. S. (2013). Real-Time Research Methods: Monitoring Air Traffic Controller Workload During Simulation Studies Using Electroencephalography (EEG). Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 57). Los Angeles, CA: SAGE Publications Sage CA, 1615–1619.

Westin, C. A., Borst, C., and Hilburn, B. (2013). Mismatches between automation and human strategies: An investigation into future air traffic management decision aiding. 17th International Symposium on Aviation Psychology. Wright University, Dayton, OH, 530–535.

Wilson, G. F. (2002). An analysis of mental workload in pilots during flight using multiple psychophysiological measures. *The International Journal of Aviation Psychology*, 12(1), 3–18.

Yang, Q., and Dattel, A. R. (2017). Task Complexity and Time Pressure Affect Air Traffic Controller's Performance and Workload. 19th International Symposium on Aviation Psychology, 359.

Zeier, H. (1994). Workload and psychophysiological stress reactions in air traffic controllers. *Ergonomics*, 37(3), 525–539.